Chapter 1

Agricultural Uses of Biosolids and Other Recyclable Municipal Residues

P.D. Millner, L.J. Sikora, D.D. Kaufman, and M.E. Simpson

In the United States, the traditional management practices used for biosolids (also known as sewage sludge) and municipal solid residues (MSW) were driven by the "disposal" concept rather than the resource recovery concept. These traditional practices are now recognized as environmentally, ecologically, and economically inadequate. As a nation we are generating more organic, recyclable municipal residues than ever before, and many areas are rapidly exhausting their standard options for the safe, effective management of these materials. Handling capacity of landfills and some older incinerators continues to decrease. Regulatory guidelines and limits to traditional biosolids and residue management practices also are being implemented at national, state, and local levels. Federal Sub-title D regulations imposing strict liner and management requirements were fully effective in 1994. Thus, it is increasingly difficult to keep existing landfills open or to establish new facilities. In 1995, a total of 3,197 landfills were in operation, but this total was 361 fewer than in 1994 and 4,803 fewer than in 1988 (Steuteville 1996). By 1997, 20 percent of states could exceed their landfill capacity (Repa and Sheets 1992).

Communities face hard choices when evaluating the array of management options available. New York City, for example, has paid premium prices to transport its residues long distances to sites willing to accept and use them. Other communities have encountered intense public debate when siting treatment facilities close to collection sites. Not all communities, however, face such problems. Some have found creative solutions through source reduction and recycling programs and have been able to site new, environmentally acceptable facilities. Still, for much of the Nation, innovative solutions for residue management are much needed.

Identification and characterization of the constituents are an essential first step in developing suitable plans and strategies to deal with the problems associated with biosolids and recyclable organic residues management. For example, characterization of municipal solids involves estimating how much of each component in the mixture is generated, recycled, incinerated, and disposed of in landfills. The data are used to establish management goals and plans at the national, state, and local levels. Characterization of the materials can reveal opportunities for source reduction and recycling and provide data on unique management and application issues (Cook et al. 1994).

Quantities and Management of Municipal Solid Residues (MSW) and Biosolids

MSW

In 1990, the U.S. Environmental Protection Agency (1990a) estimated 177.7 million Mg (1 Mg = 1 metric ton = 1.10 U.S. tons) of MSW were generated in the United States (table 1). This is equivalent to 1.95 kg per person per day (Finstein 1992). After materials recovery for recycling and composting, discards were 1.63 kg per person per day. Virtually all of these discards were incinerated or landfilled. In 1995, 297 million Mg of MSW were generated (fig. 1), with 27 percent recycled, 10 percent incinerated, and 63 percent landfilled (Steuteville 1996). The amount of MSW produced is higher than the figures reported by the U.S. Environmental Protection Agency, which based estimates on per capita rates and the use of estimated disposal by states and did not include biosolids, yard trimmings, and recycling projects (Glenn 1990).

Both volume and weight of MSW are used to evaluate the scope of the recycling problem; volume is used to estimate how quickly landfills will reach capacity and the rate of change of various materials in the residue stream. A breakdown of the 1990 MSW by weight and volume is shown in table 1. Paper and paperboard products are the largest component of MSW by weight (37 percent) and by volume (32 percent). Yard trimmings are the second largest component (18 percent by weight). Glass, metals, plastics, wood, and food residues range from 6 to 9 percent each by weight. Rubber and leather, textiles, and miscellaneous organic solids comprised less than 4 percent each of MSW. Paper and plastics (combined) accounted for over half of the volume of MSW discarded in 1990. The three methods of disposal of MSW in 1990 were landfilling, recycling, and incineration—118, 30, and 21 million Mg of residues were disposed by these methods, respectively (U.S. Environmental Protection Agency 1990a). The composition of MSW indicates

Table 1. Weight, volume, and recovery of municipal solid residues (MSW)* in 1990

	Weight generated (million Mg)	Weight recovered (million Mg)	Percent recovery of material generated	Material discarded (million Mg)	Weight of MSW (% of total)	Volume of MSW (% of total)	Ratio† of vol % to weight %
Paper and paperboard	66.6	19.0	28.6	47.6	37.5	31.9	0.9
Glass	12.0	2.4	19.9	9.6	6.7	2.2	0.3
Metals							
Ferrous	11.2	1.7	15.4	9.4	6.3	8.9	1.4
Aluminum	2.5	0.9	38.1	1.5	1.4	2.2	1.6
Nonferrous	1.5	0.7	67.7				
Plastics	14.7	0.4	2.2	14.4	8.3	21.1	2.5
Rubber and leather	4.2	0.2	4.4	4.0	2.4	6.1	2.5
Textiles	5.1	0.2	4.3	4.8	2.9	6.4	2.2
Wood	11.2	0.4	3.2	10.8	6.3	6.8	1.0
Food scraps	12.0	‡	‡	12.0	6.7	3.2	0.5
Yard trimmings	31.8	3.8	12.0	28.0	17.9	9.8	0.5
Miscellaneous inorganics	2.6	‡	‡	1.4			
Other	2.9	0.7	23.8	5.2	1.6	1.4	0.4
Total	177.7	30.3	17.1	147.4	100	100	1.0

* MSW includes durable and nondurable goods, containers and packaging material, food scraps, yard trimmings, and miscellaneous inorganics from residential, institutional, and industrial sources. Residues include appliances, newspapers, clothing, boxes, disposable tableware, office and classroom paper, wood pallets, and cafeteria scraps. Specifically excluded from MSW are construction and demolition materials, municipal sludge, combustion ash, and industrial process residues and byproducts.
† Ratios greater than 1.0 indicate that the materials are less dense and occupy a greater proportion of landfill space by volume than by weight; the converse is true for materials with ratios of 0.5 or less.
‡ Negligible.
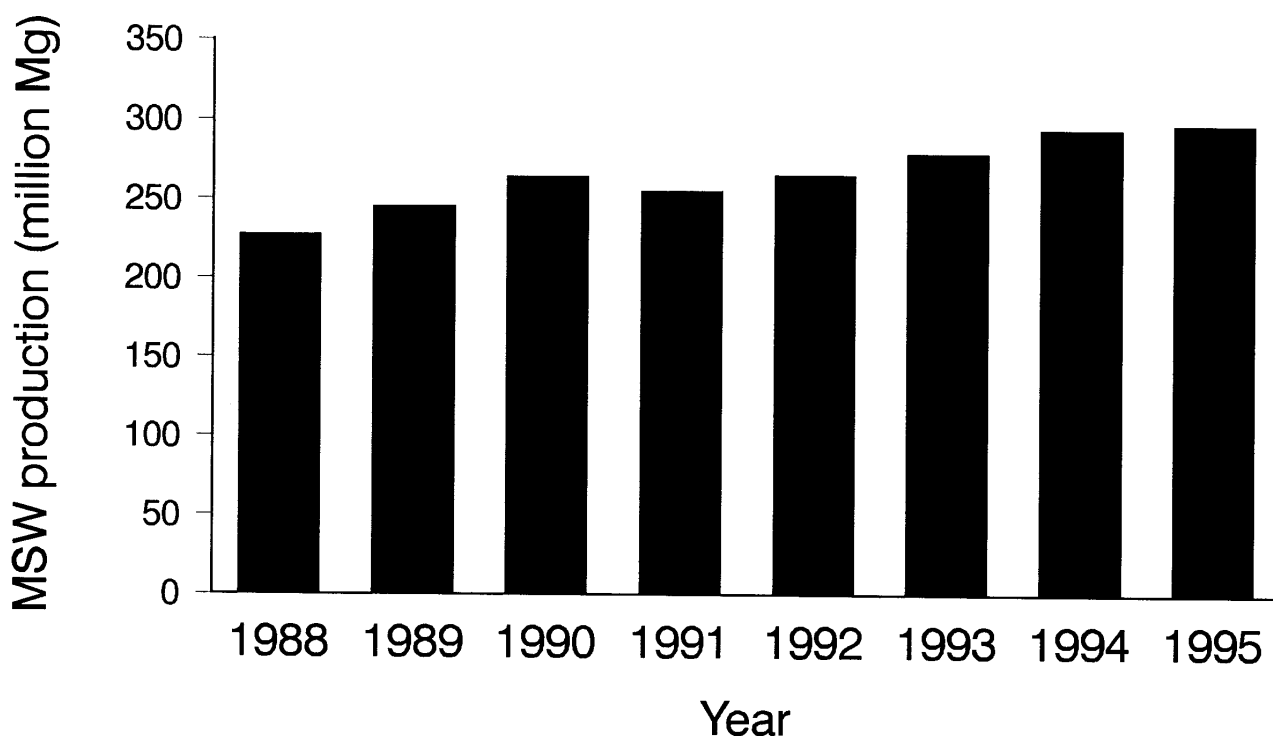
Figure 1. Municipal solid residue (MSW) production in the United States

that 70–80 percent of the residue stream is combustible, recyclable, or compostable (Clarke 1992).

The strong upward trend in recycling is evident in the 82 percent increase in the number of materials-recovery facilities operating in the United States—up from 177 in 1992 to 322 in 1995 (Berenyi 1995). Nationally, the recycling rate in 1995 reached 27 percent for MSW (Steuteville 1996), with 7,375 curbside programs serving 121 million U.S. citizens and 8,773 dropoff sites distributed among 35 states. Of the 53 million Mg of recyclables recovered (from 28 states reporting), about 14 percent (7.1 million Mg) were yard trimmings, which were primarily composted. Separated paper products, plastics, glass, metals, and commingled materials account for the majority of the remaining mass. In Florida, where segregated curbside collection is provided, 60 to 80 percent of all yard trimmings generated are collected. However, only 10 to 25 percent of the total generated volumes of yard trimmings are routed to dropoff sites when an alternative collection program is used. It is estimated that in 1997, about 35.5 million Mg of yard trimmings will be generated in the United States and about 9 million Mg will be composted (Kashmanian, 1993). Clearly, the United States is on a path of increasing recycling.

Biosolids

The U.S. Environmental Protection Agency (1990b) estimated that about 7.7 million Mg (29.1 kg per capita) of biosolids are generated in the United States annually; the projection for the year 2000 was 15.4 million Mg (U.S. Environmental Protection Agency 1989b). With the expected growth in population, technological improvements in biosolids treatment plant operations, the Federal restrictions on ocean dumping, and the 40 CFR 503 rules for land application of biosolids containing high concentrations of metals and toxic organic chemicals (U.S. Environmental Protection Agency 1993), biosolids production and concurrent disposal needs will also increase.

Landfills in the United States simply will not accommodate the expected high-volume input (U.S. Environmental Protection Agency 1990b). Unless the United States develops and implements the necessary technology to reduce its heavy reliance on landfilling and incineration, the Nation will not meet the U.S. Environmental Protection Agency's outlined goals and objectives for improving environmental (soil, water, and air) quality (U.S. Environmental Protection Agency 1989a). Equally significant to these goals is the urgent need to implement programs based on the sustainable growth and development vision that

involves all sectors of the Nation's economy. One of the clearly critical elements of this vision requires development of economic recovery methods and appropriate reuse of resources through recycling. Our national obligation to conserve and protect our natural resources can be partially fulfilled through biosolids and organics recycling.

Improving management and beneficial use of municipal solids

The national recycling goal, which encompasses resource recovery, reuse, recycling, and reduction of landfill volume, called for an increase in recycling of MSW by 25 percent by 1992 (U.S. Environmental Protection Agency 1989c). Parr and Hornick (1992) estimated that meeting this goal would result in a 55-percent decrease in the amount of MSW placed in landfills and a 20-percent increase in the amount incinerated. To achieve this goal, some municipalities have implemented source separation and collection programs to recycle paper, metals, glass, and plastics and to collect and compost yard trimmings. Jurisdictional prohibitions against landfilling yard materials have helped create municipally operated or contracted collection and composting operations, which produce compost that is used in a wide variety of horticultural and landscape situations. In addition some localities have encouraged backyard composting of yard trimmings and some other residues and have sought guidance from private foundations experienced with small-scale composting techniques (Rodale Press 1982). Other communities have selected the alkaline stabilization process to transform biosolids into a low-analysis mixture of organic fertilizer and agricultural limestone (Logan and Burnham 1995).

Composting

Composting is a time-honored practice used to convert organic residues into useful soil conditioners and biofertilizers. The practice is viewed as a viable and important means of stabilizing and transforming municipal solid residues for safe and beneficial use in agricultural, horticultural, and forestry operations (U.S. Environmental Protection Agency 1989a–c, U.S. House of Representatives 1990, Parr and Hornick 1992). Several of the problems (for example, malodors, human pathogens, and undesirable chemical and physical properties) that occur when raw and unstable organic materials are directly applied to soil can be resolved by composting.

Composting is a self-heating microbiological process in which the decomposition of organic materials is accelerated by the growth and enzymatic activity of mixed populations of bacteria and fungi (Miller 1991). Composting can occur aerobically or anaerobically (Gotaas 1956), but the aerobic mode is preferable because it minimizes the production of malodors, speeds decomposition, and produces high temperatures necessary to thoroughly and rapidly destroy pathogens and to dry the mixture.

One of three possible process styles—windrowing, static aerated piles, or in-vessel (Haug 1980)—are typically used at composting facilities concerned with high throughput of feedstocks. Both the static aerated pile and the in-vessel approaches offer more control over critical process parameters than does windrowing. The latter is often established by communities because it is far simpler to operate and has lower capital requirements than either of the other two (Reinhart et al. 1993). Such features are particularly appealing to farmers who are interested in starting on-farm operations using existing equipment with few additional capital expenditures. Windrow composting was the second most common style of composting reported in a recent survey, with 78 projects of 281 using this type of composting (Goldstein and Steuteville 1995). In-vessel composting was operating at 66 of the 281 projects in that same survey.

The Beltsville Aerated Pile Method (static aerated pile) was developed to rapidly compost biosolids and has been readily adopted by more than 111 U.S. cities and municipalities (Parr and Willson 1980, Willson et al. 1980, Goldstein and Steuteville 1995). When static aerated pile composting is operated using a temperature feedback control system, the composting materials are rapidly dried though the process of evaporative cooling.

The U.S. Environmental Protection Agency (1993a) established rules based on cumulative pollutant loading rates for application of biosolids onto agricultural and nonagricultural land. These rules apply to any materials containing biosolids regardless of their treatment (composting, chemical fixation, or digestion) or blending with other substances after production.

Alkaline stabilization

Pathogen destruction and organic matter stabilization are critical outcomes that must be achieved by good management of biosolids. In the case of composting, the destructive heat, ammonia, and consequent drying are generated by biological (microbial) activities, whereas purely chemical, exothermic reactions gener-

ate the destructive pH, heat, and drying that occur with alkaline stabilization processes.

Appropriate technology for blending alkaline byproducts (ABs) with biosolids, or with mixtures of organic materials containing biosolids, was developed in the 1980's and has been used as an alternative to composting. Logan and Burnham (1995) have described the process principles and product uses for one of the commercial processes that has successfully applied the technology to biosolids. They noted that ABs that have a large content of free lime (such as cement kiln dust, lime kiln dust, and coal combustion ash), can be mixed at a rate of up to 25 to 50 percent (wet weight basis) of dewatered biosolids. Such mix ratios can raise the pH of the resulting product to 12 or greater. The fine particle size and low moisture status of ABs contribute significantly to successful stabilization of raw primary, waste-activated, or digested biosolids, with total solids ranging from 18 to 40 percent (wet weight dewatered biosolids basis). When the blending speeds (pug mills or screw presses) are adjusted to accommodate a selected mixing ratio, the resultant product is a soil-like, granular material that can be processed further in either of two ways to assure thorough destruction of pathogens and organic matter stabilization and to increase solids content to 65 percent by weight.

Value of Recovered Organics as Biofertilizers and Soil Conditioners

Parr and Hornick (1992) have delineated the essential factors involved in assessing the value of organic residues. They stated that evaluation can be approached in terms of fertilizer equivalency, capacity to alter soil physical properties, and agronomic impact on crop yield and quality. The most direct method of evaluating organic residues is to determine crop yield from those residues and the current economic (market) value of the plant nutrients found in the product, especially of N, P, and K (table 2 lists the value of some organic residues). In some cropping situations, the secondary plant nutrients (S, Fe, Mg), micronutrients (Cu, B, Zn, Mn, Mo), and lime equivalency values also need to be assessed. The value of some materials (such as soil conditioners and biofertilizers) could be negative if they contain high amounts of soluble salts, heavy metals, or hazardous organic chemicals or have high C:N ratios or extreme pH values (Parr et al. 1983).

Table 2. Value of some organic residues based on their macronutrient content

Organic residue	Nutrients (%)			Value* ($ Mg^{-1})
	N	P	K	
Cattle manure	4.4	1.1	2.4	23.47
Crop residues	1.1	0.2	2.0	8.44
Biosolids	4.0	2.0	0.4	21.40
Municipal solids	0.7	0.2	0.3	3.66

*Value Mg^{-1} of N, P, and K was set at $0.30, $0.37, and $0.20, respectively, based on average dealer prices of fertilizers at midwest terminal locations in December 1990.

Sources: Parr and Colacicco (1987), U.S. Department of Agriculture (1978), Parr and Hornick (1992). Reprinted from Parr and Hornick (1992, p. 552) courtesy of Marcel Dekker.

The soil conditioning value of organic wastes is profound on marginal or severely eroded lands that were reclaimed through the application of composted biosolids and feedlot manure (Hornick 1982, Hornick and Parr 1987). The economic value (that is, the fertilizer, lime, and secondary and micronutrient equivalency values) of organic residues are more easily assessed than the soil conditioning value.

In addition to the nutrient equivalency and soil conditioning values, the agronomic value (crop yield or crop quality) is used to determine the benefit of adding a particular material (Parr and Hornick 1992). Whereas there is substantial evidence of a positive effect on crop yield, there are very few reliable experimental evaluations of the effects on crop quality. The yield response to organic wastes is generally nonlinear and, at present, unpredictable because the interactions and interdependency of crop, soil type, climatic factors, soil and crop management practices, and properties of the residue material are incompletely understood. Crop yields tend to follow the law of diminishing returns— the greatest yields result from application of the first several increments of material, and gradually the yield increases level off with subsequent additions (table 3). Thus, the highest agronomic value per unit of organic material occurs at lower application rates.

Because the nutrient content of most municipal, industrial, or rural organic residues is generally low (Parr and Colacicco 1987), adding small amounts of synthetic fertilizers to them may increase their agronomic value. Generally, the net profit attributable to the use of organic amendments will depend on the properties of the material, the cost of transportation

Table 3. Effects of single applications of biosolids applied to soil in 1972 and an annual application of chemical fertilizer on corn grain yields

Treatment*	Corn grain yields (hundreds of kg ha^{-1})					
	1972	1973	1974	1975	1976	Average
Biosolids						
0 dry Mg ha^{-1}	25.1	21.1	6.8	16.2	0.91	4.0
56 dry Mg ha^{-1}	55.4	68.7	64.6	54.4	38.5	56.3
112 dry Mg ha^{-1}	66.5	102.8	68.7	66.0	67.1	74.4
224 dry Mg ha^{-1}	61.2	108.4	76.5	69.4	69.2	76.9
N–P–K fertilizer[†]	34.3	51.0	57.6	50.1	47.7	48.2

* Biosolids were applied at the rates indicated (Mg ha^{-1}, dry weight basis) in 1972 only. No inorganic fertilizer was applied.

[†] Fertilizer plots received 180 kg ha^{-1} of N, 40 kg ha^{-1} of P, and 75 kg ha^{-1} of K each year of the study; no biosolids were applied.

Sources: Barbarika et al. (1980), Decker et al. (1977). Reprinted from Parr and Hornick (1992, p. 553) courtesy of Marcel Dekker.

and application, and the market value of the crop (Parr and Hornick 1992). Parr and Hornick (1992) noted that studies by Barbarika et al. (1980) and Decker et al. (1977) on corn show that the grain yields (and therefore financial gains) of a crop in subsequent years could be as high or higher than yields in the first year (table 3). This phenomenon is linked to the slow release of N and P from the decomposing organic amendments that become mineralized and available for plant uptake and growth over the long term.
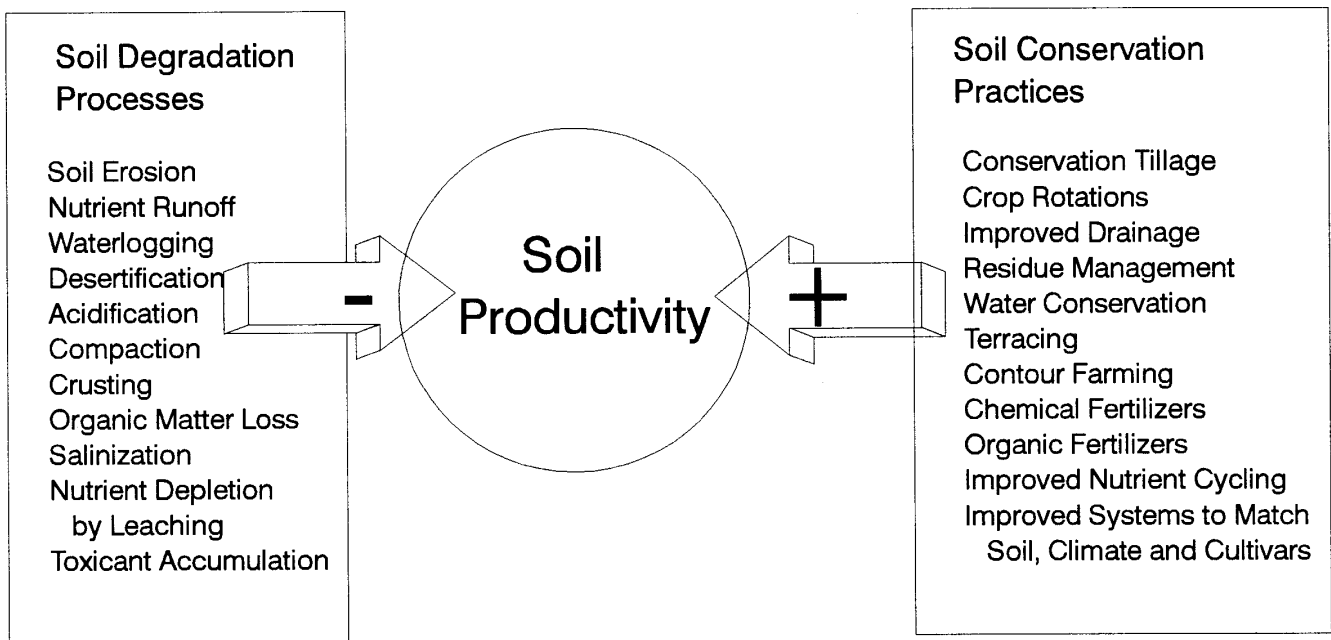
Parr and Hornick (1992) calculated the value of biosolids at $10.28 per Mg, based on the fertilizer equivalency values in table 2 and a corn grain yield of 4,800 kg ha^{-1} but excluding hauling and spreading costs. Hyatt (1995) discussed the need for a "net present value" method for calculating the financial advantage of long-term compost application versus several other alternatives. He presented a model (Hyatt 1995) designed to consider the economic value of compost's residual N (that is, N available after the year in which it was applied). The model showed that compost gave a total net return of $14.60 ha^{-1} greater than chemical N, given the carefully considered input values used for calculations in the model.

Soil productivity is affected by various factors that may degrade or improve soil properties (fig. 2). Regular recycling of organic materials on the farm such as animal manures and crop residues will improve the tilth, fertility, and productivity of agricul-

tural soils by protecting them from wind and water erosion and preventing nutrient losses from runoff and leaching. In some agricultural situations, limited supplies of good-quality organic materials are available on the farm to provide adequate soil and water conservation (U.S. Department of Agriculture 1978). In such cases, composts produced from biosolids and biodegradable fractions of MSW or alkaline stabilized biosolids or manures could be used to improve soil productivity.

Composts are more stable and easier to handle, store, transport, and apply than noncomposted organic residues. Parr and Hornick (1992) characterized noncomposted biosolids as organic material that has a high nutrient availability index (NAI) and that decomposes and mineralizes rapidly in soils. This decomposition releases significant amounts of N and P for plant uptake. In contrast, they characterized composted biosolids as an organic material with a high organic stability index (OSI), that is, a slow rate of decomposition in soil and a slow rate of nutrient release. In general the NAI value of an organic material is inversely related to its OSI value. Thus, composted or co-composted biosolids and MSW generally can be expected to have a greater inherent value as soil conditioners than as rapidly available sources of plant nutrients. Such materials may serve as fertilizer supplements but not usually as sole nutrient sources.

Parr and Hornick (1992) noted that a major part of municipal organic residues could be used beneficially

Soil Degradation Processes		Soil Conservation Practices

Soil Degradation Processes

Soil Erosion
Nutrient Runoff
Waterlogging
Desertification
Acidification
Compaction
Crusting
Organic Matter Loss
Salinization
Nutrient Depletion
   by Leaching
Toxicant Accumulation

Soil Productivity

Soil Conservation Practices

Conservation Tillage
Crop Rotations
Improved Drainage
Residue Management
Water Conservation
Terracing
Contour Farming
Chemical Fertilizers
Organic Fertilizers
Improved Nutrient Cycling
Improved Systems to Match
   Soil, Climate and Cultivars

Figure 2. Positive and negative factors influencing soil productivity

on agricultural lands, especially on highly erodible land such as that in the Conservation Reserve Program (CRP). They estimated that about half of the 14 million ha in the CRP that have been set aside and planted primarily with perennial grasses could be returned to crop production. They proposed that waste application integrated with crop rotation systems be developed to prevent soil movement on such highly erodible lands. Research supporting this use of organic residues would be highly beneficial to a vast amount of agricultural soils that are at risk of degradation.

Although the potential for agricultural use of composted, co-composted, alkaline-stabilized, or uncomposted municipal materials is very large, currently they have not been used on most agricultural soils because the quality of the finished products is unpredictable (though in only a few cases have they been shown to be detrimental to plant establishment and growth). Future development and marketability of the products will require appropriate technology for reliable production and quality-assurance testing. Soil conditioners and biofertilizers produced must be of high quality and must be economical to distribute and apply. Development of such products will require some cooperation among urban, rural, scientific, and economic communities to solve problems associated with the costs of processing, transporting, and applying municipal residues. Researchers (Kashmanian et al. 1990, Parr and Hornick 1992) agree that very large quantities of municipal residues can and should be

used on agricultural soils in the future in an effort to improve their productivity and quality. Research and solid interpretive analyses are needed to ensure that municipal residue recycling on land is safe, reliable, and beneficial, as well as economical to both the urban and agricultural sectors.

Costs of Collecting, Processing, Transporting, and Applying MSW

Continually increasing production of MSW in the United States and concurrent reduction in the number of landfills in operation, coupled with environmental pressures for a 25-percent reduction in landfilling (Gibson 1991), have strengthened the need for alternative methods for handling MSW. Costs of handling MSW have skyrocketed, controls have tightened, and technologies are slow and costly to develop. Pressures to meet Federal regulation of MSW facilities (pursuant to Subtitle D of the 1976 Resource Conservation and Recovery Act) through state and local government implementation are compounded by increased tipping fees at reprocessing and treatment facilities and public opposition to siting these facilities. Local governments historically have expended more on solid waste than have Federal or state governments because local governments bear primary responsibility for provision of services to households. In 1972 and 1987, local solid waste costs were $3.5 and $6.3 billion, respectively. Total costs are projected to reach about $9.5 billion by the year 2000 (U.S. Environmental Protec-

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tion Agency 1991). These problems and the cost of solving these problems encourage the creation of competitive uses for residues.

Tipping fees at United States landfills have increased to an average of about $29.50 per Mg, and the more densely populated areas have much higher fees (fig. 3). For example, in the Northeast, the average tipping fee is $51.51 per Mg. Connecticut has the most expensive fee at $71.50 per Mg. The Rocky Mountain states and the Midwest have the lowest fees. Compounding the problem of higher tipping fees is a reduction in usable landfill space. While some facilities have been closed because they failed to meet regulations, others are closing because they are full. In the United States, there were 7,924 operating landfills in 1988 but only 3,197 by 1995 (fig.4).

Costs for all types of processing systems are rising. In 1988, there were 115 U.S. composting facilities processing approximately 1,450 Mg of dry biosolids daily. These facilities were constructed at a capital expenditure in excess of $1 billion and have operating costs estimated at $100 million (Finstein 1989). A study of eight in-vessel composting systems revealed that each of the eight was using sawdust as an amendment. The cost of the sawdust was $3.92 to $18.64 per m^3 of sawdust. Of these eight systems, the cost per dry Mg of biosolids processed ranged from $110 to $418 (Johnston et al. 1989). In another study, 10 facilities were evaluated for capital and operational costs. Capital costs ranged from $250,000 to $78 million, and operational costs from $240,000 to $30 million (Curtis et al. 1992).

Yard trimmings have been identified in a majority of jurisdictions as the most readily and obviously compostable materials that need to be diverted from landfills to the recyclables market. Many communities now have or are planning to establish facilities for leaf and grass composting. Operating and capital costs of composting sites are important considerations for communities planning such recycling programs.

In an effort to aid planners, a comparative costs study was conducted at several composting facilities that represented a broad range of technological requirements and three levels of handling capacities (Renkow et al. 1994). Results showed that facilities handling 10 to 25 Mg yr^{-1} and turning piles only 2 to 3 times per year with a front-end loader on a packed clay surface are clearly the least costly to establish ($183,000 to

$254,000) and operate ($49,000 to $66,000 yr^{-1}). However, the product from these facilities will likely be unscreened and of poor quality unless extra measures are taken to refine the material after composting. Furthermore, it was estimated that the process would take 36 mo, and the volume of the materials processed would be reduced only 30 percent. In comparison, facilities that are paved with asphalt or concrete and on which piles are turned once a month will have startup costs ranging from $280,000 to $440,000 when they process 10,000 Mg yr^{-1} and will have startup costs of $446,000 to $646,000 when they process 25,000 Mg yr^{-1}. Operating costs for these low-technology, paved sites range from $77,000 to $98,000 when they process 10,000 Mg yr^{-1} and $138,000 to $190,000 when they process 25,000 Mg yr^{-1}. With such increased costs, the product can be expected to be of low-to-moderate quality (unscreened), and the volume will be reduced 40 percent in 12 mo. Use of more sophisticated equipment, such as compost turners and screeners, along with a more frequent turning schedule will result in a consistently better quality product and a 50 to 55 percent reduction in volume within a shorter time (6 mo). From this comparative study, it is clear that lower cost methods of paving sites need to be explored so that startup and operating costs can be reduced without having to sacrifice the benefits of a stabilized work surface. Also, the use of alkaline byproducts as surface stabilizers should be investigated.

The city of Scranton, PA, built a biosolids composting facility with a processing capacity of 23 dry Mg of biosolids (aerated static pile method). The cost of construction was $3,338,000, and operational and maintenance costs were calculated to be $18.81 per wet Mg of biosolids processed (Elliott and Polidori 1988).

Agronomic Uses of Untreated and Treated Municipal Residues

Nutrient properties of treated and untreated residues

Municipal residues have variable nutrient values (or fertilizer values) depending on their source and treatment. Untreated residues such as raw biosolids may be similar to animal manures, which have a relatively high NAI and high N and P contents. MSW's are generally low in nutrients because they contain considerable paper and yard waste. Processes such as digestion or composting result in the loss of
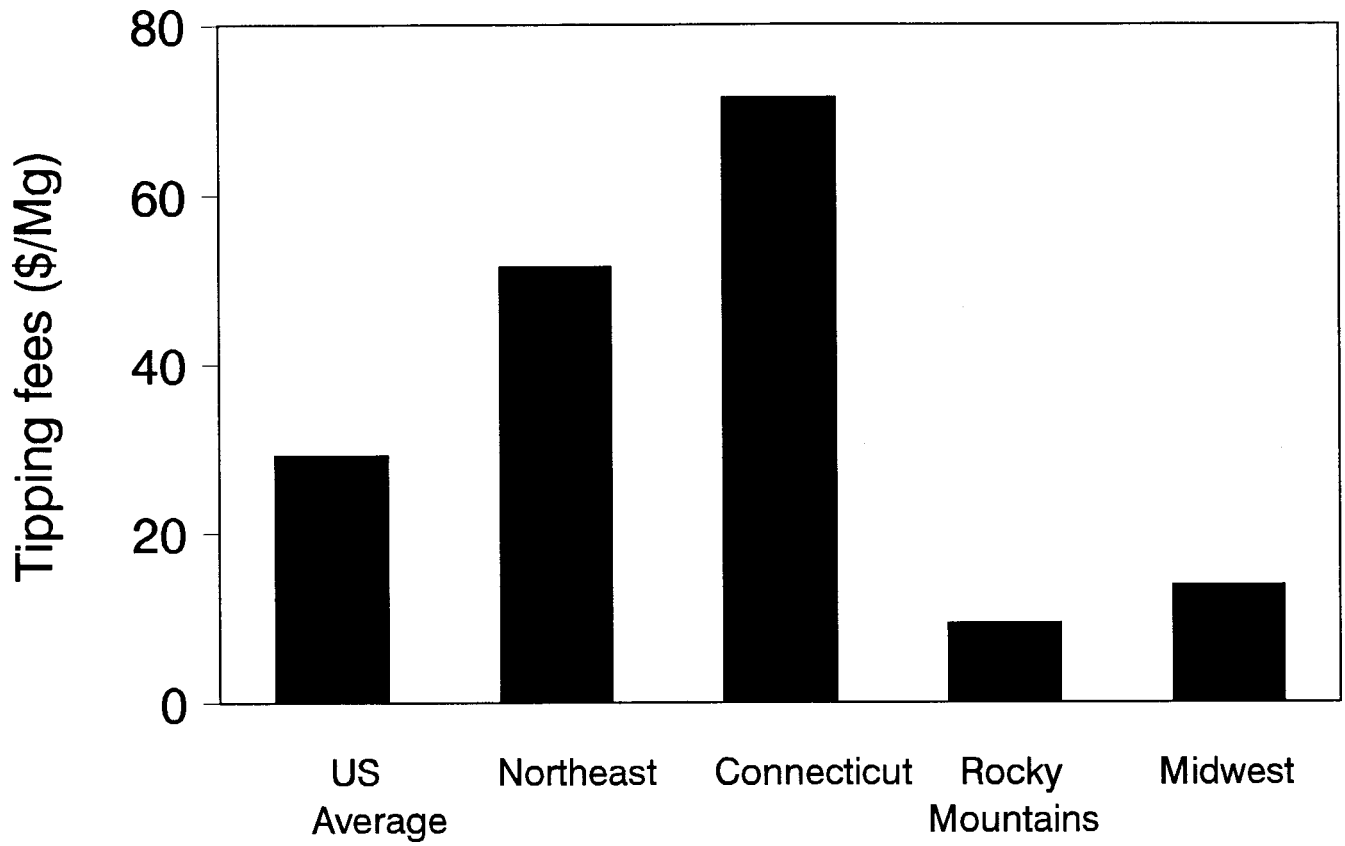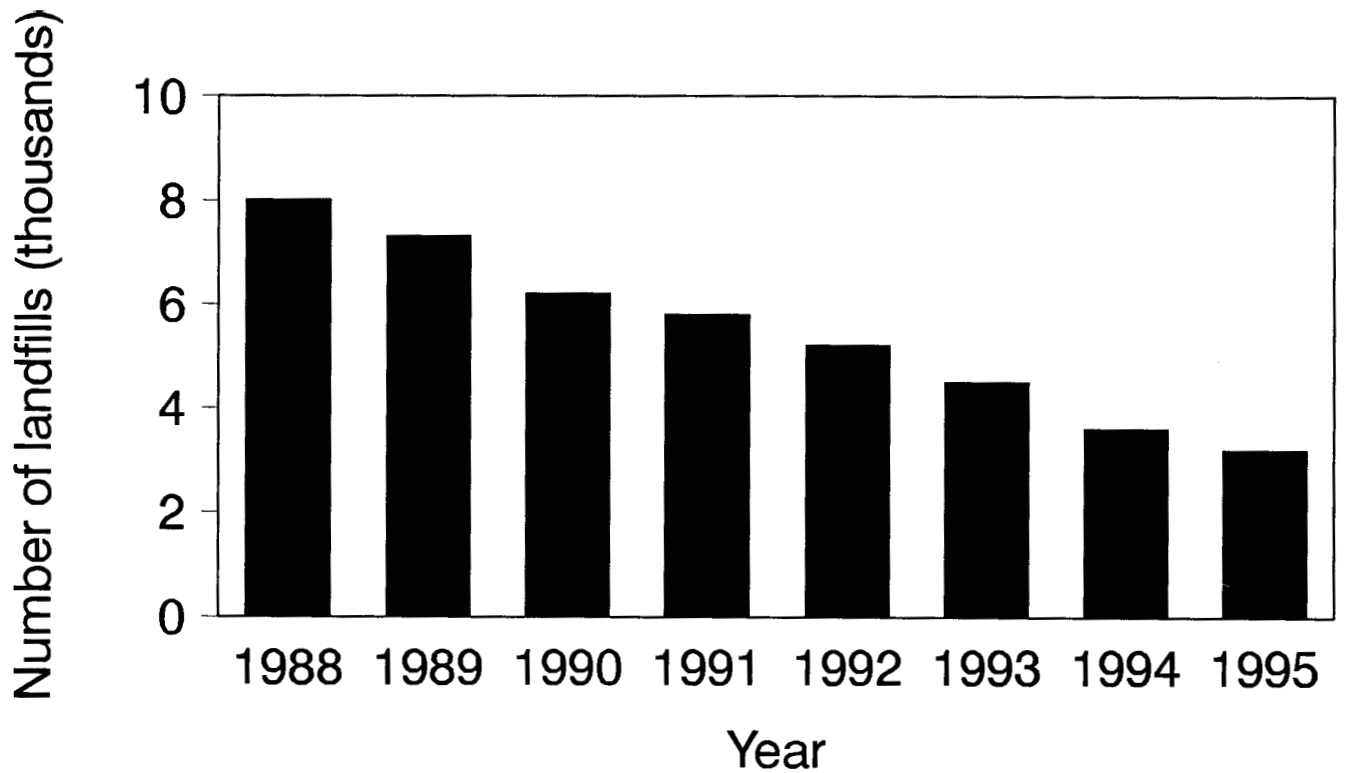
Figure 3. Average landfill tipping fees

Figure 4. Number of landfills in operation in the United States

organic matter through decomposition and will (1) increase concentrations of "conserved" (slightly soluble and nonvolatile) nutrients such as P and trace metals, (2) decrease ammonia-N by volatilization, and (3) decrease K by leaching.

When biosolids are added to soil, the type of soil, the methods used to produce the biosolids, and the C:N ratios of the biosolids and the soil affect the mineralization of the biosolids N (Parker and Sommers 1983, Barbarika et al. 1985, Douglas and Magdoff 1991), P (Soon and Bates 1982, McLaughlin 1984, McCoy et al. 1986) and S (Taylor et al. 1978, Tabatabai and Chae 1991). O'Keefe et al. (1986) and Douglas and Magdoff (1991) demonstrated that mineralization rates ranged from nearly zero to 60 percent of the organic N added; in general, the more extensive the biological treatment or degradation of the residues, the lower the N-mineralization potential of the product. Composted biosolids usually have a mineralization rate of about 10 percent or less (Tester et al. 1977, Haan 1981, Douglas and Magdoff 1991).

The effect of a composted product on crop performance is determined by the product's maturity and mineralization rate in soil. A biogenic residue compost can provide 60 to 90 kg of available N ha^{-1} at an application rate of 54.5 Mg ha^{-1} (Vogtmann and Fricke 1989), and an MSW compost can provide 90 kg N ha^{-1} at a rate of 25.4 Mg ha^{-1} (Mays et al. 1973). Evaluation of the fertilizer value of a compost must include an analysis of the nutrient element and organic matter contents, mineralization rates, and C:N and C:P ratios.

Because composts have low levels of nutrients, they are often considered more valuable as sources of organic matter; but when used in large quantities, composts are sources of slow-release nutrients. Hortenstine and Rothwell (1972) showed that an application of 63.6 Mg ha^{-1} of MSW compost to phosphate-mining sand tailings increased the soil content of extractable K, Ca, and Mg. Bengtson and Cornette (1973) found that an application of 40 Mg ha^{-1} of MSW compost increased the concentration of exchangeable Ca in the soil after 28 mo. Comparisons of MSW compost with mineral fertilizer showed that compost additions did not maintain sufficient levels of available P in the soil (Cabrera et al. 1989), but these additions did increase the K level in the soil. Additions of an MSW compost on a sandy loam and a silty clay loam initially increased the percentage of organic C in the soils by 100 and 34 percent, respectively (Giusquiani et al. 1988).

Applications of 531 Mg ha^{-1} of a compost mixture of MSW and biosolids resulted in a 66-percent increase in the carbon content of the soil over 3 yr (Zan et al. 1987a). Soil N increased from an average concentration of 0.12 to 0.15 percent, but the C:N ratio of the soil did not change. P levels increased with the addition of compost. Applications of 9, 18, and 36 Mg ha^{-1} of the composted mixture of MSW and biosolids over a 24-yr period increased the total C and N content and the N-mineralization potential of the soil (Werner et al. 1988). The higher total N content was a result of higher hydrolyzable as well as nonhydrolyzable organic N compounds. The level of extractable P and S in a soil amended with composted biosolids is determined by the rate of P and S immobilization due to reactions with Fe and Al and by the rate of P and S mineralization from microbial action (Taylor et al. 1978). Phosphorus levels in soils can also be affected by organic residues containing septic tank effluent, which is high in P and results in high P loading (Sikora and Corey 1976).

Ticknor and Hemphill (1990) found that a wide range of herbaceous and woody plants can be grown in undiluted composted yard trimmings (N–P–K ratio of 0–0.1–0.25). Supplemental fertilizer was necessary and additions of bark or pumice were beneficial for optimum plant growth. Vegetable market refuse composted with slaughterhouse waste increased yields of sunflower as application rates were increased (Marchesini et al. 1988); the compost additions improved levels of several soil fertility factors. Biogenic composts, which are made from separately collected food and yard residues, have a relatively high fertilizer value. Vogtmann and Fricke (1989) showed that with additions of biogenic composts and N–P–K fertilizer to soils, crop yields of kohlrabi increased.

MSW compost (pH of 8, with a relatively low C:N ratio of 17, and N–P–K values of 1.67–0.55–0.40) produced a positive growth response in an acidic soil (Wong and Chu 1985). Peach trees treated with MSW compost applications showed greater growth than untreated controls but had lower average fruit weights (Strabbioli and Angeloni 1987). The average yield per tree, however, was not significantly different. The N–P–K ratio for the compost was 1.4–0.15–0.2. Heavy applications of MSW compost (102, 204, or 408 Mg ha^{-1}) on corn caused poor growth initially, but had a significantly delayed fertilizing effect (Stone and Wiles 1975). At 408 Mg ha^{-1}, normal growth was delayed 7 mo, but at the end of the experiment these treatments had favorable yields when compared to the

yields from inorganic fertilizer treatments of 89.6 and 179.2 kg N ha^{-1}. An application of mature MSW compost at a much lower rate of 9 dry Mg ha^{-1} resulted in more growth of *Brassica rapa* var. *perviridis* compared to growth from an equal application of nutrients in the form of mineral fertilizer (Chanyasak et al. 1983).

Compost applied in conjunction with mineral fertilizers increased yields compared to those from fertilizer or compost alone. Yield of corn grain was increased from 3–4 Mg ha^{-1} for fertilizer alone to 10 Mg ha^{-1} for compost with fertilizer (Wang 1977). Grass mixture yields increased from 14.0 g pot^{-1} with N–P–K fertilizer to 24.8 g pot^{-1} with a mixture of Dano compost and fertilizer (Kropisz and Kalinska 1983). The dry weight of sorghum seed heads increased from 298 kg ha^{-1} with N–P–K applications and 206 kg ha^{-1} with compost applications to 618 kg ha^{-1} with applications of both (Hortenstine and Rothwell 1972). Oat forage yields (dry weight) increased from 2,144 kg ha^{-1} with N–P–K applications and 1,405 kg ha^{-1} with compost applications to 3,860 kg ha^{-1} with an application of a mixture (Hortenstine and Rothwell 1972). Corn treated with either 179.2 kg ha^{-1} of fertilizer N or 16 Mg ha^{-1} compost yielded 187.8 bushels ha^{-1} but yielded 222.4 bushels ha^{-1} when treated with both (Hortenstine and Rothwell 1972, Kropiscz and Kalinska 1983).

Hortenstine and Rothwell (1972) and Kropisz and Kalinska (1983) concluded from their results on grasses that physical changes (improvements in nutrient release, water, and soil aeration properties) in compost-amended soil allow more efficient use of mineral fertilizer. The increased yields when compost and inorganic N are combined are thought to result from a synergistic effect of the compost and inorganic N. They believe this to be true because, in the case of their corn studies, 16.3 Mg ha^{-1} of compost probably would not supply enough N, or the added organic matter does not increase the water storage capacity of soil enough to account for the yield increase obtained.

It is unclear which nutrient source—fertilizer or compost—generates more plant growth by itself. Fertilizer sometimes generates more growth than compost alone because compost is often comparatively low in nutrients. For example, fertilizer increased dry weights of *Brassica chinensis* by 190 to 1,000 percent and of *Lycopersicum esculentum* by 18 to 190 percent over dry weight produced at varying compost rates (Chu and Wong 1987). However, the fruit of *L.*

esculentum showed variable growth responses to fertilizers and composts; some compost applications produced better yields than were obtained with fertilizer. Carrots amended with 45.4 to 113.5 Mg ha^{-1} of compost yielded larger roots and foliage than fertilized carrots, and sorghum amended with 58.1 Mg ha^{-1} of compost attained greater height than fertilized sorghum (Hortenstine and Rothwell 1973). Although N deficiencies were noted in corn treated with unscreened MSW compost applied at rates of 8, 18, 102, 204, and 408 Mg ha^{-1} without fertilizer, plots treated with 89.6 kg ha^{-1} of inorganic N or 204 or more Mg ha^{-1} of compost yielded more (188 bushels ha^{-1}) than untreated plots (136 bushels ha^{-1}) (Stone and Wiles 1975). Dry sorghum forage yields increased from 10 Mg ha^{-1} without compost or inorganic N to 15.4 Mg ha^{-1} with 173 Mg ha^{-1} compost and to 16.3 Mg ha^{-1} with 179 kg ha^{-1} inorganic N. Cabrera et al. (1989) found no noticeable growth differences from treatments consisting of a small application of MSW compost (12.7 Mg ha^{-1}), a fertilizer treatment (500 kg ha^{-1} of 15–15–15), or a mixture of the two. Highest yields of field and adzula beans were attained with compost-fertilizer combinations (Robinson 1983). The mixtures of compost and fertilizer, however, did not result in a positive synergistic response in all cases.

Applications of co-composted MSW and biosolids have been at least as successful as MSW applications alone. Co-compost applications resulted in a 1.7-fold increase in the total stem biomass of slash pine compared to the biomass yield of control plots (Jokela et al. 1990) and resulted in a greater yield of maize compared to the yield from MSW compost alone (Zan et al. 1987b). The yields of sorghum, common bermudagrass, and corn responded in a positive manner when the crops were amended with annual applications of 130, 72.6, and 101.7 Mg ha^{-1} of co-composted MSW/biosolids (N–P–K of 1.3–0.30–0.91), respectively. The yields were surpassed by applications of N at the rate of 180 kg ha^{-1} together with adequate P and K (Mays et al. 1973). Applications of co-composted MSW and biosolids produced higher forage yields of corn than were obtained with the untreated control (Giordano et al. 1975).

Songmuang et al. (1985) showed that long-term applications of compost (at 12 Mg ha^{-1}) made from rice hulls and manure eventually led to a buildup of organic matter in the soil and that this buildup and the subsequent compost applications could replace the fertilizer application. Similarly, Brinton (1985)

hypothesized that long-term use of composted manure could eventually lead to a buildup of organic matter that would supply all of the N needs of the plant. In the 1st yr of Brinton's study, the mineralization rate of composted manure was 9 percent of the total N added.

Application of MSW results in accumulations of trace metals. Vineyards that received several applications of MSW had 2 to 20 times the amount of metals in the soils (Furrer and Gupta 1983). Jokela et al. (1990) studied a slash pine plantation that had been treated with three rates of garbage compost 16 yr earlier; significant but modest treatment effects were associated with increases in concentrations of N, P, B, Fe, Al, and Zn in pine tissues. Examples of successful uses of organic residues in soils are summarized in table 4.

Nonnutrient properties of treated and untreated residues

Addition of biosolids or compost to soil almost always improves the physical properties. However, with certain types of composts, such as biosolids, it may take much more of the compost to affect physical properties of the soil than it does to provide the necessary nutrients for plants. Chang et al. (1983) reported that more than 72.6 Mg ha^{-1} of biosolids compost was necessary to significantly affect the physical properties of soil, that is, aggregate stability, bulk density, porosity, organic matter content, and moisture holding capacity.

Soil aggregate size and stability are affected by the physical, chemical, and biological activities existing in the soil, especially the microbial decomposition of

Table 4. Examples of organic residue uses that result in adequate plant growth

Residue type	Application rate (Mg ha^{-1})	Crop	Source
Biosolids compost	69–122	Legumes and reed canary grass	Watkin and Winch (1974)
Biosolids compost	204	Spruce and pine trees	Gouin (1977)
Biosolids compost	134	Fescue	Tester (1989)
MSW compost	58	Sorghum	Hortenstine and Rothwell (1973)
MSW compost	45	Carrot	Chu and Wong (1987)
MSW compost	64	Bermudagrass	Wong and Chu (1985)
MSW/biosolids compost	224	Slash pine	Okela et al.(1990)
MSW compost	9	*B. rapa*	Chanyasak et al. (1983)
SW compost plus fertilizer	9	Corn	Wang (1977)
Biosolids plus fertilizer	4.5	Corn, winter wheat	White and Brown (1981)
Biosolids	134	Corn	King and Dunlop (1982)
MSW compost	91	Peas	Purves and Mackenzie (1973)

organic matter. Aggregate stability refers to the ability of soil aggregates to withstand disruptive influences such as water and pressure. Organic matter in the soil provides a substrate for microbial growth; the microorganisms in turn produce substances such as polysaccharides, which are necessary for aggregation. Biosolids increase stable aggregates (Epstein 1975) and water holding capacity (Khaleel et al. 1981) and decrease bulk density of soils (Khaleel et al. 1981). Although a wide range of application rates was used in these studies, no minimum application rate has been recommended for achieving specific minimum physical changes.

Many reports indicate that compost increases the aggregate stability of soil. MSW compost applied at 9 Mg ha^{-1} to a highly weathered clay-textured soil increased aggregate stability by 4 percent (Wang 1977). After 90 days, applications of 27.2 to 54.4 Mg ha^{-1} of MSW compost to a soil with low organic matter and high base saturation increased aggregate stability by 11 and 18 percent, respectively (Hernando et al. 1989). Soil carbon content after 90 and 180 days was correlated to the aggregate stability. MSW compost applied at 36.3 Mg ha^{-1} increased the water stability index in an alluvial soil after 3 yr, but had no effect on calcium-rich soil (Guidi and Poggio 1987).

MSW compost applied at 9 Mg ha^{-1} to a clay-textured latosol did not change the bulk density of the soil significantly (Wang 1977). An MSW compost applied at several rates caused no change in the total porosity or pore size distribution in either a Calcic Cambisol or a Eutric Fluvisol after 3 yr (Guidi and Poggio 1987). After 5 yr of amendments with a biosolids compost, a loamy sand soil had reduced penetration resistance and bulk density, increased soil water content and specific surface area, and a modified pH below the tillage depth (Tester 1990). Applications of mixed MSW and biosolids compost at rates of 45.4 and 136.2 Mg ha^{-1} increased the porosity of a sandy loam soil (Guidi et al. 1981, Pagliai et al. 1981) and increased total porosity significantly and soil aggregate stability slightly (Pagliai et al. 1981). An application of 63.6 Mg ha^{-1} of MSW compost on phosphate-mine sand tailings increased the organic matter content from 0.39 to 1.05 percent after one cycle of sorghum and oats (Hortenstine and Rothwell 1972). Applications of 27.2 Mg ha^{-1} of compost increased the soil organic matter content from its initial range of 1.6 to 2.1 to about 3.3 percent (Gabriels 1988). Duggan and Wiles (1976) showed similar results with compost additions of up to 181.6 Mg ha^{-1}. Elemental compositions, functional group contents, E_4/E_6 (absorbance at 400 nanometers to absorbance at 600 nm) ratios, and spectral characteristics were not useful for detecting differences in the structure of humic acids isolated from the soil before and after the addition of compost (Gonzalez-Vila and Martin 1985).

The term "moisture holding capacity" indicates the amount of water a soil can hold, while the term "moisture retention capacity" refers to the length of time a soil can retain water (Epstein et al. 1976). Both properties are greater in soils with large amounts of organic matter or clay particles (Einspahr and Fiscus 1984). Although these two factors together indicate how much water is in the soil, they do not necessarily indicate the availability of that water for plant use (Chang et al. 1983). Heavy applications of MSW resulted in decreased bulk density and compression strength and increased soil moisture content and moisture holding capacity (Mays et al. 1973). Addition of nonsegregated MSW increased aggregate stability, but the availability of moisture, as determined by relative soil moisture curves at 0.33 and 15 bar, was not increased (Webber 1978). Additions of composted and vermi-composted (worm-worked) biosolids increased the available soil moisture of a sandy soil from 10.6 to 54.4 and 31.6 percent, respectively (Einspahr and Fiscus 1984).

Applications of 9 Mg ha^{-1} of MSW compost increased the moisture holding capacity slightly at .33 bar (Wang 1977); the moisture content during a dry period was higher in the soil amended with compost. Hortenstine and Rothwell (1972) found that applications of 63.6 Mg ha^{-1} of MSW compost increased the moisture holding capacity after a 1-year rotation of sorghum and oats. Applications of 13.6, 27.2, and 54.4 Mg ha^{-1} of MSW compost increased the water holding capacity slightly throughout the 180-day monitoring process (Hernando et al. 1989), and the highest application rate produced the largest increase. An MSW compost application of 40 Mg ha^{-1} in a young slash pine plantation increased the soil moisture retention ability, especially during the first months after the application (Bengtson and Cornette 1973). In summary, depending on the type of residue and the application rate, improvement in several soil properties were generally recorded.

Spreadability of materials

Residue products applied to soils are most beneficial if they are uniform in composition and texture. MSW usually is highly variable in organics, glass, plastic, and metals; increased uniformity results from segregation of the inert materials. Grinding or composting of the organic fraction generally improves the uniformity and particle size distribution. Liquid or semisolid (<10 percent solids) residues are more uniform and can be sprayed onto the surface or injected below the surface of the soil. Below-surface applications greatly reduce the loss of nutrients by volatilization.

Solids can be (1) surface applied with little or no tillage, (2) surface applied and incorporated into the soil, (3) applied as a mulch, or (4) applied in a furrow or trough. The choice of application method depends on several factors, including the size and uniformity of the material, its nutrient content, the amount available, the crop being grown, and the application and tillage equipment available. Large-particle solid residues with low nutrient content may be best applied as a mulch where revegetation is necessary or prevention of wind or water erosion is important. Small-particle (<1 cm) materials are easily and uniformly spread with commercial fertilizer and manure spreaders. Experience with manures and biosolids indicates that nonuniform applications result in variable plant stands across the field. Preservation of nutrients is best accomplished by mixing materials with soil after application. Small particles are more easily mixed with soils, especially in areas where minimal disturbance is desired. Furrow or slot application results in less uniform mixing.

Application of solids in narrow trenches of less than 60 cm wide and 60 to 120 cm deep is generally considered a disposal operation rather than a treatment operation. This is because large amounts of material can be applied to small land areas. However, agronomic benefits can be obtained in areas where impervious boundaries exist in soil profiles. Deep trenches may penetrate the barriers and allow roots to penetrate into lower soil layers. If the trenches are filled with organic material, significant nutrient benefits will be obtained by roots.

Product quality standards

Product quality standards are related to the proposed use of the solid materials (table 5).

Techniques to reduce loss of nutrients

Losses of nutrients by volatilization or leaching of soluble components can reduce the value of a recycled material for both agricultural and horticultural uses. Losses of key soluble components such as K and nitrate can occur by leaching. Volatilization of ammonia from manures and biosolids is a critical problem. Prevention of losses by leaching during storage simply requires that materials be kept relatively unexposed to rainfall, that liquids not enter the material, and that excessive drainage be collected and recycled. Proper storage of products is required in lieu of soil application.

Volatilization of ammonia occurs when the pH of the medium is alkaline (8.0 or higher) or when the solubility of ammonia in the solution is exceeded. Ammonia is a product of N mineralization in organic residues. Volatilization of ammonia can be prevented if the pH is reduced below 7.0 and the accumulation of ammonia is reduced. Microorganisms use ammonia as a preferential N source, and, if microbial activity is maintained at a relatively high level, ammonia will be transformed into organic N as microbial biomass. Sikora and Sowers (1985) found that ammonia volatilization occurred during the first 10 days in the composting of lime-stabilized biosolids, but that only 10 percent of the total N was lost during this time. If microbial activity is inhibited (as when temperatures exceed 70 °C), more N would be lost. Addition of P to organic residues also reduces N loss possibly by stimulating decomposition of the materials.

Research needs

Determination of the heterogeneity and range in chemical and physical characteristics of the components in compostable residues is necessary so that maximal benefits can be achieved. The application of biosolids or composts to soil as a complete fertilizer is not a viable option. Many factors are involved in this conclusion, namely the amount of biosolids or compost necessary (demand) versus the amount available (supply), the restrictions on adding excess nutrients other than the macronutrients N and P, and concerns about accumulation of non-nutrient chemicals such as heavy metals. Because of these concerns, research on amendment combinations with mineral fertilizer is needed to address environmental, agronomic, and economic factors associated with the use of recyclable residues.

Table 5. Product quality standards for solid residues

Quality	Size uniformity	Analysis needed	Toxicity to plants	Inert materials allowed	Probable uses
Low	Uniformity and size analysis not necessary	Approximate analysis of nutrients	Nontoxic to hardy plants	2–5% inert material	Revegetation of barren or disturbed land
Medium	Particle size within range for uniform application	Sufficient analysis to make application to non-food-chain crop	Nontoxic to moderately sensitive crops	Percentage below that considered injurious or unsightly	Agriculture, silviculture, turf amendments
High	Particle size within guaranteed range of sieve size	Guaranteed analysis	Nontoxic to sensitive plants	Percentage below that considered injurious or unsightly	Potting mix, home gardens, all food-chain crops

The role of organic matter from municipal or industrial residues in maintaining or improving soil physical properties needs further clarification. Specifically, proper amendment rates need to be determined for increasing soil organic matter by 10 percent in 5 yr and for maintaining present organic matter levels in agricultural soils in which adequate amounts currently exist.

Agricultural and municipal residues can be mixed, but little data are available on the techniques, mixing ratios, benefits, and potential uses of mixtures. Procedures must be developed for blending organics and industrial byproducts to generate materials that are tailored to specific applications. The bioavailability of metal and organic contaminants in some of these byproducts needs to be reduced for the transformed products to be desirable.

Horticultural Uses of Untreated and Treated Residues

Products from the horticultural industry in the United States have an estimated value of approximately $9 billion annually; this figure includes the value of fruits, vegetables, flowers, ornamentals, and landscaping. In 1991 containerized plant production accounted for a $4.7-billion segment of the horticultural industry. Containerized growth media typically contain 60 to 70

percent organic substrata. The "ball and burlap" technique of harvesting trees and shrubs from nurseries results in the removal of approximately 227 Mg of topsoil per year. Together the containerized and field sectors of the horticultural industry have a continuing need to replenish the organic matter lost through normal production and sales activities. Presently, the industry relies on imported Canadian peat, domestic milled pine bark, and shredded hardwood bark. Familiarity with the performance characteristics and nutrient composition of these growth media encourages growers to continue using the same media unless it can be shown that new or alternative products have equivalent or superior properties.

Materials-reclamation managers need to be informed that recycled residues and byproducts represent a possible low-cost substitute for peat and bark. In order for managers to consider using these recycled materials, reclaimed organics need to have a dependable standard of quality in terms of pH, soluble salts, particle size, macroelement and microelement content, moisture, and pathogens. There has been much interest in the United States and Western Europe in finding an alternative organic substitute for peat and bark. Materials such as manure, MSW, biosolids, and leaves may all be acceptable substitutes after appropriate treatment and transformation.

Table 6. Compostable organic residues from various economic sectors

Economic sector	Residue type or source
Agriculture	Coco fibers, cork, cotton seed hulls, poultry carcasses, rice husks, rice straw
Aquaculture	Shellfish
Food	Chaff, coffee, tea, food flavor production, fruit culls and processing residues, hop processing
Paper industry	Bark, sludge
Pharmaceutical	Spent fermentation liquids or biomass
Textile	Cotton wastes, flax residues, wool residues
Town residues	Biosolids, garbage, gardens, grass clippings, leaves, night soil, restaurant and supermarket discards, wood chips
Wood industry	Bark, sawdust

Research has shown that untreated byproduct materials are often unsuitable for horticultural applications because of phytotoxicity, N immobilization, high salt content, or structural incompatibility (Verdonck 1988). A variety of compostable organic residues and byproducts from different industries have potential uses in horticultural media (table 6). Composts often compare favorably with peat as a major component of horticultural potting media (Bugbee and Frink 1989) (table 7), assuming that the quality control of the compost product is high enough to meet the required horticultural-grade criteria. Proper composting stabilizes organic residuals, reduces their water content for transport and storage, improves structural characteristics of the product compared to the raw stocks, and eliminates certain phytotoxicity problems (Hornick et al. 1984).

Of the organic materials used in potting media, at least 40 percent could be supplied from sources other than peat or pine bark (Sanderson 1980, Conover and Poole 1983, Fitzpatrick and Carter 1983, Marcotrigiano et al.

1985). Composted organic residues, such as sawdust, biosolids, and residues from fruit processing and pharmaceutical and food flavor production are all acceptable in some form for incorporation into potting media for the culture of nursery and greenhouse plants (Bugbee and Frink 1989). Properly managed composts can reduce the need for fertilizer (Falahi-Ardakani et al. 1987). Experience has shown that containerized plants grow as well in mixes containing up to 50 percent composted MSW, 30 percent composted biosolids, or 50 percent each of composted biosolids and MSW as in standard mixes, provided that the composts are mature and stable.

Phytotoxicity and growth-rate suppression, however, result when the MSW content exceeds 50 percent. These problems have been attributed to high content of soluble salts (Conover and Joiner 1966, Sanderson 1980, Lumis and Johnson 1982), boron toxicity (Lumis and Johnson 1982), poor aeration (Sanderson 1980), and heavy metal toxicity (Chu and Wong 1987). Phytotoxicity is associated with the presence of volatile fatty acids such as formate, butyrate, and propionate, and phenolic compounds, but is also dependent on the species and age of plant. For example, MSW levels above 50 percent inhibit early root growth in cress and tomato but not in ryegrass, pansies, salvia, or wallflowers (Keeling et al. 1991).

An active area of composting research has been in using wood-processing wastes in horticultural mixtures. Uncomposted bark, sawdust, and shavings of coniferous trees can be used to improve the physical qualities of horticultural mixtures. Up to 80 percent by volume of bark composts can be used in potting mixes or as substitutes for peat in growing many vegetable and ornamental plants (Pudelski 1983 and 1985). Short-term composting (for example, 3 wk to 3 mo) with the addition of nitrogenous materials (for example, sludge from soy scraps) (1) inactivates phytotoxic substances that may be present in the raw material, (2) corrects the C:N ratio and thus counteracts sorption of mineral N, and (3) initiates humification—a process that aids in the water holding capacity of the mixture. The mixtures require the addition of slow-release fertilizers (for example, sulfur-coated urea) containing necessary microelements and macroelements.

Bark, sawdust, and wood shavings from hardwood species require longer composting times (for example, 6 to 9 mo) because they contain greater amounts of phytotoxic substances requiring degradation. Beech

Table 7. Comparison of the important horticultural properties of peat, composts (prepared from source-separated organic residues such as wood, leaves, and grass clippings), and the ideal horticultural growing media

Quality criteria	Properties of:		
	Peat	Composts	Ideal growing media
Impurities (plastic, rubber, glass, stone, etc.)	None	Low (very low if source-separated and screened)	No sharp pieces or articles >2 mm
Growth-inhibiting substances	None	None if composted properly	None
Plant pathogens, viable seeds, plant parts	None	Virtually none if composted properly	None
Heavy metals	None	Low if from organic household residues; very low if from composted green residues	As low as possible
Volume weight ($g\ L^{-1}$ dry matter)	40–80 for white peat; 120–250 for frozen black peat	300–700 (max. 1,300)	200–400
Porosity (% volume)	Very high (85–98)	Lower than peat in all composts (50–80)	As high as possible (75)
Water capacity (% volume)	Very high (40–87)	45–65	As high as possible (60)
pH ($CaCl_2$)	2.5–3.5	6.5–8.5	5.5–6.6
Salinity	Very low <0.5 g L^{-1}	Average to high (max. 6.5 g L^{-1} for organic household compost; max. 3.0 g L^{-1} for green matter compost)	As low as possible (max. 3.0 g L^{-1})
N ($mg\ L^{-1}$) available	Very low (0–80)	50–500	200 avg.; 100–300
P_2O_5 ($mg\ L^{-1}$) available	None	High to very high	150 avg.; 100–200
K_2O ($mg\ L^{-1}$) available	Very low (0–20)	Extremely high (max 6,000 mg L^{-1})	300 avg.; 200–400
Mg ($mg\ L^{-1}$) available	Present (20–200)	High to very high	100 avg.
Trace elements	Very low	Unknown	Level varies by plant type
Organic matter (% volume)	100	99	60–70

bark compost is well recognized as a media compo-
nent for growing vegetables in the field and in green-
houses (Pudelski l980, Baumann and Schmidt l981).

Sims and Pill (l987) found that tomato seedlings grow
well in sphagnum peat amended with ≤30 percent (by
volume) biosolids or poultry manure (≤1 kg N m^{-3}).
Incorporation of composted biosolids or poultry
manure into growth media can eliminate the need for
preplant fertilization. Gouin (l985) reported that a
single N supplement of 600 mg L^{-1}, 2 to 3 wk after
transplanting was the only fertilization needed for
bedding plants grown in potting media containing
composted biosolids.

The capacity for organic materials in municipal
residues to absorb significant amounts of heavy metal
cations, thereby reducing the availability and toxicity
of the metals to plants, animals, and humans, suggests
a potential for using residues in horticultural mixes to
make use of this notable "sink" feature (Jones et al.
l978). Addition of a compost made from municipal
leaves, sand, and biosolids to horticultural growing
media did not increase the heavy metal content of
container leachate (Bugbee et al. 1991).

Compost is being used successfully as a growing
medium for sod production. As much as 189 m^3 ha^{-1} of
biosolids compost, leaves, or other yard trimmings are
used when sod is grown on a plastic liner; these
compost additions lower the water requirement of the
sod and reduce the number of natural weeds (Anony-
mous 1991b).

Plant disease suppression
Organic matter (for example, green and animal ma-
nures and composts) is well known for affecting crop
production in agricultural soil. Among the many
benefits described for the use of organic matter (U.S.
Department of Agriculture l978), the effects on plant
disease control and suppression are the least thor-
oughly understood. Soilborne diseases result in losses
of more than $4 billion annually to U.S. agriculture
(James l981). Compost made from a variety of organic
materials reduces plant diseases caused by such
soilborne pathogens as *Phytophthora*, *Pythium*,
Rhizoctonia, and *Sclerotinia*. Currently, however, from
the standpoint of using composts in container media in
the nursery industry, the plant disease suppression
afforded by compost is offset by inconsistency in
maturity and horticultural and microbial quality of
composts. Methods for predicting compost maturity

(Zucconi et al. 1981, Hirai et al. 1983, Garcia et al.
1991 and 1992, Grebus et al. 1994) and stability
(Iannotti et al. 1993) are available, and more are being
developed by the Agricultural Research Service and
their cooperators; these methods are also being used to
measure and enhance the quality and disease suppres-
siveness of composts (Inbar et al. l989).

Certain precautions must be followed when composts
are added to horticultural growing media. A 4-mo
curing period for the compost is required before it is
mixed with other container media components. Once
the mixture is made, it should be allowed to stand for 3
to 4 wk prior to use (Kuter et al. 1988). This is suffi-
cient time for the saprophytic microorganisms respon-
sible for biocontrol of specific plant pathogens, such as
Pythium and *Rhizoctonia*, to become established
(Kwok et al. 1987). Because of differences in the
amounts of microbial biomass present in composts as
well as differences in bulk density, up to 55 percent
(by volume, v/v) composted pine bark can be used in
potting mixes (Hoitink et al. 1991), but only 15 to 30
percent (v/v) composted biosolids can be used (Gouin
1985, Sims and Pill 1987). Similar information about
the use of MSW compost needs to be obtained and
related to standard measurements for stability and
maturity.

**Research needs for developing horticultural uses
of recyclable residues**
There are several areas in which research is needed in
order for compost to have more uses in the horticul-
tural industry. One such area is in defining quality and
maturity criteria for composts that will be used in the
industry. These criteria are critical for developing the
market and achieving grower acceptance for
composted products.

Research is also needed to develop process technology
for co-composting biosolids and the biodegradable
fractions of MSW to enhance product quality and
acceptability for agricultural and horticultural use.
Two important tools useful in developing co-
composting operations have been developed: (1) a
program, suitable for hand-held programmable calcu-
lators, for computing blend ratios for two feedstocks
based on the C:N ratio (Fitzpatrick 1993), and (2) a
program, suitable for laptop or desktop computers, for
determining mix ratios of multifeedstock composts
(Brodie 1994). The feasibility and practicality of
improving the agronomic value of MSW as
biofertilizers need to be determined. One method for

improving the agronomic value might be "spiking," a process in which the MSW is enriched with chemical fertilizers. In view of the increasing rate of landfill closures and the increasing costs of landfilling, enhancing the safe and beneficial use of co-composted MSW and biosolids in the United States may provide the lowest cost option for recycling and byproduct transformation.

Methods need to be developed to dependably enhance the microbially mediated plant disease suppression characteristics of compost. This would significantly lessen the need for biocides in the horticultural industry and would reduce multipoint sources of pollutants in runoff water.

Methods also are needed to reliably inoculate horticultural grade composts with beneficial rhizosphere microbes that can biologically mediate nutrient uptake by the plant or aid root conditioning to lessen transplant shock. These microbes help reduce the plant's dependence on synthetic fertilizers and reduce the resultant nutrient leachate from the compost.

Other Uses for Treated and Untreated Organic Residues and Byproducts

Incineration, composting, and recycling are increasingly significant alternatives to landfilling (Clarke 1992). Ideally, residuals management begins with source reduction, followed by recycling, then composting, with the remainder incinerated or landfilled. During 1988 through 1991, recycling in the United States increased and landfilling decreased; but incineration increased (fig. 5).

Yard-waste composting facilities have increased by a factor of four (fig. 6), and curbside recycling programs (fig. 7) have increased by a factor of seven between 1988 and 1995. The number of operating material-recovery facilities (MRF's) has increased from 17 to 322 between 1990 and 1995 (Berenyi 1995). These figures are based on the following definition of MRF (defined by Governmental Advisory Associates): "a facility receiving multimaterial or multigrade recyclables for processing and marketing; with some sorting of commingled recyclables, and a substantial portion collected in a municipal program" (Berenyi 1995). The recent dramatic increases in operating MRF's in the United States have contributed to increased employment at these facilities; about 7,350

people were employed nationwide in MRF's in 1995, up from about 1,500 in 1990 and 3,300 in 1992.

Paper is one of the more routinely recycled products. By late 1990, used corrugated paper sold for $27.50 to $30.29 per Mg and used computer paper sold for $154 to $198 per Mg. Recycled newsprint has experienced a decline in production because of the insufficient number of processing facilities available (Anonymous 1991c). However, by 1990 there were 25 newsprint mills in the United States, of which nine used secondary fiber to recycle newsprint. Of the 5.0 million Mg of newsprint produced yearly, 1.2 million Mg (fig. 8) are recycled to make more newsprint (Sparks 1990). Some of the remaining newsprint is used as animal bedding or as bulking agents for composting, and much of the remainder is either incinerated or landfilled. Five towns in eastern Long Island have formed an alliance under a New York Department of Environmental Conservation grant and have more than doubled newsprint recycling rates from 4 to 10 percent; the newsprint is recycled into insulation, animal bedding, and soil additives (Arner 1991).

Annually, about 544,800 dry Mg of biosolids are generated by approximately 11,500 publicly owned wastewater treatment facilities (Finstein 1989). The number of biosolids composting facilities (fig. 9) increased from 67 to 338 operating plants between 1985 to 1996 (Goldstein 1988, Goldstein and Riggle 1990, Steuteville 1996). Mixed-residue composting is increasing; 18 plants are now operating in the United States and at least 7 more are being constructed.

MSW composting is not a simple solution to the reduction in the number of landfills. Only 10 to 20 percent of MSW is actually composted. After composting, screening removes reject materials ranging from 10 to 30 percent by volume of the mixture. The reject material is placed in landfills, and normal tipping fees are assessed by weight (Goldstein and Spencer 1990). As of mid-1991, the vast majority of MSW compost was landfilled as either cover or fill. This resulted from the fact that many compost production facilities regarded composting as a means of volume and weight reduction rather than as a means of producing a highly desirable horticultural or landscaping material. In the future, MSW composting facilities must view their processes as manufacturing operations that produce an end product to vend rather than to dump (Richard 1992).
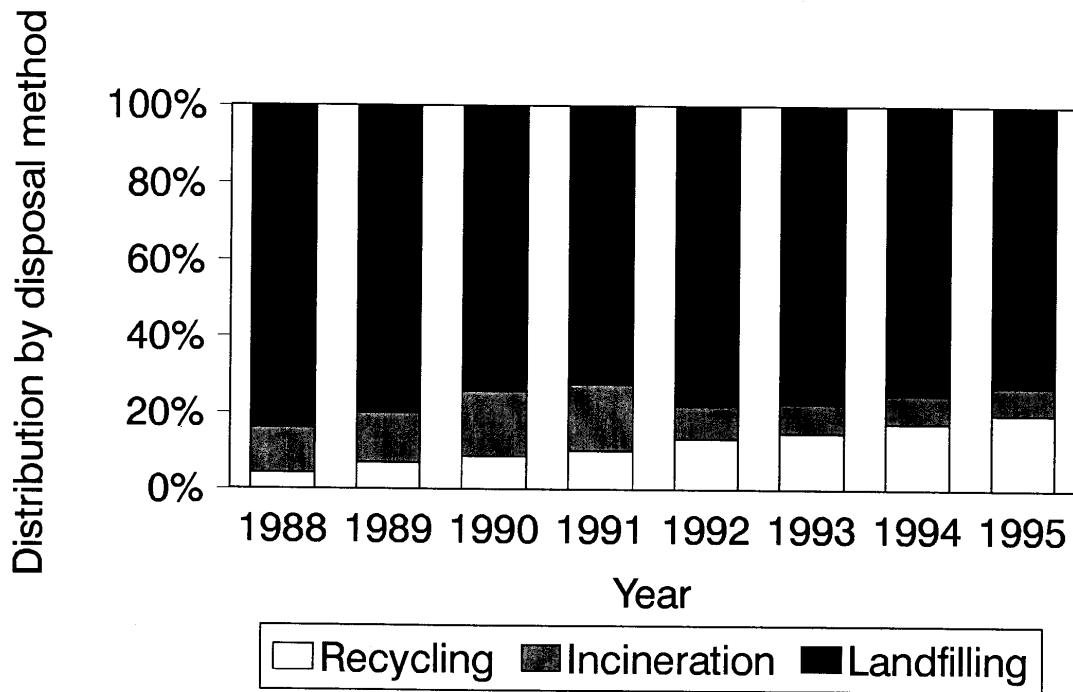
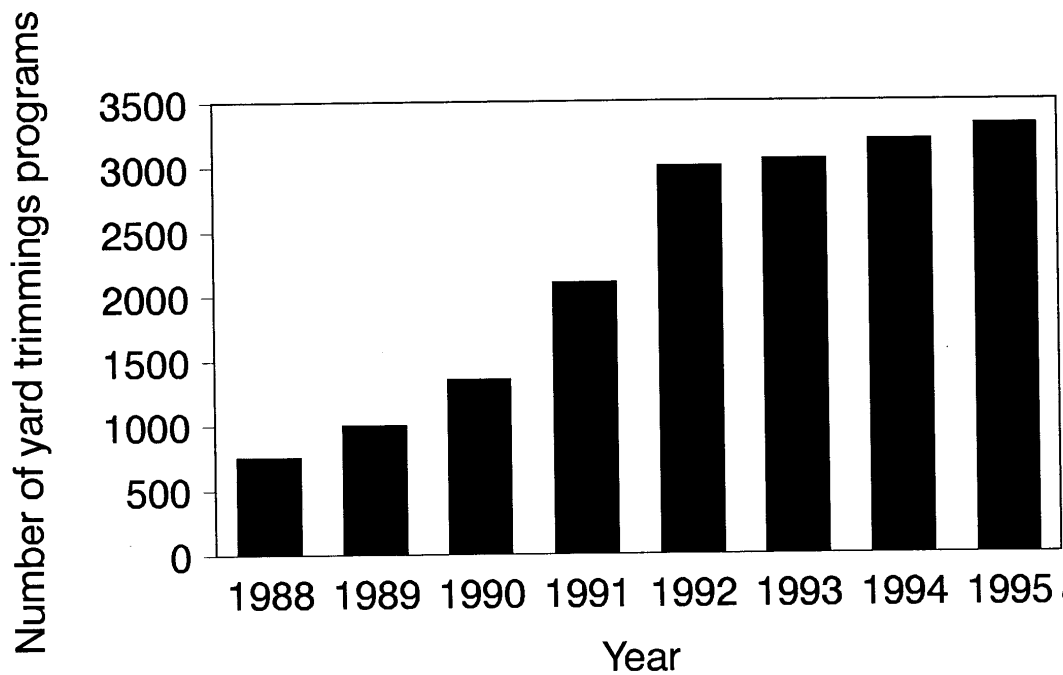**Figure 5**. Percentage of U.S. municipal residues and byproducts processed by various methods

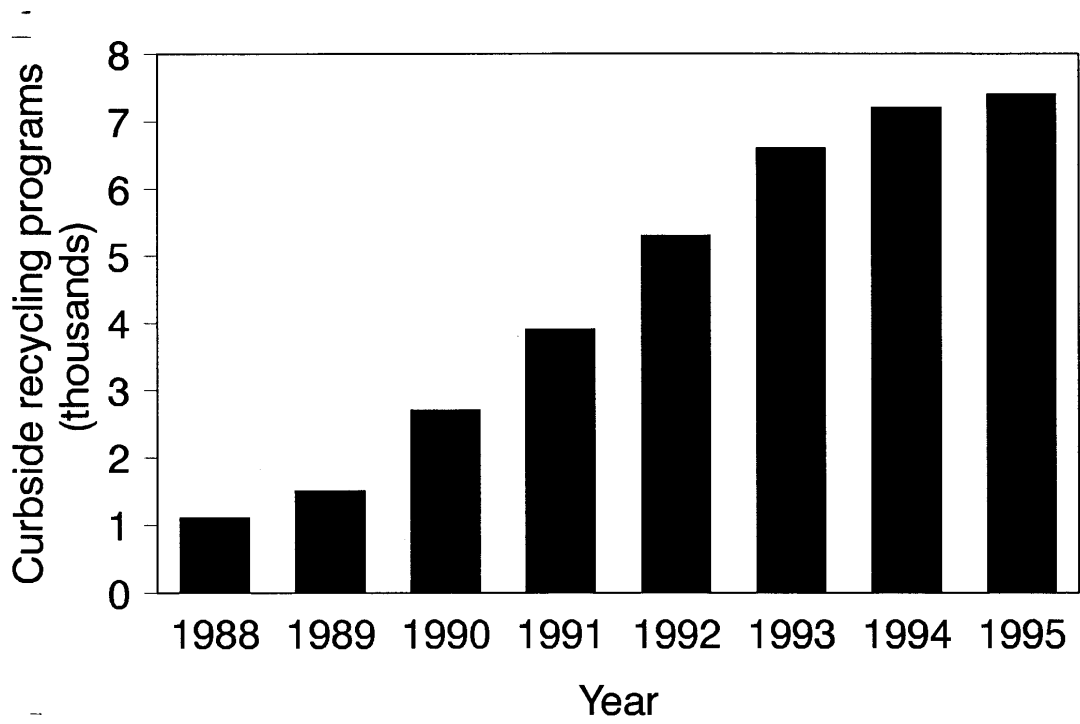**Figure 6**. Number of yard trimmings programs in the United States

Figure 7. Number of curbside recycling programs in operation in the United States

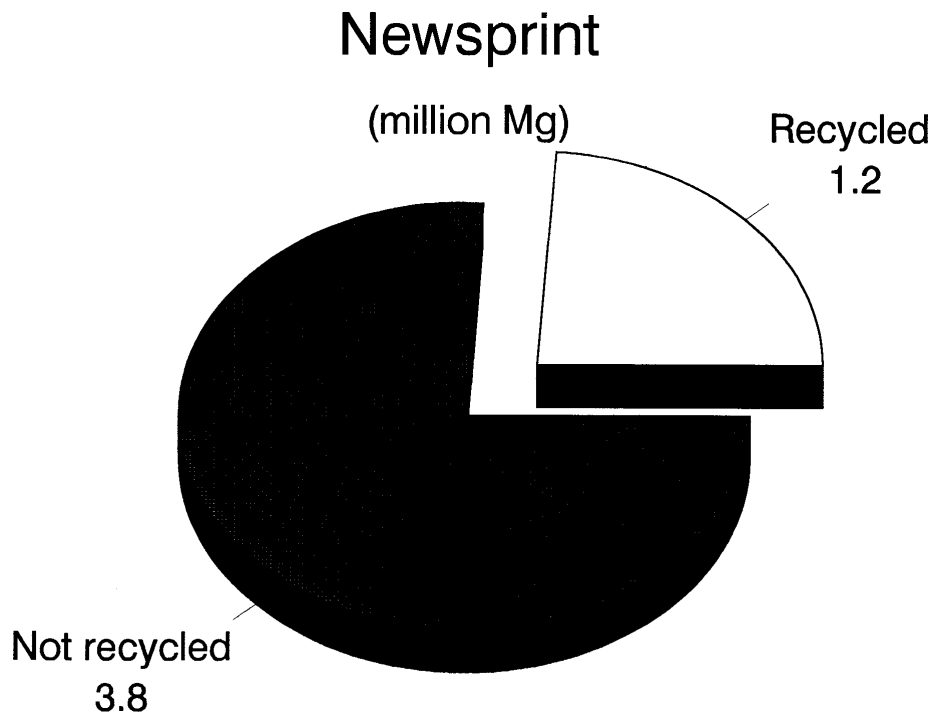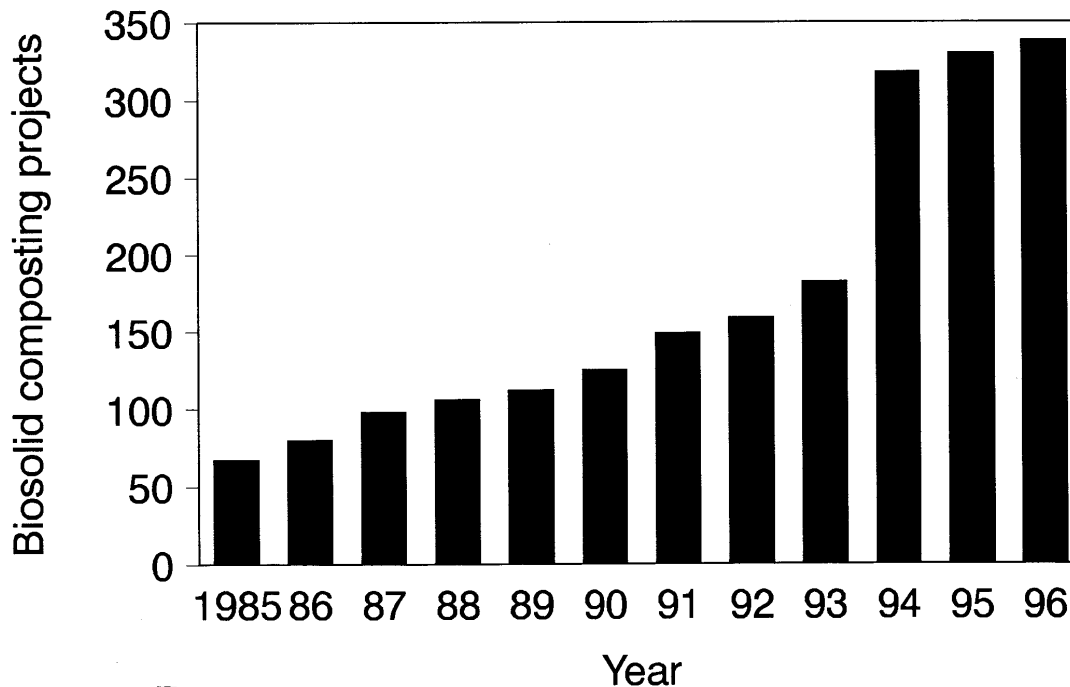# Newsprint

(million Mg)

Recycled
1.2

Not recycled
3.8

Figure 8. Recycling of newsprint in the United States

Figure 9. Number of biosolids composting projects in operation in the United States

Compost is not being marketed well so far, and substantive efforts in market development for compost will be required in the future. In a November 1990 survey of four facilities marketing MSW compost in Minnesota, Delaware, and Florida, only the Delaware facility reported income from marketing the composting product (Spencer and Goldstein 1990). In Memphis, TN, a large facility known as The Earth Complex combines biosolids composting and yard-trimmings composting with landfilling and a proposed methane-recovery system (Riggle 1991). In Austin, TX, the Hornsby Bend Waste Water Treatment Facility processes about 227 million liters of wastewater daily from which it extracts 40.9 to 45.4 dry Mg of biosolids. The majority of the material is windrow composted and then distributed and marketed under the trade name Dillo Dirt® (this trade name was registered in Texas). Dillo Dirt® is available to registered vendors at $6.50/m³ and to all city departments without cost. During most of the year, demand far exceeds supply. Texas and the U.S. Environmental Protection Agency released Dillo Dirt® for general use, but recommended that it not be used for growing crops for human consumption (Doersam and Armstrong 1992).

New applications for composted solid waste are currently being developed. Studies show potential uses outweighing current production by a margin of 47 to 1, with the largest potential use in agriculture (Slivka et al. 1991). Cooperative research projects on new uses are under way between the University of Maryland and the Composting Council, and these projects also involve private companies in New Jersey, Rutgers University, and the New Jersey Departments of Environmental Protection and Energy, Commerce, and Agriculture. The projects are designed to determine the potential agricultural uses for composted solids (Anonymous 1992).

Constructed wetlands are being designed and implemented to treat wastewater. By late 1990 there were 154 systems in operation or in design or construction, including systems that can treat as much as 454 million L per day (Reed 1991).

Some progress is also being made to reduce the production of toxic or noncompostable materials. Many printers are testing and using soy-based inks. Packers are using biodegradable materials with less bulk and fewer toxins.

The list of uses for recycled or composted materials expands daily. Processed garbage has been tested as a filler in concrete with good results in non-load-bearing situations. The processed garbage in the mix results in lower thermal conductivity, lower capillary suction, and lighter weight (Zhang and Whittmann 1991). Coal fly ash, the residue of coal-fired electrical generators, has been added to cement, sand, and water to produce Lytag-concrete, also known as power concrete. This mixture is almost as strong as and can be used as a general substitute for gravel concrete. Lytag concrete weighs 20 percent less than gravel concrete and has less potential to crack during hardening (Faase et al. 1991).

Composts made with coal fly ash have an increased availability of nutrients. This increased availability indicates that one or more chemical reactions and mineralization of N are occurring during composting. When compost amended with 20 to 40 percent coal fly ash was applied to soil, plant use of nutrients was more efficient (Menon et al. 1992). Furthermore, co-utilization of ash and biosolids ameliorated the reduced soil microbial activity that resulted from ash applications alone (Pichtel & Hayes 1990). Although considerable information is available on the use of fly ash and other combustion residues on land (Adriano et al. 1980, Clark et al. 1995, Korcak 1995, Norton 1995), specific research is needed to evaluate the effects of co-utilization of ash byproducts with organic materials.

Used tires, if recycled rather than being placed in landfills, can be used for several purposes. More than 200 million tires are disposed of annually. Some are reused after retreading or recapping; others find new life in the creation of playgrounds or reefs (Sienkiewicz 1990). Tires can be ground and mixed with asphalt to make an asphalt rubber, or they can be used as a rubber-modified asphalt concrete for road paving (Anonymous 1991c). Also, tires can be processed into chips that can be burned as a substitute for high-grade bituminous coal (Sienkiewicz 1990) or used as a bulking agent during composting. In the latter use, they can be recovered and reused in the process numerous times when finished compost is screened before release and delivery to the user.

Most resources used as substitutes for traditional materials are currently more expensive than the traditional ones. However, when the benefits of residuals reduction are taken into account, the cost of using recycled materials is closer to the price of using traditional materials. Lack of regulations and lack of time and funding for testing and classifying various composts have caused delays in the development of marketing programs for compost products. Development of methods for classifying and grading MSW and biosolids and composts for specific uses will help spur the development of marketing programs.

Potential Barriers and Constraints to Residuals Composting

Public perceptions and sociopolitical issues

Residuals composting has a consistent appeal to the public because it is viewed as an environmentally beneficial and economical way to return nutrients to soils and to transform unusable material into a valuable commodity. Several states presently permit MSW composting and co-composting as part of local solids-recovery plans. In most areas land application of municipal byproducts and residuals is regulated by Federal, state, and county agencies. Large, centralized municipal resource recovery facilities can be supplanted by smaller and simpler community-based composting facilities. Many local areas are now expected to compost their own MSW; this way the burden of processing is not unfairly put on a neighboring community. However, odor management remains a concern for citizens adjacent to smaller facilities.

The public's perception of composting facilities can affect whether or not a facility is built, where it is sited, and how it is operated. Public opinion is not necessarily the major factor presently influencing the future of MSW composting, but it is likely to carry more weight than in the recent past (Miller and Golden 1992).

Projects currently in place for screening and separating harmful components from MSW require expansion to provide the quality MSW needed to produce marketable compost. This accomplishment will require a coordinated effort at the local level and involve education of the public.

Odors

Odor management is a necessity for successful composting of biosolids, yard trimmings, manures, food market residuals, MSW, and other organic substances. Although composting can transform very odorous mixtures into useful soil conditioning and low-analysis fertilizer products, it can also generate odors if the process is improperly managed. Consider-

able information is available for characterizing odors from composting materials; new methods are being developed to abate or control the production or escape of odors.

Odors may be controlled by optimizing the composting process to minimize anaerobiosis; maximizing microbial metabolism of odorous substrates; and collecting, treating, and dispersing odors that are formed. A crucial part of planning for treatment is identifying and characterizing odors and predicting their path of transport by use of appropriate models. Ideally, these planning and modeling activities should precede the design and operation of the composting facility. More often than not, however, control efforts are initiated only after community opposition has threatened to shut down the facility (Libby 1991, Anonymous 1992, Goldstein 1994). Before new facilities are opened in the future, more proactive approaches to odor management should be applied to the various situations projected.

Control of odors should focus not only on treatment of odors, but also on preventing their generation by applying knowledge about the environmental conditions that favor and interfere with odor production. Since the conditions for producing many different odors are similar, several odors can be controlled with just a few strategies. Odor control in composting is therefore much simpler than chemical control, which might require a number of different processes to handle different chemical classes.

Odors from composts can be analyzed by gas chromatography and mass spectrometry (GC/MS). These procedures are being used more than ever because they are now more affordable. Hundreds of odorous components can be found in almost any odorous compost sample, and any of the odors produced can be at an intolerable level (that is, above their "threshold level"). Hentz et al. (1992) and Van Durme et al. (1992) have published GC/MS analyses of odorous air from various sources around wastewater and biosolids processing facilities, including around composting plants. Kissel et al. (1992) described the odorous compounds potentially emitted from MSW composting facilities. Hydrogen sulfide seems to cause odor problems in mainly acidic oxygen-starved points in wastewater treatment or anaerobic windrows. Odorants from properly operated biosolids composting plants typically arise from more alkaline and oxidizing environments, which are more likely to occur in wastewater treatment plant emissions. Alkaline and

oxidizing environments also typically produce detectable odor levels of ammonia, dimethyl disulfide, and terpenes such as limonene in excess of threshold levels. Relatively less odorous compounds such as methylethyl ketone, terpene alcohols, and alkylbenzenes may produce odor levels above their threshold in alkaline or oxidizing environments.

Odorous compounds are grouped according to the method used for their removal. These groups are as follows:

Type of compound (example in parentheses)	Method for removal
Semivolatile (isoborneal)	Condensation
Volatile (limonene)	Sorption
Alkaline (ammonia)	Acidification
Acidic (butyric)	Alkalization
Reducing (dimethyl sulfide)	Oxidation
Oxidizing (dichloramine)	Reduction

There are three main treatment processes for removing odors from composting facilities: condensation—thermal or steam swept, or activated sorption; neutralization—with organic or inorganic acids or bases; oxidation and reduction—with air, organic or inorganic reagents.

A phase diagram can be used to predict the type of odor likely to be emitted from a compost. A phase diagram is based on the sulfur/carbon ratio, nitrogen/carbon ratio, and available oxygen/oxygen demand ratio of the contents of the compost. Once the likely odors to be emitted are identified, rational pretreatment strategies and odorant treatment processes can be compared in terms of their implementation requirements, such as capital, operating costs, manual labor, operator training, and maintenance training. Generally, options that decrease the air volume that needs to be treated generate large savings in compost treatment costs. Proper chemical pretreatment, compost operations, gas cooling, and air auto-oxidation reactions are cheaper than chemically treating the odors in stacks.

For several decades biofilters have been used as a means to treat odorous compounds and potential air pollutants in gas streams from wastewater facilities, MSW processing facilities, rendering plants, chemical manufacturing facilities, and composting facilities. In recent years the interest and use of biofilters for odor control in composting facilities has increased dramati-

cally. Organic and inorganic compounds that are biodegradable and in the gas phase can be treated effectively (that is, greater than 95 percent can be removed) by biofilters.

More information is needed on the benefits of various media used for biofilters. These media must provide optimal absorption capacity, minimize system head loss, and provide an environment suitable for the proliferation of microorganisms that oxidize odorous compounds.

Pathogen and parasite destruction
Research on the infectious disease hazard of spreading biosolids on land was reviewed by Burge and Enkiri (1978); they noted that most sewage-related disease outbreaks resulted from (1) use of raw sewage waste-water, raw biosolids, or night soils on food crops that were consumed raw; (2) contamination of drinking water from septic tanks; or (3) consumption of raw shellfish from waters polluted with biosolids.

After raw biosolids are applied to the soil surface, surface movement of water could increase the hazard for pathogen distribution. Lime addition or composting, however, stabilize biosolids and reduce

the hazard significantly by inactivating pathogens. Other methods for processing biosolids can also destroy pathogens but also lead to putrifaction and persistent instability. Regrowth of human pathogens, fecal coliforms, and *Salmonella* spp., has occurred even in biosolids treated by a process to further reduce pathogens, for example, heat drying, high-temperature composting, irradiation, and pasteurization (Yanko 1987). Other studies have shown that regrowth is negligible or nonexistent in well-managed biosolids composting operations (Hussong et al. 1985, Burge et al. 1987, Millner et al. 1987). In addition to human pathogens, certain plant pathogens can colonize in compost if the indigenous microflora of the compost are not too competitive (Hoitink and Poole 1980, Hoitink et al. 1991). Other plant pathogens are de-stroyed by heat produced during composting if tem-peratures are high enough for a long enough period (Hoitink and Fahy 1986, Bollen 1993).

Time and temperature criteria for destroying human and plant pathogens in biosolids are shown in figure 10. These criteria should also be applicable for de-stroying pathogens in composts containing MSW, manure, leaf or yard trimmings, and food-processing residuals or any of these materials co-composted with
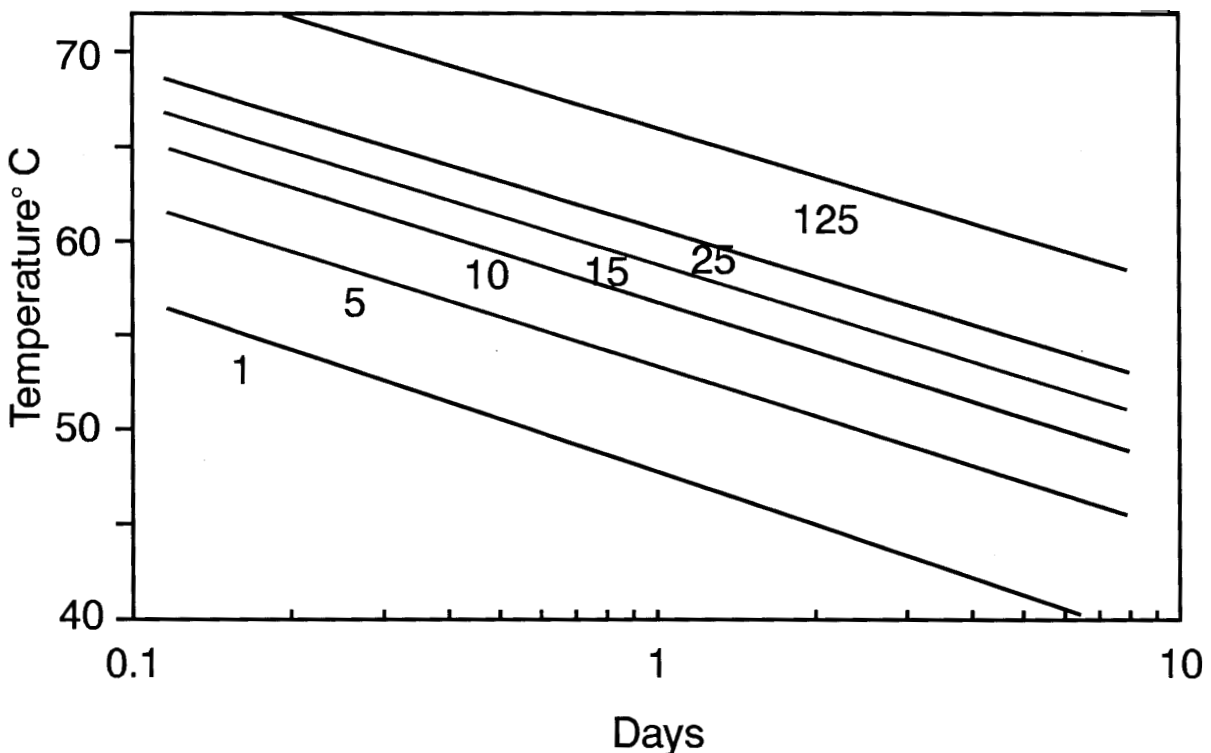
Figure 10. Curves showing the time-by-temperature regimes necessary to inactivate a desired number of logs of f_2 bacteriophage. Number of logs for each respective curve is shown below each curve.

biosolids. However, only composts that include biosolids are required to meet specific Federal regulations (EPA 40 CFR Part 503—see U.S. Environmental Protection Agency 1993) for pathogen destruction. Time and temperature criteria studies for pathogen destruction in nonbiosolids-based composts still need to be conducted.

The methods for detecting *Salmonella* spp. in biosolids, that is, the methods specified in EPA 40 CFR Part 503 regulations (U.S. Environmental Protection Agency 1993), in Hussong et al. (1984), and in Walter and Yanko (1984), were compared by Yanko et al. (1995). Ten samples of activated biosolids, anaerobically digested biosolids, and compost were included in the study. The study showed that the methods mentioned in the Part 503 regulations detected significantly fewer *Salmonella* than the two specially designed methods, which were equivalent. One of the Part 503 methods was regarded as acceptable, whereas one failed to detect the pathogen in 43 percent of known positive samples.

Additional methods for pathogen detection are still being developed using molecular biology methods, for example, the amplification by polymerase chain reaction of *Escherichia coli* to the level of 1,000 cells per gram of compost (Pfaller 1994). The use of such methodology offers the potential of detecting specific strains of pathogens such as *E. coli* O157:H7.

Water-quality factors in relation to residual use on land

Reducing the impact of agricultural practices on groundwater and surface water has been a goal of farmers and government officials for decades. A number of key factors have evolved from research efforts in this area. These factors include adding residuals to soils only in amounts in which the nutrient supply of the residue equals the nutrient requirement of the crop for that season. Because N in its soluble form does not bind appreciably to soil particles, residue application rates are generally adjusted to the potentially mineralizeable N content of the residue to prevent N loss in leachate (Sowden and Hore 1976, Sikora et al. 1979).

The P supply in residues added to soil is sometimes in excess of plant needs, but the form of P in residues and the soil type greatly affect the movement of the nutrient through the soil profile (Sikora and Corey 1976); the abundant supply often results in more P

being absorbed than predicted. Because soil has the ability to remove P from percolating leachate, the occurrence of P in groundwater is rare.

The enrichment of surface (runoff) water from organic materials or fertilizers placed on land is of genuine concern. Soil conservation practices such as contour tillage, use of buffer strips, and residue management help control losses from fields. The effectiveness of these practices was evaluated by measuring overland flow areas from which organic materials had been applied (Tedaldi and Loehr 1990). This measurement is made simply by applying liquid residues to the soil surface and allowing them to flow down slope. In general the slope of the land, the infiltration capacity of the soil, the vegetation present, and the volume of rainfall in any one event determines the probability of nutrient runoff and surface water pollution (Wendt and Corey 1980, Sharpley et al. 1981, Ahuja et al. 1982).

Soil conservation practices are usually sufficient for controlling losses from highly erodible soils amended with composts and fertilizers; therefore research aimed at further reducing losses is not of high priority. Compliance with suggested soil management and farming practices normally controls contamination of groundwater or surface water by nutrients or chemicals from all amendments.

Metals and organics

In an effort to reduce the volume of materials being sent to landfills, Federal and state agencies have promoted the composting of leaves and yard trimmings. However, the environmental impacts of the various types of compost applications have not been researched or evaluated specifically with regard to the environmental fate of nutrients, metals, and pesticide residues. Previously, most research focused on the mechanics of composting. Information is still needed on (1) the range and quantities of toxic residues in yard trimmings, (2) degradation of residues during composting, (3) leaching of residues into soils and water during and after composting, and (4) concentrations of toxic constituents in finished (marketable) products.

A survey of nine composting facilities in the United States showed that the mean levels of potentially toxic metals in MSW compost were about half the mean levels in biosolids compost (Walker and O'Donnell 1991). However, there still is a need to determine (1) whether MSW composts are similar to composted

biosolids in terms of capacity to limit bioavailability of metals, (2) the extent of microbially mediated degradation and immobilization of potentially toxic metals and synthetic organics in MSW and biosolids, (3) safe and beneficial methods for decreasing the bioavailability of toxic metals and synthetic organic contaminants in MSW compost, and (4) reliable methods for achieving rapid stabilization of composts.

A few investigators have reported on the occurrence and fate of organic toxicants in yard trimmings or MSW composts (Sikora et al. 1982 and 1983, Petruska et al. 1985, Savage et al. 1985, Racke and Frink 1989, Fogarty and Tuovinen 1991, Shimp 1993, Williams and Keehan 1993, Cook et al. 1994). A very high temperature is needed to destroy some toxic compounds, for example, a temperature of 427 °C is needed to destroy dicamba and trifluralin (Kennedy and Stajanovic 1969)—an unachievable, undesirable temperature for composting. At 65 °C, 28 percent of 2,4–D in MSW compost was degraded (Snell 1982).

Much of the risk of contaminants in MSW is eliminated by up-front processing of the input materials to separate organics from glass, metals, plastic, and so forth. In addition to improving the compost quality,

this procedure greatly increases materials recovery (Glenn 1991) and essentially rids the compost of especially hazardous materials such as polychlorinated biphenyls (PCB's) and cadmium.

Separating motor oil from MSW is still a problem. Of more than 2,250 million L of motor oil waste generated annually, 1/3 of the used oil (or 750 million L) is poured onto the ground or into storm drains or put into the trash (fig. 11). The used oil contains carcinogenic and other toxic substances, including large amounts of lead. If it is spread on land, motor oil will reduce soil productivity, contaminate groundwater, and possibly be directly consumed in contaminated water or in plants that can accumulate hazardous levels of toxic substances. A U.S. Environmental Protection Agency report shows that 1 L of oil will foul the taste of 1,000,000 L of water. Used motor oil does not need to become a contaminant or pollutant; it can be recycled as a valuable resource. It can also be re-refined for reuse as motor oil or as heating fuel (Sienkiewicz 1989).

Proper mixing of composts—a critical step
Composting is a heat-producing biological process that begins with the decomposition of organic material and
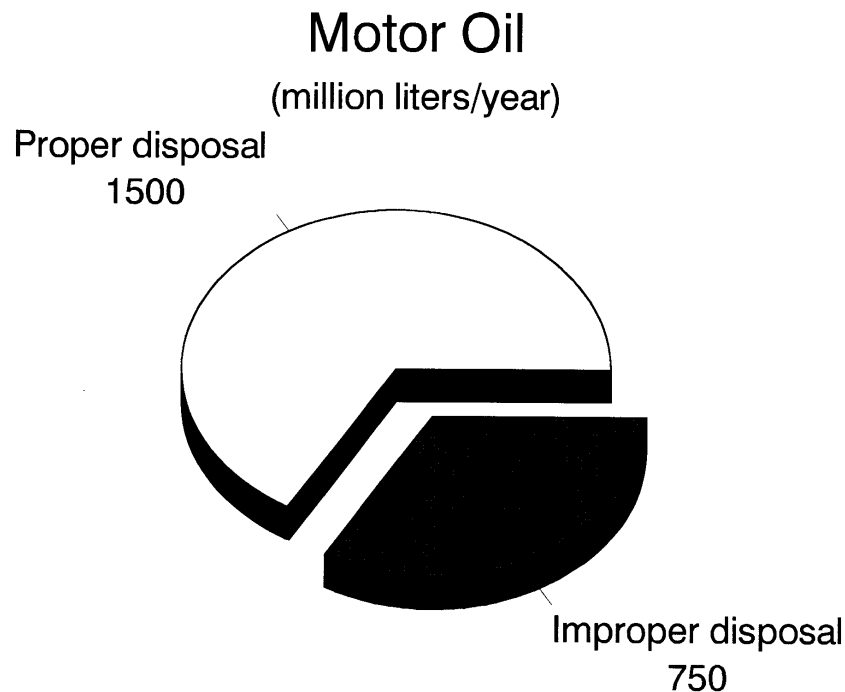
Figure 11. Disposal of motor oil in the United States

ends when energy, moisture, or oxygen become limiting. To achieve maximum degradation, it is critical that these limits not be imposed prematurely by improper combinations or improper mixing of ingredients. Premature halting of decomposition can be caused by material being too wet (reduces oxygen exchange), too dry (reduces biological activity), or poorly mixed (composting occurs in pockets rather than being uniform). For composting to be successful, mixing of the feedstocks is, therefore, the most critical step after ingredient quality.

Several types of mixers are appropriate for compost production. Batch mixers such as those used to mix livestock feed are successful for several ingredients (Rynk et al. 1992). Others include rotary drum mixers, pug mill mixers, and windrow machines (Willson et al. 1980). If materials of assorted sizes such as grass clippings and tree limbs are to be mixed, shredders, grinders, or hammer mills can be used to prepare uniform-size particles. For farm use, front-end loaders or manure spreaders have also been successful as mixers (Rynk et al. 1992). If mixtures are too wet, additional dry ingredients should be added. If wastes are too dry, additional water or aqueous residues should be sprayed over the contents during mixing.

Various manipulations of compost increase time and labor costs that must be considered in the final use of the product. The more uniform and stable the compost, the higher its value. Mixing is critical to achieve both uniformity and stability in the final product.

Limitations to on-farm composting of municipal organics

Interest in on-farm composting of municipal leaves, food, and other organic materials has been increasing. Some of the reasons for this interest include the potential for reduced disposal costs to municipalities, extra income to farmers, and a source of humus for farm soils.

Since the advantages of on-farm composting are so obvious, researchers have begun to look at the limitations to see how they can be overcome. Oshins and Kelvin (1992) studied opportunities for municipalities and farms to work together to manage rural and urban residues and byproducts. They identified six general limitations that farmers or municipalities experienced in working together (table 8). These limitations include transporting the material to the farm, farmer reliability, regulations, contamination, costs, and education. Key strategies to overcome these limitations include farmer compensation, resource coordination, and streamlining of regulations.

The study by Oshins and Kelvin (1992) was conducted in two phases. The first phase involved surveys of 60 selected municipalities and provided a cross section of demographic areas, which ranged from high-quality agricultural lands to rapidly urbanizing areas. The second phase of the study involved interviews of 71 municipal officials (elected officials, recycling coordinators, and public works directors). This phase also involved a series of focus groups, each comprised of mixed personnel (farmers, municipal officials, county personnel, and private interest groups). The function of these groups was to rank the limitations in order of importance and to propose solutions.

A primary conclusion from the study by Oshins and Kelvin (1992) was the need to develop methods for compensation of farmers. The value of the service that the farmer is providing to the municipality needs to be recognized and adequately compensated. Although some municipal residues have value to farmers, research showed that the costs of processing the material exceed the value. Tipping fees and contracts could be used to compensate the farmer for direct costs of using the materials. Contracts and compensation also help promote farmer reliability by giving the farmer incentive to stay with the program and providing the farmer with a sense of responsibility, obligation, and value.

A second conclusion of the study by Oshins and Kelvin (1992) was the recognition of the importance of an intermediary in coordinating the connection between municipalities and farmers. A broker can coordinate the delivery of materials from several municipalities to several farms more easily than individual farmers or municipalities. The highest rate of diversion of materials to farms occurs in areas having brokers (Anonymous 1991a).

A third conclusion from the study by Oshins and Kelvin (1992) identified government regulations as a problem. Existing guidelines were initially written for municipal audiences and are difficult for farmers to decipher. Co-composting municipal residues with farm manures has frequently not been addressed in either the municipal residues guidelines or manure management guidelines. Farmer-friendly guidelines for appropriate agricultural uses of municipal residues

Table 8. Limitations, factors to limitations, and strategies to working with farmers to manage municipal yard trimmings

Limitations[*]	Factors	Strategies
Transportation of materials to the farm	Coordination of collectors, haulers, and farmers; distance to sites; requirements for different materials	Have a broker (public or private) serve as coordinator for several municipalities.
Reliability of farmers	Availability of fields during inclement weather and during the growing season; dependability of farmers over time	Provide multiple dropoff storage sites during poor weather. Provide compensation to farmers and negotiate a contract with them.
PA–DER[†] management	Regulations are hard to understand, ambiguous, and inconsistent; farmers have antiregulation attitude; future regulation changes could create liability problems.	Rewrite guidelines for municipal yarn trimmings in farmer-friendly format; incorporate these guidelines into manure-management guidelines.
Contamination	Trash level	Design collection system to minimize trash. Tell residents where materials are going and provide them with compensation. Provide for disposal of trash in yard trimmings at no cost to farmer.
	Pesticide level	Preliminary data show that pesticides are not a problem, but more research is needed to allay fears. Reduce potential for contamination through a residential program that minimizes pesticide use and promotes grass recycling and not mowing sprayed lawns for several days.
Costs (other than for collection and transportation)	On-farm expenses for equipment, operations, site improvements, guideline compliance	Provide direct compensation to farmers. Costs can be shared by perhaps PA–DER[†] recycling grants, USDA's FSA, and EPA's Chesapeake Bay Program.
	Municipal expenses for administration and personnel	Compare cost reduction to cost of other available options.
Education	Promotion of awareness of on-farm composting of municipal residues	Included in PA–DER[†] yard-trimmings manual. Increase visibility of composting programs.
	Promotion of further participation by cooperating farmers	Host or attend field days and workshops on composting research.

[*] Listed in order of most frequently cited.
[†] PA–DER = Pennsylvania Department of Environmental Resources.

alone or in combination with farm operation residues is urgently needed.

When developing residue reduction and recycling strategies, municipalities should consider involving local farmers and should compare disposal on farms with other available options for disposal. Farmers often have the land, equipment, and knowledge to compost more cheaply than a municipality. Disposal on farms reduces the output transportation costs to municipalities. Another advantage to farm use of municipal residues is that the farmer is the end user of the compost.

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