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16. Abstract

TxDOT reports that composted manures have been used in 22 of the 25 TxDOT districts, usually with excellent results. The application of composted manures to rights-of-way successfully improved growth of vegetation and controlled erosion of slopes on highway embankments. However, consistent availability of compost of the quality and quantity required for use in roadside projects is problematic in some states. Many states have adopted specifications for compost characteristics to ensure consistent quality of compost. The objectives of this literature evaluation are identification of the constituents and composition of various types of composted materials including animal manures, municipal wastes (solid waste and wastewater sludges), and other waste materials, as well as documentation of application of the composted materials alone as well as mixed with different soils (composted manufactured topsoil).

Most compost has a pH in the neutral range, organic matter content ranges from 30% to 60%, moisture content ranges from 30% to 50% range, and the concentrations of N, P, K, and salts are higher than those typically found in agricultural soils. Compost addition to soil is considered Compost Manufactured Topsoil (CMT). CMT has improved soil structure, reduced bulk density, increased permeability, and increased aggregate stability compared to soil alone. These improvements reduce erosion and increase the water holding capacity of CMT. CMT also increased availability of soil nutrients, microbial population and activity, and reduced the incidence of soil nematodes and other pathogens. Potential problems with compost use include water quality impacts caused by nutrient loss and leaching of high salt concentrations, as well as potential accumulation of heavy metals in the soil zone.

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A Review and Evaluation of Literature Pertaining to Compost Characteristics and to the Application of Compost Alone and Mixed with Different Soils

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Characteristics of Compost:
Moisture Holding and Water Quality Improvements

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PREFACE

Environmentally sound methods of disposing of vast quantities of organic wastes generated by municipalities, agricultural farming, animal agriculture, logging, and industries has been a hot issue in recent decades. The passage of the Pollution Prevention Act in 1990, which stressed pollution reduction through reuse and recycling, coupled with the knowledge that organic wastes could be beneficially reused, has sparked greater interest in investigating reuse of these wastes. A generally accepted means of recycling organic material and reducing the quantity of waste material is through composting. Once composted, the composted product materials can be beneficially applied to the land, provided the materials meet federal and state regulations and are applied in a controlled manner.

With the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, which encouraged the use of environmentally safe compost along highway rights-of-way of federally funded projects, state Departments of Transportation (DOTs) began in earnest to investigate compost and compost use. The Texas Department of Transportation (TxDOT) and the Texas Natural Resource Conservation Commission (TNRCC) have joined forces to investigate application of composted animal wastes to highway rights-of-way. Results of these efforts to date have demonstrated that the application of composted manures has been successful in vegetating slopes and controlling erosion of slopes on highway embankments. To date compost has been used in 22 of the 25 TxDOT districts, usually with excellent results.

However, consistent availability of compost of the quality and quantity required for use in roadside projects is problematic in some states including Colorado, Massachusetts, Nebraska, South Dakota, Texas, and Wyoming. To combat the uncertainties in compost quality, many states have adopted specifications for compost characteristics. Templates for those specifications have included the *Model Procurement Specifications for Source-Separated Compost*, published in February 1996 by the Coalition of Northeastern Governors (CONEG) Source Reduction Task Force, and the 1995 *Suggested Compost*

Parameters and Compost Use Guidelines, developed by the Composting Council, the Florida Department of Agriculture and Consumer Services, and the Clean Washington Center, among others. Besides issues related to quality and quantity, compost use has also been impeded both directly and indirectly for economic reasons by lobbyists or contractors who see it as an infringement on their cost of business or as competition to already established products.

The purpose of this literature review is twofold: first, to identify the constituents and composition of various types of composted materials including animal manures, municipal wastes (solid waste and wastewater sludges), and other waste materials, to the extent information is available; and second, to document application of the composted materials alone as well as mixed with different soils.

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EXECUTIVE SUMMARY

Environmentally sound methods of disposing of vast quantities of organic wastes generated by municipalities, agricultural farming, animal agriculture, logging, and industries has been a hot issue in recent decades. The passage of the Pollution Prevention Act in 1990, which stressed pollution reduction through reuse and recycling, coupled with the knowledge that organic wastes could be beneficially reused, a desire to reduce the amount of organic wastes landfilled each year, technological advances, greater confidence in composting, and more favorable economics, has sparked greater interest in investigating composting of these wastes in more detail. Composting of organic wastes has become a principal method of waste reduction, disposal, and reuse because it produces a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Haug, 1993). Composting also reduces greenhouse gas emissions by reducing the quantity of material that is landfilled and decomposed, a process that produces methane (Daigle et al., 1989). Composting is the microbial conversion of organic matter in the presence of suitable amounts of air and moisture into a humus-like product (de Bertoldi et al., 1983). The compost can be beneficially applied to the land, provided the compost meets federally regulated metals limits (40 CFR 503) and is applied in a prudent manner with regard to nutrient content, soil characteristics, and other environmental conditions.

Compost has been investigated for use as a substitute landfill liner (Benson & Othman, 1993), as an alternative soilless plant growth media (Freeman & Cawthon, 1999), as a soil amendment and conditioner, as a fertilizer, for erosion control, and as a method for reducing herbicide use (Mitchell, 1997b). With the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, which encouraged the use of environmentally safe compost along highway rights-of-way of federally funded projects, state Departments of Transportation (DOTs) began in earnest to investigate compost and compost use.

In order to facilitate use of compost, the material must be characterized both physically and chemically to match the compost to the landscape applications and to ensure any state standards or state and federal regulations are met. Of particular concern are metals, compost stability, organic matter content, cation exchange capacity (CEC), nutrient content, and pH. A review of the literature has revealed a wide variation in compost quality and characteristics.

Generally, most compost has a pH in the neutral range, organic matter content in the 30% to 60% range, moisture content in the 30% to 50% range, and higher values of N, P, K, and salts than typical agricultural soils. Some compost (especially compost derived from MSW) typically has higher levels of trace metals especially Cu, Zn, and Pb, which can cause accumulation problems in soils with repeated applications (He et al., 1992).

Generally, compost amendment of soils decreases bulk density while increasing porosity, water holding capacity, soil aggregation, microbial levels, organic carbon levels, salts, nutrients, metals, and pH.

Erosion is a naturally occurring process that is exacerbated by new construction and road building. As such, many state DOTs and the United States Department of Transportation have initiated studies to combat erosion along roadsides. Much of this research has been geared toward the use of compost for erosion control, as a soil conditioner, and for added nutrients. Research indicates compost amendment generally decreases soil erosion.

Potential problems with compost use include quality, nutrient loss through erosion and leaching, accumulation of heavy metals, and the introduction of high salt levels.

1. INTRODUCTION

Environmentally sound methods of disposing of vast quantities of organic wastes generated by municipalities, agricultural farming, animal agriculture, logging, and industries has been a hot issue in recent decades. The United States Environmental Protection Agency (USEPA) estimated that publicly owned treatment works would produce roughly 15 million dry metric tons of biosolids annually by 2000 (Haug, 1993). Of the 7.7 million dry metric tons of biosolids produced in 1989, less than 3% were composted. The food and textile industry contributes a million dry metric tons of sludge per year and the pulp and paper industry produces 2 million dry metric tons of sludge per year (Haug, 1993). Animal wastes are an even bigger source of organic materials as animal farming has shifted from small animal feeding operations (AFOs) to very large confined animal feeding operations (CAFOs). The CAFOs produce enormous amounts of wastes on a daily basis. Disposal of those wastes are a significant issue. Past practices of lagooning and surface applying the wastes without treatment has lead to surface and groundwater contamination, air pollution, and has presented other health and safety concerns. Landfilling of the wastes has reduced contamination but has placed a burden on shrinking landfill space. Many cities have passed legislation banning "clean wastes" such as yard trimmings from landfills to conserve landfill space. Furthermore, many landfill operators have banned wastewater sludges from landfills, making alternative disposal options such as land application and composting more attractive. Composting has become the preferred management practice for most diverted yard waste (Haug, 1993) and is being investigated for use with many other wastes.

The passage of the Pollution Prevention Act in 1990 stressed pollution reduction through reuse and recycling. The tenants of the Act coupled with the knowledge that organic wastes could be beneficially reused, a desire to reduce the amount of organic wastes landfilled each year, technological advances, greater confidence in composting, and more favorable economics, has sparked greater interest in investigating composting of these wastes in more detail. Composting of organic wastes has become a principal method of waste reduction, disposal, and reuse because it produces a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Haug, 1993). Composting also reduces greenhouse gas emissions (Daigle et al., 1989). Composting is the microbial conversion of organic matter in the presence of suitable amounts of air and moisture into a humus-like product (de Bertoldi et al., 1983). The compost can be beneficially applied to the land, provided it meets federally regulated metals limits (40 CFR 503) and is applied in a prudent manner with regard to nutrient content, soil characteristics, and other environmental conditions.

Compost has been investigated for use as a substitute landfill liner (Benson & Othman, 1993), as an alternative soilless plant growth media (Freeman & Cawthon, 1999), as a soil amendment and conditioner, as a fertilizer, for erosion control, and as a method for reducing herbicide use (Mitchell, 1997b). With the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991, which encouraged the use of environmentally safe compost along highway rights-of-way of federally funded projects, state Departments of Transportation (DOTs) began in earnest to investigate compost and compost use.

In 1997, 19 state DOTs had specifications for compost, and 34 DOTs reported experimental or routine use of compost on roadsides in one or more applications, including as a soil amendment, as mulch, for erosion control, and in other applications (Mitchell, 1997b). States have reported satisfactory or better results from using compost for such applications when the compost has met specified standards (Mitchell, 1997b). In 2001, the number of states with compost or compost related specifications had increased to 31 (Alexander, 2001). Of the 31 states specifying compost use, 26 specify it for soil amending purposes, 11 for planting backfill mixes, and 9 for erosion control.

In Texas, a significant issue is disposal of animal manures because Texas leads the nation with roughly 220 billion pounds of animal manures produced per year. Texas A&M University estimated the year 2000 manure production per animal, as is shown in Table 1.

Table 1: Year 2000 manure production in Texas

Animal	Manure (tons/year)
Beef Cattle	86,048,750
Dairy Cattle	7,345,625
Other Cattle	24,907,500
Swine	439,619
Sheep	876,000
Horse	4,927,500
Poultry	2,402,718

According to the Southwest Dairy Center, Texas ranks sixth in the number of dairy cows per state, and Texas has three of the top 100 dairy counties in the nation with Erath, Hopkins and Comanche counties. Rounding out the top 10 dairy producing counties in Texas are El Paso, Archer, Hamilton, Wood, Johnson, Cherokee, and Lamb counties.

The Texas Department of Transportation (TxDOT) and the Texas Natural Resource Conservation Commission (TNRCC) have joined forces to investigate application of composted animal wastes to highway rights-of-way. Results of these efforts to date have demonstrated that the application of composted manures has been successful in vegetating slopes and controlling erosion of slopes on highway embankments. TxDOT reports that composted manures have been used beneficially in 22 of the 25 TxDOT districts, usually with excellent results.

To assess the potential for compost use, the United States Composting Council (USCC) and the United States Department of Transportation attempted to project the potential demand for compost usage. Their projections, based on typical acreage planted annually by state DOTs, indicate a potentially significant market for compost. Projections for the three largest states are summarized in Table 2, and the full 50 state projections are included as Figure 1.

Table 2: USCC/DOT estimated and projected compost use for three largest states

	Specification	Estim. Current Usage (cu/yds)	Estim. Annual Potential Usage (acres)	Projected quantities of compost usage		
				At 1"/acre 134 yds/acre	At 1.5"/acre 201,000 yds/ac	At 2"/acre 269,000 yds/ac
California	Yes	225,000	25,000	3,350,000	5,025,000	6,725,000
Missouri	No	0	4,000	536,000	804,000	1,076,000
Texas	Yes	100,000	80,000	10,720,000	16,080,000	21,520,000
Total	--	480,350	139,160	18,647,440	27,971,160	37,294,880

State DOT	Compost Use Specification	Estimated Current Useage - cu. yds.a	Estimated Annual Potential Usage - acresb	1"-134 yds./acre	1.5"-201 yds./acre	2.0"-269 yds./acre
				Application Rate - total cubic yards		
ALASKA	yes	250	200	26,800	40,200	53,800
ALABAMA	no	0	1,000	134,000	201,000	269,000
ARIZONAd	no	0	0	-	-	-
ARKANSAS	no	0	1,000	134,000	201,000	269,000
CALIFORNIA	yes	225,000	25,000	3,350,000	5,025,000	6,725,000
COLORADO	yes	n/a	200	26,800	40,200	53,800
CONNECTICUTf	yes	n/a	n/a	n/a	n/a	n/a
DELAWAREc	yes	n/a	$50,000/yr.- 3 years	n/a	n/a	n/a
FLORIDA	yes	n/a	2,000	268,000	402,000	538,000
GEORGIAe	yes	10,000	2,000	268,000	402,000	538,000
HAWAII	no	0	0	-	-	-
IDAHO	yes	10,000	150	20,100	30,150	40,350
ILLINOISg	yes	n/a	n/a	n/a	n/a	n/a
INDIANA	no	0	200	26,800	40,200	53,800
IOWA	yes	12,000	2,000	268,000	402,000	538,000
KANSASf	yes	n/a	n/a	n/a	n/a	n/a
KENTUCKY	no	0	300	40,200	60,300	80,700
LOUISIANA	no	0	2,500	335,000	502,500	672,500
MAINEb	yes	17,000	n/a	n/a	n/a	n/a
MARYLAND	yes	75	n/a	n/a	n/a	n/a
MASSACHUSETTS	yes	n/a	n/a	n/a	n/a	n/a
MICHIGAN	yes	n/a	n/a	n/a	n/a	n/a
MINNESOTA	yes	10,000	3,000	402,000	603,000	807,000
MISSISSIPPI	no	0	1,500	201,000	301,500	403,500
MISSOURI	no	0	4,000	536,000	804,000	1,076,000
MONTANA	yes	600	1,000	134,000	201,000	269,000
NEBRASKAd	no	0	150	20,100	30,150	40,350
NEVADA	no	0	n/a	n/a	n/a	n/a
NEW HAMPSHIRE	yes	3,500	10	1,340	2,010	2,690
NEW JERSEY	yes	50	100	13,400	20,100	26,900
NEW MEXICO	no	0	2,000	268,000	402,000	538,000
NEW YORK	yes	n/a	400	53,600	80,400	107,600
NORTH CAROLINA	yes	0	250	33,500	50,250	67,250
NORTH DAKOTA	no	0	300	40,200	60,300	80,700
OHIO	yes	75	n/a	n/a	n/a	n/a
OKLAHOMA	no	0	2,000	268,000	402,000	538,000
OREGON	yes	3,600	60	8,040	12,060	16,140
PENNSYLVANIA	yes	n/a	1,000	134,000	201,000	269,000
RHODE ISLAND	no	0	1,000	134,000	201,000	269,000
SOUTH CAROLINA	yes	100	n/a	n/a	n/a	n/a
SOUTH DAKOTA	no	0	250	33,500	50,250	67,250
TEXAS	yes	100,000	80,000	10,720,000	16,080,000	21,520,000
UTAH	yes	8,000	400	53,600	80,400	107,600
VERMONT	no	n/a	n/a	n/a	n/a	n/a
VIRGINIAf	yes	n/a	30	4,020	6,030	8,070
WASHINGTON	yes	80,000	400	53,600	80,400	107,600
WEST VIRGINIA	no	0	10	1,340	2,010	2,690
WISCONSIN	yes	100	750	100,500	150,750	201,750
WYOMING	yes	n/a	4,000	536,000	804,000	1,076,000
TOTAL		480,350 yd3	139,160 Acres	18,647,440	27,971,160	37,294,880

Figure 1: Estimated and potential compost use for the 50 United States.

Frequently noted benefits to application of compost along roadsides include improvement of soils through addition of organic matter, nutrients, and microbes, improved plant growth, erosion control, slope stabilization, and reduction in the use of chemical fertilizers and herbicides (Mitchell, 1997b).

The purpose of this literature review is twofold: first, to identify the constituents and composition of various types of composted materials including animal manures, municipal wastes (solid waste and wastewater sludges), and other waste materials; and second, to document application of the composted materials alone as well as mixed with different soils. Of particular interest regarding the first objective is the gather as much data as is available in the literature pertaining to the characteristics of composted municipal wastewater sludge, composted poultry litter, composted dairy cattle manure, and composted feedlot manure. The primary focus of the second objective is to gather published data from research or projects involved with application of composted materials along highway slopes, medians and rights-of-way. Research that included compost specifications, rates of application, compost amendment effects on the water holding capacity of amended soils, issues related to measuring water holding capacity of amended soils, and pollutant attenuation in roadside applications was of particular interest.

2. CHARACTERISTICS OF COMPOST

In order to facilitate use of compost, the material must be characterized both physically and chemically in order to match the compost quality with the intended landscape application and to ensure any state standards or state and federal regulations are met. Of particular concern are identifying and quantifying any metals present in the compost, compost stability, compost maturity, organic matter content, cation-exchange capacity (CEC), nutrient content, and pH. A review of the literature has revealed a wide variation in compost quality and characteristics. Details of the review are presented in Section 2.1. Information on published state and national standards and compost use guidelines are included in Section 2.2.

2.1 Physical and Chemical Characteristics of Compost

Physical characteristics of compost include but are not limited to stability and maturity, amount of inert materials, bulk density, and particle size distribution. Stability measurements are used to determine if the compost has cured adequately so that it will not inhibit plant growth or leach excessively. Typically, stability is measured using the Dewar self-heating test or the Solvita test for carbon dioxide respiration, although there is some debate over what test or combination of tests and indicators provides the best means of stability measurement. The CEC has also been used as an indicator of relative stability. The amount of inert materials is an indication of the quantity of glass or other debris that has been incorporated into the compost. The amount of inert material should be limited owing to the health and safety concerns of handling the material with excessive inerts. Particle size distribution is determined through sieving. Particle size distribution affects materials handling and the void ratio and resulting particle size distribution of soil and mulch mixed with compost.

Chemical characteristics of compost include pH, percent moisture, percent organic matter, electrical conductivity, CEC, carbon to nitrogen ratio (C:N), metals, and nutrients (including P, K, and N). As mentioned previously, CEC has been used as an indicator of compost stability and the relative ability of a soil to retain nutrients. Higher CEC indicates a more stable compost. The C:N is also an indicator of compost stability. A low C:N indicates instability. pH affects the availability of nutrients, particularly microelements.

2.1.1 Municipal Solid Waste (MSW) Compost

Composting of MSW has become more and more prevalent since the 1980s owing to several factors, including closure of landfills, the high cost of incineration, improvements in composting methods, and successful marketing and utilization of MSW compost. However, the variability in MSW compost characteristics is quite dramatic and is influenced by season, region, pretreatment practices, and process control. Generally, most MSW compost contains organic carbon levels at about 30%, organic matter in the range of 50% to 60%, and higher values of N, P, and K than typical agricultural soils (He et al., 1992). MSW compost also typically has higher levels of trace metals, especially Cu, Zn and Pb, which can cause accumulation problems in soils with repeated applications (He et al., 1992).

Several studies reported values on characteristics of MSW compost. In one study, 74 municipal solid waste (MSW) composts produced in Valencia, Spain were analyzed for chemical characteristics (Canet et al., 2000). Results of those analyses are summarized in Table 3.

Table 3: Characteristics of 74 MSW composts from Valencia, Spain

Characteristic	Range	Mean	Std. Dev.	# of Samples
Moisture (%)	5.4-45.9	26.2	11.9	70
Inert Materials (%)	2.0-55.9	22.9	16.6	46
pH	6.09-8.25	7.15	0.49	72
EC (dS/m)	3.1-14	9.5	2.1	74
Organic Matter (%)	22.4-71	53.9	10.4	74
Total N (%)	0.6-2.32	1.55	0.37	72
Organic N (%)	0.6-2.27	1.54	0.36	69
C/N Ratio	9-36.5	21.2	4.9	72
P2O5 (%)	0.4-2.4	1.27	0.5	70
K2O (%)	0.27-1.6	0.73	0.28	70
CaO (%)	7.7-27	14	5.28	70
MgO (%)	0.54-3.1	1.32	0.53	70
Na (%)	0.1-1.5	0.76	0.26	70
Fe (mg/kg)	5,000-25,600	11,700	5,200	33
Mn (mg/kg)	85-743	262	177	33
Cd (mg/kg)	<0.4-6.23	1.66	1.58	67
Cu (mg/kg)	100-1,790	400	270	68
Cr (mg/kg)	16-944	198	240	67
Hg (mg/kg)	<0.2-14.7	1.5	2.2	49
Ni (mg/kg)	10-415	61	63	67
Pb (mg/kg)	110-771	326	188	67
Zn (mg/kg)	340-2,100	820	390	68

Results from the Canet study indicate MSW composts near neutral pH, high organic matter content, high nitrogen levels, C:N ratio near optimum (20), an EC near 10 dS/m, and heavy metal contents typically lower than the maximum levels allowed by legislation.

A second study analyzed compost produced from wastewater sludges from the Valdemingomez treatment plant in Madrid in 1997 (Cuevas et al., 2000). Like the Canet results, compost was near neutral and had EC near 10 dS/m. Chemical and physical properties of the composted sludge are summarized in Table 4.

Table 4: Chemical and physical properties of composted wastewater sludge

			Organic	Phosphorus		Nitrogen			Potassium		
PH	EC	CaCO3	Carbon	Total	Avail.	Total	NH_4N	NO_3N	Total	Avail.	
SU	dS/m	g/kg	g/kg	g/kg	g/kg	g/kg	mg/kg	mg/kg	g/kg	mg/kg	
6.7	9.5	ND	331.7	3.73	47.5	17.7	865	16.5	5.0	ND	
Total and DTPA Extractable Metals											
Zinc		Lead		Cadmium		Nickel		Chromium		Copper	
Total	DTPA	Total	DTPA	Total	DTPA	Total	DTPA	Total	DTPA	Total	DTPA
334.1	259.4	193.1	87.4	1.48	1.38	21.62	8.48	32.88	1.03	203.4	82.7

Another study utilizing MSW from the Valdemingomez treatment plant had somewhat different values than those presented in the previous table (Diaz-Marcote & Polo, 1996). Compost prepared from the same feedstock had a higher pH (7.9) and a lower EC (7.0).

A study by Bresson et al. (1991) utilized MSW compost and reported values for the soil, compost, and a soil-compost mixture. The reported values are included as Table 5. Results indicate an increase in water content, pH, organic N, and organic C in the soil with compost addition.

Table 5: Physiochemical data for soil, MSW, and soil + MSW

		Particle Size Distribution								
	G/kg									
	Water Content	<2µm	2-20	20-50	50-200	200-2000	$CaCO_3$	Org. C	Org. N	pH
Soil	170	132	140	466	256	6	<1	7.3	0.9	6.7
MSW							57	275	11.6	
Both	200	136	144	459	246	15	<1	10.9	1.3	8.6

Villar et al. (1993) reported values for four industrially produced composts in Spain. The values are included as Table 6. Again, pH was near neutrality, organic C was in the 30% range, and organic matter was in the 40% to 60% range.

Table 6: Physical and physio-chemical characteristics of four composts

	Particle size of the whole material (%)					Particle size of the non-soluble mineral fraction				
						>0.2mm			0.2-0.02mm	<0.2mm
	10-5mm	5-2mm	2-1mm	1-0.5mm	<0.5mm	Minerals	Glasses	Plastics		
C1	1	25	20	11	39	11	8	0.5	12	4
C2	6	17	12	12	53	11	8	1.1	24	5
C3	1	6	7	11	75	5	6	1.6	22	6
AC	1	18	20	15	46	23	10	1.6	9	3
	True Density	Bulk density	Water content	WHC	pH	pH	EC	Dry matter	Ashes	Organic C
	Mg/cm^3	mg/cm^3	%	%	H_20	KCl	mS/cm	%	%	%
C1	1.9	0.4	30	83	6.95	6.95	11	70	58	25.8
C2	2.1	0.4	32	84	7.7	7.7	8	68	52	31.53
C3	2.1	0.4	42	63	6.25	6.3	12	58	39	30.04
AC	2.6	0.6	24	96	7.55	7.4	7	76	83	10.6
	Organic Matter	Total N	C/N	CO3	Salts					
	%	%		%	%					
C1	42	1.34	18	10.9	0.7					
C2	48	1.38	22	5.7	0.51					
C3	61	1.85	16	1.1	0.77					
AC	17	1.07	7	23.8	0.45					

A study by Walker and O'Donnell (1991) reported concentrations of metals from compost produced by nine operational MSW composting facilities in the United States. The reported values are summarized in Table 7.

Table 7: Heavy metals in MSW compost from operating facilities

	Agrisoil	Fairgrow	Fillmore	St. Cloud	Sumter	Sludge
MEAN (mg/kg dry weight)						
Cd	4.1	3.4	2.9	2.2	5.0	6.9
Cr	20.5	223	12.8	33.5	--	119
Cu	246	285	101.5	180	250	741
Hg	2.4	4.0	1.2	1.8	--	5.2
Ni	34	77	15.1	28	27	43
Pb	124	496	82.4	185	290	134
Zn	607	1008	329	390	580	1202
RANGE						
Cd	ND-8.3	2.3-7.0	1.4-4.4	1.3-3.03	1-8.2	
Cr	2.1-43.4	159-828	9.3-16.2	23-44	--	
Cu	5.1-1053	190-972	101-102	110-250	240-260	
Hg	1.5-3.2	0.6-5.9	0.1-1.4	0.7-1.2	--	
Ni	3.2-99	139-709	12.4-17.8	20-36	14-49	
Pb	<.6-287	348-1250	--	140-230	280-300	
Zn	4.1-4886	596-1370	328-330	310-470	560-600	

The results tabulated above indicate low levels of metals in compost for the facilities tested. The low levels indicate metals content in MSW compost should be generally a minor concern, with the possible exception of lead.

2.1.2 Mixed Feedstock Compost

Some studies reported characteristics of compost made from various feedstocks. One study performed at the Washington State University (WSU) Spillman Farm analyzed compost produced from unspecified animal manures (85%), coal ash, food waste, and landscaping waste (Cox et al., 2001). The chemical analysis of the compost is summarized in Table 8. Results indicate the characteristics of the mixture are similar to those of MSW compost with the exception of a slightly elevated pH.

Table 8: Chemical analysis of Washington State University compost

	EC	C	N		P	K
PH	DS/m	%	%	C:N	µg/g	µg/g
8.9	7	29.3	0.92	31.9	2,700	7,200

Another study by Mamo et al. (2000) analyzed a compost made from cardboard, paper, food waste, and yard waste. The chemical characteristics of compost used in their study are summarized in Table 9. Results indicate values are within the expected ranges for all of the parameters reported except EC, which appears to be lower than the normal range.

Table 9: Selected chemical characteristics of compost

		Organic C	N		Inorganic N	Organic N	EC
		G/kg	G/kg	C:N	Kg/ha	Kg/ha	DS/m
1993	**1**	200	9	22	27	783	1.7
1993	**2**	170	11	15	46	944	1.6
1994	**1**	240	9	27	66	744	1.5
1994	**2**	180	10	18	31	869	0.9
1995	**1**	230	10	23	27	873	1.3
1995	**2**	200	9	22	27	783	1.6

Similar values were reported by Mamo et al. (1999) in a separate paper published a year earlier. Both research endeavors examined the same compost.

Zaccheo et al. (2002) studied two composts: MWC1 and MWC2. The first compost was prepared from a mixture of yard wastes, municipal solid waste, and sewage sludge. The second compost was prepared from yard wastes, municipal solid waste, and olive husks. The chemical and physical characteristics of MWC1 and MWC2 are summarized in Table 10.

Table 10: Chemical and physical characterization of MWC1 and MWC2 composts

	pH	EC DS/cm	Ash G/kg	P %	Ca %	Mg %	Fe Mg/g	TKN Mg/g	Org C G/kg
MWC1	7.7	3.4	523	0.64	7.8	1.4	18.2	17.9	232
MWC2	7.1	2.4	577	0.52	5.0	1.2	12.2	15.4	216

Zinati et al. (2001) reported characteristics of three types of composts: MSW, Bedminster, and biosolids. The MSW compost was prepared from 100% yard trimmings and food wastes. The Bedminster compost was produced using 75% municipal solid waste and 25% biosolids. The biosolids compost was produced from 100% biosolids. The characteristics of the composts are presented in Table 11.

Table 11: Chemical characteristics of compost

	PH	EC DS/m	C G/kg	N G/kg	C:N
MSW	8.0	4.24	242	13.9	17
Bedminster	7.7	10.41	341	11.9	29
Biosolids	6.0	17.58	282	47.5	6

A study by Mays et al. (1973) published characteristics for compost produced from garbage waste and up to 20% sewage sludge. The values are reported in Table 12.

Table 12: Chemical characteristics of compost

	N	P	K	C	Ca	Na	Mg	S	Zn
	% dry weight								
1st	1.2	0.24	0.8	34.2	3.6	0.49	0.49	0.4	0.13
2nd	1.3	0.4	0.96	26.8	6.4	0.82	0.87	0.4	0.15
3rd	1.3	0.26	0.97	27.3	4.6	0.67	0.60	0.5	0.15
Avg.	1.27	0.30	0.91	29.43	4.87	0.66	0.65	0.43	0.14

Tester (1990) reported on the characteristics of compost produced from a mixture of woodchips and undigested sewage sludge with lime added. The characteristics of the compost are summarized in Table 13.

Table 13: Physical and chemical properties of undigested sewage sludge compost

Parameter	Value
PH	7.0
-34 kPa, g/kg	750.0
Total P, g/kg	15.1
Total N, g/kg	11.2
C, g/kg dry wt.	190.0
C/N ratio	17.0
Bulk density, mg/m^3	0.37

2.1.3 Poultry Litter Compost

In 1987 broiler production in the United States increased to more than 5 billion birds. The continued rise in broiler production has led to increasing quantities of poultry litter. As with other manures, land application of poultry litter has become less of an option, and more and more operations are turning to composting. Compost produced from poultry litter varies according to the bird type, number of birds, type and quality of feed, and other parameters. Henry and White (1993) performed research on compost produced via two methods. Results are included as Figure 2. Results indicate compost with a pH near neutrality, moisture capacity in the 60% range, and organic matter ranging from 30% to 40%.

2.1.4 Manure Compost

No studies were found that focuses on compost produced in large part or exclusively from composted dairy cattle manure or feedlot manure.

Parameter		MP1 Litter		MP1 Compost		MP2 Litter		MP2 Compost	
MC	(%)†	60.9	acd	59.2	bd	61.1	acd	60.0	abcd
TS	(% w.b.)	39.1	acd	40.8	bd	38.9	acd	40.0	abcd
FS	(% d.b.)	18.9	ac	24.2	bd	20.6	ac	26.3	bd
VS	(% d.b.)	81.1	ac	75.8	bd	79.4	ac	73.8	bd
Mass	(kg)‡	74.1	a	55.4	bd	68.8	c	53.3	bd
Mass Red	(%)	-		25.2		-		22.6	
Dry Matter	(kg)	28.9	ac	22.6	bd	26.8	ac	21.3	bd
DM Red	(%)	-		21.8		-		20.5	
MC	(kg)	45.1	ac	32.8	bd	42.0	ac	32.0	bd
MC Red	(%)	-		27.3		-		23.9	
BD	(g / cm^3)§	0.75	ac	0.64	bcd	0.69	abcd	0.63	bcd
BD Red	(%)	-		13.9		-		9.01	
Volume	(m^3)	0.099	ac	0.086	bd	0.099	ac	0.084	bd
Vol Red	(%)	-		12.9		-		14.8	
pH	-	6.14	ac	6.61	bc	6.52	abc	7.46	d
NH_3-N	(% d.b.)	0.37	ac	0.16	bcd	0.30	abc	0.07	bd
NO_3-N	(% d.b.)	0.07	abcd	0.02	abd	0.13	ac	0.01	abd
TKN	(% d.b.)	4.44	a	2.95	b	3.80	c	2.45	d
Total N	(% d.b.)	4.51	a	2.98	b	3.93	c	2.46	d
TOC-1	(% d.b.)‖	29.7	abcd	30.2	abcd	30.2	abcd	29.0	abcd
TOC-2	(% d.b.)‖	45.1	ac	42.1	bd	44.1	ac	41.0	bd
C:N-1‖	-	6.6	ac	10.2	bd	7.7	ac	11.8	bd
C:N-2‖	-	10.0	ac	14.1	b	11.2	ac	16.7	d
P	(% d.b.)	0.67	a	0.81	b	0.91	c	1.15	d
K	(% d.b.)	2.58	a	3.40	b	4.14	c	5.23	d
Ca	(% d.b.)	2.54	ac	3.20	b	2.63	ac	3.51	d
Mg	(% d.b.)	0.31	a	0.39	b	0.47	c	0.55	d
Na	(% d.b.)	0.63	a	0.80	bc	0.80	bc	1.08	d
Cl^-	(mg / kg)	711	a	885	bc	865	bc	1056	d
Zn	(mg / kg)	415	ac	535	bcd	433	abcd	541	bcd
Mn	(mg / kg)	399	a	466	b	544	c	655	d
Cu	(mg / kg)	530	a	641	b	733	c	865	d
Pb	(mg / kg)	40	ab	43	ab	70	c	80	d
Ni	(mg / kg)	134	ab	96	ab	229	c	285	cd
Cd	(mg / kg)	< 10	abcd	< 10	abcd	< 10	abcd	< 10	abcd

* The same letters within a row show no statistical difference 0.05 confidence level.

† The mean MC of the litter before wetted for composting was 20.2% for MP1 and 24.1% for MP2.

‡ This mass includes both the moisture and dry matter for the litter and compost.

§ The mean bulk density (BD) of the litter before wetted for composting was 0.42 g / cm^3 for MP1 and 0.44 g / cm^3 for MP2.

‖ TOC-1 was determined using the modified Walkley-Black method (Crane, 1978), while TOC-2 was calculated based on the volatile solids (Schulze, 1960). C:N-1 and C:N-2 were determined using the respective TOC concentrations.

Figure 2: Average physical and chemical characteristics of poultry litter compost.

2.2 Published Compost Standards Specifications

A review of available literature revealed a relative abundance of published standards for compost quality. The published standards were relatively consistent in both identified parameters and values for those parameters. For example, Alexander (2001) reported typical ranges of compost specification data for state departments of transportation. The typical ranges are summarized in Table 14.

Table 14: DOT compost specification data

	Range of values	Typical Range
PH	5.0 – 8.5	5.5 – 8.0
Organic Matter (%)	35 - 60	35 – 55
Soluble Salts (dS/m)	<3 - 10	<4
Moisture Content (%)	35 - 60	35 – 55
C:N	<6 – 30:1	<10 – 20:1
Inerts (%)	<0.3 - 1	<1
Particle Size (inches)	<0.5 - 1	<0.5 – 1

In 1996, the United States Composting Council published a model specification for compost use for soil amendment, which differed somewhat from that published by Alexander. The model specification included requirements for both stability and maturity, placed limits on metal contaminants, and also placed limits on biological contaminants. The model specification is included as Figure 3.

Parameters[1,6]	Reported as (units of measure)	General Range
pH[2]	pH units	5.0 - 8.5
Soluble Salt Concentration[2] (electrical conductivity)	dS/m (mmhos/cm)	Maximum 10
Moisture Content	%, wet weight basis	30 – 60
Organic Matter Content	%, dry weight basis	30 – 65
Particle Size	% passing a selected mesh size, dry weight basis	98% pass through 3/4" screen or smaller
Stability[3] Carbon Dioxide Evolution Rate	mg CO_2-C per g OM per day	< 8
Maturity[3] (Bioassay) Seed Emergence and Seedling Vigor	%, relative to positive control %, relative to positive control	Minimum 80% Minimum 80%
Physical Contaminants (inerts)	%, dry weight basis	< 1
Chemical Contaminants[4]	mg/kg (ppm)	Meet or exceed US EPA Class A standard, 40 CFR § 503.13, Tables 1 and 3 levels
Biological Contaminants[5] Select Pathogens Fecal Coliform Bacteria, or Salmonella	MPN per gram per dry weight MPN per 4 grams per dry weight	Meet or exceed US EPA Class A standard, 40 CFR § 503.32(a) levels

Figure 3: Model compost specification for soil amendment.

In the same year Craul and Switzenbaum (1996) developed a separate specification for compost used in amending soils in transportation projects. The specifications were similar for all values and identical for pH range and soluble salt limits. The specification differed by requiring at least 40% organic matter, a C:N ratio of 10:1 to 25:1, and stability of no more than 5 mg CO_2 per gram or no more than 20°C of heat rise.

Block (2000) published specifications adopted by the Connecticut Department of Transportation (ConDOT). The ConDOT compost specifications had a lower minimum organic matter percentage of 30%, a higher upper limit on moisture content of 60%, and included a requirement for maturity testing using the Solvita Compost Maturity Test to achieve a score of 6 or more.

Cole (1997) published requirements for preparation of compost-manufactured topsoil (CMT). The CMT was prepared by combining a one- to three-inch layer of compost into the top four- to six-inches of existing soil. The compost specifications include a pH between 6.0 and 8.0, a C:N ratio less than 33:1, a value of 7 or 8, corresponding to an indication of stable to very stable compost in accordance with the Solvita Maturity Test, and soluble salts less than 4.0 mmhos.

3. CHANGES IN SOIL PHYSICAL AND CHEMICAL PROPERTIES WITH COMPOST AMENDMENT

The application of compost to soils changes soil chemical and physical properties. These changes impact runoff and erosion and thereby affect potential pollution of surface and groundwater. The transport of potential pollutants such as N, P, and O-demanding compounds (biochemical oxygen demand (BOD) and chemical oxygen demand (COD)) in runoff may occur owing to the large quantities of organic matter in the applied materials and runoff of soluble nutrients originating from the waste. Therefore a thorough understanding of the benefits and potential limitations associated with compost addition to soil and the effects on the soil-waste system is important from a water quality standpoint. Furthermore, certain chemical changes in the soil can have important effects on toxicity to plant growth. For example, composts with a high C:N ratio immobilize N, which can cause N deficiency in plants. In addition, organic acids present in the compost may contribute to phytotoxicity.

Generally, compost addition has been shown to increase soil pH in acid soils but have little or no effect in alkaline soils. Compost addition has also been shown to increase soil CEC (McConnell et al., 1993).

Khaleel et al. (1981) provided a summary of changes in soil physical properties owing to organic waste application. In general, they found that the effect of solid waste on soil physical properties largely depends on the rate of decomposition of wastes and its contribution to soil organic C. Short-term experiments indicate significant to very significant increases in C, whereas long-term studies indicate C increases to a lesser degree. Soil type is also a factor, with higher rates of decomposition found in silt loam and lower rates in clay loam. Organic matter (OM) addition also appears to decrease in bulk density. The decrease in bulk density is attributed by some to a dilution effect brought on by mixing OM with the more dense mineral soil fraction. The change in bulk density appears to be more pronounced in coarse soils than in finely textured soils. Water holding capacity (WHC) tends to increase with addition of organic matter. This increase has been attributed to increased aggregation, which increases total pore space, and the decrease in bulk density, which changes the pore-size distribution. McConnell et al. (1993) confirmed the reported decrease in bulk density with compost application. Increases in WHC at both field capacity and wilting point are indicated for both fine-textured and coarse-textured soils. If increases in organic C cause an increase in WHC at both field capacity and wilting point, the net result is that the amount of water available (AWC) may not be affected. Hydraulic conductivity is expected to increase with increased porosity. However, data relative to hydraulic conductivity have shown extreme variability. Limited available data suggest that waste applications may improve both the initial infiltration rate and the steady-state infiltration rate. But, negative effects of waste applications on infiltration rates have also been reported owing to a build-up of sodium and potassium. Incorporation of organic matter has been shown to stabilize soils against erosion by improving aggregation and thereby reducing nutrient runoff. Research has also shown a reduction in runoff volume from plots with manure incorporated into the soil.

Researchers reasoned that the improvement of the physical properties of the soil after the application of organic wastes is related to an increase of the total porosity (Ortega et al., 1981) owing to the dilution of the mineral fraction when a material of lesser density is added (Mbagwu, 1992). When porosity rises, the area of water and gas interchange is increased, thus favoring the microbial and root development. However, Bresson et al. (2001) countered this assessment, offering instead that structural changes resulted from interactions between added organic matter and the soil.

He et al. (1992) published a summary table of the changes in soil properties owing to application of MSW compost. The table is included as Figure 4.

Property	Change	Reference
	Physical properties	
Bulk density	decreased	Mays et al. (1973); Duggan & Wiles (1976)
Porosity	increased	Pagliai et al. (1981)
Water holding capacity	increased	Mays et al. (1973); Bengston & Cornette (1973); Hernando et al. (1989)
Aggregation	stabilized	Pagliai et al. (1981); Gallardo-Lara & Nogales (1987); Guidi & Petruzzelli (1989)
	Microbiological properties	
Bacteria population	increased	Pera et al. (1983); Diaz-Ravina et al. (1989)
Fungi and actinomycetes population	increased	Miyashita et al. (1982)
Cellulolytic activity	increased	Rutili et al. (1987)
Autotrophic nitrifier	increased	Rutili et al. (1987); Diaz-Ravina et al. (1989)
Vesicular-arbuscular-mycorrhizae	increased	Jodice & Nappi (1987)
Urease activity	increased	Godden et al. (1987)
	Chemical properties	
Total C content	increased	Mays et al. (1973); Guidi et al. (1983); Hernando et al. (1989)
Total salt content	increased	Gallardo-Lara & Nogales (1987)
CEC	increased	Bengston & Cornette (1973)
N, P, and S	conflicting	Gallardo-Lara & Nogales (1987)
Ca, Mg, and K	increased	Bengston & Cornette (1973); Mays et al. (1973)
pH	increased	Mays et al. (1973); Duggan & Wiles (1976); Hernando et al. (1989)
Total trace metals	increased	De Haan (1981); Andersson (1983); Barbera (1987)
Trace metal extractability	increased	Petruzzelli et al. (1981, 1985); Barbera (1987)
Trace metal bioavailability	increased	Petruzzelli & Lubrano (1987); Petruzzelli (1989); Petruzzelli et al. (1989a)
Organic pollutants	increased	Ellwardt (1977); De Haan (1981); Gallardo-Lara & Nogales (1987)

Figure 4: Changes in soil properties with the addition of MSW compost.

3.1 Moisture Retention

Moisture retention is an important parameter that is difficult to measure in the laboratory, owing to the difficulty of translating laboratory values to field values and in simulating actual field conditions. Early in the literature review, a subtask was to identify the most widely used and accepted methods of measuring moisture retention in the laboratory as reported by other researchers so as to employ a similar method for this research project. Review of the literature indicated several methods have been used with some success over the years. The most widely used procedure was the pressure plate method for determination of water retention over a range of pressure values. The literature review also revealed some disagreement and dialogue as to whether or not available water capacity changes with organic matter addition or whether the entire moisture retention curve shifts upward. Lastly, the literature review identified which pressures provide the best estimate of field capacity and permanent wilting point. Results from the literature review are included in this section.

Huberty (1936) reported that the addition of organic matter to soil increased the soil storage of water, which can be used by plants. However, the application of organic matter appears to increase both the field capacity and the permanent wilting point so that the available water capacity, which is the difference between the capacity at the permanent wilting point and field capacity, is not changed. The primary benefit of adding organic matter to soil is to increase the overall water storage capacity of the soil. Confirming Huberty's earlier findings, Diaz-Marcote and Polo (1996) found that compost application (addition of organic matter) increased the water holding capacity at both the field capacity and at the permanent wilting point, resulting in no net change in the available water capacity. A similar tendency was reported by Berdal et al. (1992), by Fernandez et al. (1987), and by Gupta et al. (1977). Epstein (1975) found similar results in a pot study involving incubation of sewage sludge (5% by weight) with a Beltsville silt loam for 54 days. Tests of the amended soils indicated a shift in the water retention curve of the soil to higher water content at a given suction. However, the amount of water retained between 0.33 and 15 bars suction remained essentially the same as the original soil. Contradicting the above is an earlier paper by Bouyoucos (1938), which asserted that the addition of organic matter increased available water in both clay and sandy soils.

Huberty (1936) found that fine-textured soils hold more water at field capacity than coarse-textured soils. Jamison and Kroth (1958) found that organic matter appears to influence available water capacity more than silt content. However, research indicated that available water capacity also depends on both particle size distribution and soil structure. In general, available water capacity increases with silt content and decreases with clay or sand content. Results from their study indicate that as the proportion of clay in a soil increases, the available water capacity decreases, confirming Huberty's earlier findings.

Naeth et al. (1991) determined the water holding capacity of litter and soil organic matter by using 7 cm tall by 7 cm diameter plastic cylinders, with cotton fabric secured to the bottom of the cylinders with a rubber band. The cylinders were saturated for 48 hours, then allowed to drain for 48 hours on a tray of damp sand. The samples were weighed, oven dried at 105°C for 48 hours, and then reweighed. The water holding capacity was calculated by subtracting the oven dry mass from the drained mass, dividing by the oven dried mass, and then multiplying by 100. Hernando et al. (1989) used a similar method to determine the water holding capacity of a compost-amended soil saturated and then allowed to drain freely for 24 hours.

Hafez (1974) used the pressure plate method to determine the water holding capacity of different manures mixed with both sandy and clay soil at various percentages at 1/3 bar tension. The samples were saturated and maintained at 1/3 bar tension for 8 hours prior to measurement of the water holding capacity. Unger and Stewart (1974) also used a pressure plate apparatus for determination of water retention at saturation, 0.2, and –1.5 bars. Sommerfeldt and Chang (1986) used a pressure plate to determine soil moisture retention at 20 kPa and a pressure membrane to determine the soil moisture at 1500 kPa. Jamison and Kroth (1958) used the pressure plate method for determination of moisture release curves at 0.33, 1, 3, and 15 atm suctions. The 0.33 atm value was used as an estimate of available water capacity, whereas the 15 atm value was used as an estimate of the permanent wilting point. Diaz-Marcote and Polo (1996) and Epstein et al. (1976) used the same pressure plate method and points in determining field capacity and permanent wilting point.

Mamo et al. (2000) used a combination of the hanging water column method (Klute, 1986) and the pressure plate method to develop moisture retention curves for compost-amended soils. The hanging water column was used at lower pressures (0.0005, 0.001, 0.003, 0.005, 0.0075, and 0.01 Mpa), whereas the pressure plate method was used to determine moisture retention at higher pressures (0.03, 0.05, and 0.1 Mpa). Results indicate that compost treatments did not significantly affect moisture retention. Instead, the moisture retention curve was shifted upward, increasing moisture retention at both field capacity and wilting point, which resulted in no net change in available water holding capacity.

Bauer and Black (1992) reported that the general consensus is that the 10-kPa tension values approximate the field capacity of coarse and moderately coarse-textured soils, whereas the 33-kPa pressure values approximate that of all other textures. Furthermore, the 1500-kPa pressure is used to approximate the permanent wilting point. For their experiments, soil water concentration was measured with a pressure plate apparatus after equilibrating the samples to the required pressure for 24 hours (except for the 1500-kPa sample, which was equilibrated for 72 to 96 hours). Some 50 years earlier, Colman (1946) evaluated the relationship between the 33-kPa pressure value and the estimate of moisture equivalent (field capacity) and found good correlation.

3.2 Sandy Soils

3.2.1 Physical Changes to the Soil

Bulk density

Mamo et al. (2000) found that application of 270 Mg per hectare of compost decreased soil bulk density. These findings are similar to those obtained by Kreft (1987), Gupta et al. (1977), Khaleel et al. (1981), and Tester (1990).

Water holding capacity (WHC)

Hernando et al. (1989) found that the water holding capacity increased with compost addition at rates of 15, 30, and 60 tons per hectare. Mamo et al. (2000) investigated the effect of compost addition to a well-drained sandy soil. Results indicate that the moisture retention curve shifted upward, increasing moisture retention at both field capacity and wilting point, which resulted in no net change in available water holding capacity. Similar results were reported by Diaz-Marcote and Polo (1996).

Aggregate stability

Hernando et al. (1989) found that the aggregate stability was increased by addition of compost at rates of 30 and 60 tons per hectare. Albiach et al. (2001) found that, after five years of amending a sandy silt loam soil with 24 tons per hectare per year of composted municipal refuse and sludge, aggregate stability increased significantly more than the control. Diaz-Marcote and Polo (1996) reported that the percentage of stable aggregates tended to increase in the plots with compost applied at a rate of 80 tons per hectare per year.

3.2.2 Chemical Changes to the Soil

pH

According to the literature review, compost addition appears to have a varied effect on soil pH. A study by Giusquiani et al. (1987) found no change in pH with addition of 2.5% of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. Similarly, Cuevas et al. (2000) found no significant change in pH with addition of composted municipal solid waste. Conversely, Hernando et al. (1989) found that pH increased with the addition of compost but that the increase in pH was likely due to the high calcium content of the compost. Research by Diaz-Marcote and Polo (1996) also found a gradual increase in pH in compost-amended soils. The researchers stated that the increase in pH with the incorporation of organic wastes has been observed by numerous authors (Buchanan & Gliessman, 1991; Gollardo & Nogales, 1987; Hernando et al. 1989). In contrast, Zinati et al. (2001) found a decrease in the soil pH with the addition of compost prepared from 100% yard trimmings and food wastes and compost prepared from 100% biosolids.

Cation Exchange Capacity (CEC)

A study by Giusquiani et al. (1987) showed no change in CEC with addition of 2.5% of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. Hernando et al. (1989) and Cuevas et al. (2000) achieved similar results, with CEC unaffected by compost addition. Conversely, Diaz-Marcote and Polo (1996) found CEC increased with addition of 80 tons per hectare of MSW compost and increased to a lesser extent in plots treated with 20 tons per hectare.

Salts

Cuevas et al. (2000) found electrical conductivity (EC) increased with addition of municipal solid waste compost and was significantly higher at higher compost application rates than in the control plots. Similar results were reported by Zinati et al. (2001), who found a substantial increase in EC with addition of compost prepared from 100% yard trimmings and food wastes and compost prepared from 75% municipal solid waste and 25% biosolids. Diaz-Marcote and Polo (1996) also reported that the increase in EC was considerable.

Nitrogen

Cuevas et al. (2000) found inorganic N increased with addition of municipal solid waste compost but found no change in total N, as compared with control. The researchers also found significantly higher nitrate concentrations in the intermediate to high compost treatments, whereas ammonia nitrogen showed a significant increase at only the highest compost application rate. Mamo et al. (1999) found that additions of compost made from cardboard, paper, food waste, and yard waste to a Hubbard sandy loam soil significantly affected nitrate-nitrogen leaching.

Organic Matter

A study by Hernando et al. (1989) found that the carbon content increased in proportion to the amount of compost added. Compost addition varied from 15 tons per hectare to 60 tons per hectare. Albiach et al. (2001) found increased levels of soil organic matter after five years of amending a sandy silt loam soil with 24 tons per hectare per year of composted municipal refuse and sludge. Zinati et al. (2001) found that utilization of composts as a soil amendment increases soil organic carbon more than using inorganic fertilizer in calcareous soil of South Florida.

Available Potassium (K)

A study by Giusquiani et al. (1987) showed an increase in concentration of available potassium with the addition of 2.5% of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. Similar results were obtained by Cuevas et al. (2000).

Available Phosphorus (P)

A study by Giusquiani et al. (1987) showed a decrease in concentration of available phosphorus with the addition of 2.5% of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. However, the compost addition increased the solubility of P, which was attributed to the formation of phosphohumic complexes that reduce the ability of the soil to fix P. Cuevas et al. (2000) found levels of available P increased as rates of municipal solid waste compost increased, although the rise in available P was not proportional to the amount of P supplied by the compost.

Metals

A study by Giusquiani et al. (1987) showed a significant increase in Zn concentration, an increase in Fe and Cu, and a significant increase in available Mn with the addition of

2.5% of composted municipal sewage sludge to sandy silt loam during a 12-month incubation period. Only the Zn posed a potential threat in terms of toxicity if applied in greater than allowable amounts. Cuevas et al. (2000) found that concentrations of all heavy metals rose. However, the rise was significant only for Zn, Pb, and Cu, whereas Cd, Ni, and Cr did not change appreciably.

3.3 Clay Soils

3.3.1 Physical Changes

Bulk Density

Aggelides and Londra (2000) found that addition of compost produced from a mixture of sawdust, sewage sludge, and town wastes reduced bulk density.

Water Holding Capacity

Aggelides and Londra (2000) found that addition of compost produced from a mixture of sawdust, sewage sludge, and town wastes improved the water retention of the soil.

Aggregate Stability

Aggelides and Londra (2000) found that addition of compost produced from a mixture of sawdust, sewage sludge, and town wastes improved aggregate stability.

3.3.2 Chemical Changes

pH

A study by Giusquiani et al. (1987) showed no change in pH with addition of 2.5% of composted municipal sewage sludge to clay silt loam during a 12-month incubation period.

CEC

A study by Giusquiani et al. (1987) showed no change in CEC with addition of 2.5% of composted municipal sewage sludge to clay silt loam during a 12-month incubation period.

Exchangeable Potassium (K)

A study by Giusquiani et al. (1987) showed an increase in concentration of exchangeable K with the addition of 2.5% of composted municipal sewage sludge to clay silt loam during a 12-month incubation period. The increase was three times that of the control soil.

Available Phosphorus (P)

A study by Giusquiani et al. (1987) showed no change in concentration of available P with the addition of 2.5% of composted municipal sewage sludge to clay silt loam during a 12-month incubation period. However, the compost addition increased the solubility of P, which was attributed to the formation of phosphohumic complexes that reduce the ability of the soil to fix P.

Metals

A study by Giusquiani et al. (1987) showed a significant increase in Zn concentration, an increase in Fe and Cu, and an increase in available Mn with the addition of 2.5% of composted municipal sewage sludge to clay silt loam during a 12-month incubation period. As in the sandy soils, only the Zn posed a potential threat in terms of toxicity if applied in greater than allowable amounts.

3.4 Silt Soils

Cox et al. (2001) performed experiments with compost made from animal manure (85%) and coal ash (10%), with the remainder being food and landscaping waste. The experiments were conducted on silt loam. The researchers found that the compost amendment decreased soil bulk density, improved water stable aggregate formation, and improved water infiltration rates. The increase in water infiltration rates is beneficial because it results in less runoff and erosion.

Epstein et al. (1976) performed experiments on Woodstown silt loam with compost made from municipal sludge. Results indicated soil moisture contents increased in the compost-amended plots more than the control plots and that more water was retained at both the field capacity and permanent wilting points.

Mays et al. (1973) found an increase in water content corresponding to the 0.33 bar suction of a silt loam soil after an application of 327 metric tons per hectare of municipal compost (garbage waste plus 20% sewage sludge by weight) for two years. The researchers also found a decrease in bulk density, an increase in soil organic matter, and increases in K, Ca, Mg, Zn, and pH with heavy compost applications.

Aggelides and Londra (2000) found that addition of compost produced from a mixture of sawdust, sewage sludge, and town wastes increased aggregate stability, reduced bulk density, and improved water retention.

4. APPLICATION OF COMPOST

Erosion is a naturally occurring process that is exacerbated by new construction and road building. As such, many state DOTs and the United States Department of Transportation have initiated studies to combat erosion along roadsides. Much of this research has been geared toward the use of compost for erosion control, as a soil conditioner, and for added nutrients.

4.1 Compost Use as a Soil Amendment and Conditioner

As discussed at length in the previous section, the addition of compost to soil changes the chemical and physical properties of the soil. In general, compost addition improves soil structure by reducing the bulk density, increasing the permeability, and increasing aggregate stability. These improvements reduce erosion (Kreft, 1987; Tester, 1990) and increase the water holding capacity of soils (Kreft, 1987). There is also evidence that compost addition improves drought resistance (USCC, 1996). Khaleel et al. (1981) reports that compost amendment improved soil physical properties (Khaleel et al., 1981), increased availability of soil nutrients, microbial population and its activity, reduced the incidence of soil nematodes and other pathogens (Gallardo & Nogales, 1987), and increased crop yields (Roe et al., 1993). Compost addition may also aid in the capacity of the soil to bind heavy metals by altering soil chemistry, including pH and CEC (USCC, 1996).

4.2 Compost Use for Erosion Control

Factors affecting runoff are numerous and complex. According to Wischmeier and Mannering (1969), soils that are high in silt, low in clay, and low in organic matter tend to erode the most. Soils that are high in silt become less erodible as the silt levels decrease. For high silt soils, pH is also extremely important to erodibility. Wischmeier and Mannering also found that the permeability of the surface seals decreased as organic matter content, percent sand, aggregation index, bulk density, or lime requirement decreased and as silt, clay ratio, suspension percentage, moisture equivalent, pH, or modulus of rupture increased. Generally, compost amendment decreases soil erodibility.

The Federal Highway Administration and the United States Environmental Protection Agency joined forces to investigate the use of composted yard trimmings versus hydromulch for controlling erosion on highway embankments at a site in Washington, DC. One site had a 2:1 slope, whereas the other had a 3:1 slope. Results indicated that compost treatment outperformed all other treatments (USEPA, 1997).

Alexander (2002) reported that the efficacy of compost used for erosion control applications depends on the characteristics of the compost. In general, compost that is coarse and applied at relatively high application rates are required in areas where the soil has a high erosivity index. The coarseness of the particles in the compost absorbs the energy of the rain and reduces the flow velocity. Furthermore, coarse particles are heavier and are therefore more difficult to erode than smaller particles. Compost also aids in the rapid establishment of vegetation and slows surface flow velocity.

Demars et al. (2001) investigated the use of mulches derived from wood residuals applied to 1:2 slopes at rates of 0.75 inches to 3 inches. Erosion was minimized in the mulch-applied slopes, as compared with the control. Results also indicate that the mulch reduced runoff during storms in which less than 0.5 inches fell.

Research conducted by Hamilton Manufacturing (1999) evaluated a hydrocompost material comprised of three parts dairy manure compost and one part recycled paper mulch plus tackifier and water applied to one highway site and three residential plots. Performance of the hydrocompost was compared with plots prepared with mat fiber mulch with guar tackifier. Qualitative results indicated that the hydrocompost resulted in lower soil erosion rates but higher water runoff rates than the mat fiber mulch plots and that the hydrocompost provided better seed germination performance.

Goldstein (2002) reported research conducted by Risse et al. that involved the use of composted poultry litter, composted biosolids, and mulch in simulated rainfall experiments. The researchers found the mulch and composted biosolids outperformed composted poultry litter in terms of total solids lost owing to erosion. Research also indicated the mulch treatments were better overall than the compost treatments, having lower solids loss and less runoff than the composts. Nutrient losses were higher in the compost treatments than in the mulches. Total nitrogen losses were much higher from the composted biosolids than from any other treatment, and total phosphorus losses were much greater for poultry litter than for any other treatment.

Goldstein (2002) also reported on research conducted by Page and Leonard. Their research investigated composted municipal solid waste and biosolids used for erosion control in simulated rainfall experiments on a 50:1 slope. Results indicate that soils amended with compost delayed surface degradation and decreased sediment runoff. These results are consistent with those found by Bresson et al. (2001).

Block (1999) reported field studies using a mixture of coarse, unscreened compost and woodchips. Successful field studies indicated use of the compost and woodchip mix reduced erosion. Additional studies using yard trimmings compost, conducted in the following year, found that the compost-amended soils reduced erosion by an order of magnitude over the untreated soils and significantly improved turf establishment (Block, 2000).

Harrison et al. (1997) examined the effectiveness of using compost as a soil amendment to increase surface water infiltration, to reduce the quantity and/or intensity of surface and subsurface runoff from the land, and to reduce the transport of dissolved or suspended phosphorus and nitrate-nitrogen. Water runoff properties were improved with compost amendment, with the compost-amended soils showing greater lag time to peak flow at the initiation of a rainfall event and greater base flow in the interval following a rainfall event. In addition, runoff from compost-amended soils had 70% less total P, 58% less soluble P, and 7% less nitrate-nitrogen than the control.

Bresson et al. (2001) studied the effects of compost addition to a silt loam soil in the northern Paris basin. The compost came form an Office Technique de Valorisation des Dechets (OTVD) commercial plant (Orleans, France). The compost was mixed with the soil material at a rate of 15 g/kg and placed in runoff trays at a 5% slope. Rainfall simulation with deionized water was performed using a 361 needles, 1m by 1m simulated, located 6 m high, to simulate a 3-year storm event. The compost addition delayed runoff and decreased sediment loss.

4.3 Compost Use Guidelines

McConnell et al. (1993) outlined recommendations for improving several important physical and chemical properties of soil through compost addition. The recommendations include the following:

- Composted MSW that contains more than 50% organic matter should be at least 15 tons per acre (about 0.25 inches thick) to noticeably increase OM in soil.
- To increase water holding capacity, apply 10 to 15 tons per acre to most mineral soils in order to increase WHC by 5% to 10%.
- MSW compost applied at rates of 10 to 20 tons per acre usually increase pH by 0.5 to 1.0 pH unit in acid soils (Hernando et al., 1989), whereas slightly alkaline soils (pH of 7.1 to 7.5) exhibit little or no change.
- Application of composted MSW increases soil CEC. Rates of 15 tons per acre have increased CEC of a sandy soil by almost 10% (Hortensine & Rothwell, 1973).

The *Field Guide to Compost Use* recommends the following:

- Moisture content to be in the range of 30% to 60%;
- Heavy metal content must meet EPA 503 Regulations; and
- Bulk density ranges from 700 to 1,200 lbs/cy.

Alexander (2001) reported typical ranges of compost specification data for state DOTs. The typical ranges are summarized in Table 15.

Table 15: TxDOT compost specification data

	Range of values	Typical Range
PH	5.0 – 8.5	5.5 – 8.0
Organic Matter (%)	35 - 60	35 – 55
Soluble Salts (dS/m)	<3 - 10	<4
Moisture Content (%)	35 - 60	35 – 55
C:N	<6 – 30:1	<10 – 20:1
Inerts (%)	<0.3 - 1	<1
Particle Size (inches)	<0.5 - 1	<0.5 – 1

Alexander (2002) reported compost use specifications for products to be used in erosion control. The national specifications for highway use of compost blankets for erosion control are presented in Table 16.

Table 16: Compost blanket parameters

Parameter	Unit	Vegetated	Unvegetated
PH	Std. Units	5 – 8.5	NA
Soluble Salt	dS/m	<5	<5
Moisture Content	% wet weight	30 – 60	30 – 60
Organic Matter	% dry weight	25 – 65	25 – 100
Particle Size	% passing	100% passing 3”, 90% passing 1”, 65% passing ¾”, 75% passing ¼”	100% passing 3”, 90% passing 1”, 65% passing ¾”, 75% passing ¼”
Stability	mg CO2/gOM	<8	NA
Physical Cont.	% dry weight	<1	<1
Chemical Cont.	mg/kg (ppm)	Ar 41, Cd 39, Cu 1,500, Pb 300, Hg 17, Mb 75, Ni 420, Se 100, Zn 2800	Ar 41, Cd 39, Cu 1,500, Pb 300, Hg 17, Mb 75, Ni 420, Se 100, Zn 2800
Biological Cont.	MPN	Salmonella <3MPN/4 grams of TS, Fecal <1000 MPN/gram of TS	Salmonella <3MPN/4 grams of TS, Fecal <1000 MPN/gram of TS

The article also included application rates for compost, incorporating both rainfall and soil erosivity. The recommended application rates are summarized in Table 17.

Table 17: Compost blanket application rates

Rainfall	Total Precipitation And Erosivity Index	Application Rate for Vegetated Compost	Application Rate for Unvegetated Compost
Low	1 - 25” 20 – 90	½ - ¾”	1 – 1 ½”
Average	26 – 50” 91 – 200	¾ - 1”	1 ½ - 2”
High	≥51” ≥201	1 – 2”	2 – 4”

4.4 Potential Problems Associated with Compost Use

Mitchell (1997c) reports the most common problem encountered when using compost for transportation projects is compost quality. Most failures have involved use of immature compost, which can be detrimental to plant growth. Research has shown that a single parameter may not be adequate in the assessment of compost maturity and stability. Depending on the feedstock, some stable composts may require more time to break down toxic substances, whereas in other cases some mature compost may have a relatively high respiration rate (Wu et al., 2000). Other problems include lack of availability of compost of the quality and quantity required and costs associated with long hauling times.

Eghball and Gilley (2001) reported loss of P from a silty clay loam treated with composted and noncomposted beef cattle feedlot manure. The researchers found that erosion was the main cause of total and particulate P loss owing to loss of sediment-bound P. Loss of P from compost and manure treatments was less than that from fertilizer treatments but may still be problematic, depending on the application rates and characteristics of the soil. In an earlier study, Eghball and Gilley (1999) reported an increase in runoff concentration of dissolved P, bioavailable P, and ammonia nitrogen from soils where compost had been applied but not incorporated into the soil. The researchers also found that the runoff from the compost-treated soils had higher EC values, indicating greater salt leaching.

One study by Benson and Othman (1993) investigated using municipal solid waste compost as a landfill cover or liner. Their research indicated that compost could be compacted to achieve sufficiently low permeability, that the compost has sufficient shear strength to resist slope sloughing, and that compost has better resistance to freeze/thaw cycles and to desiccation than clay liners. However, their research confirmed that hazardous constituents (including metals, if present, and nitrogen) leach from the compost but that the amount of leaching decreases after a period of time. Their findings confirm earlier work by Christensen and Nielsen (1983), Christensen (1983, 1984), Christensen and Tjell (1984), Diaz et al. (1977), Diaz and Trezek (1979), and Haan (1979) whose research showed increased amounts of carbonaceous oxygen demand and leaching of nitrogen, inorganic ions, and metals.

Research conducted by Pare et al. (1998) on the transformations of carbon and nitrogen during composting of animal manures indicates that composting decreased all forms of carbon except nonhydrolyzable C, which remained relatively constant during the composting period. On the other hand, ammonia nitrogen and acid-hyrolyzable N were converted into nitrate nitrogen and nonhydrolyzable N forms only toward the end of the composting period. Those results indicate immature compost will contain ammonia nitrogen and acid-hydrolyzable N and could lead to considerable leaching of N.

With the reported increase in EC owing to compost addition, the risk of salinization in arid and semiarid conditions is high. However, compost with high salt levels has been shown to perform well once the salt has been leached in areas where sufficient rainfall exists (Mitchell, 1997a).

Epstein et al. (1976) found an increase in Redox potential and higher levels of carbon dioxide concentrations in compost-amended soils. The researchers noted that under extremely reduced conditions (e.g., minus 150 to minus 250 mV), other phytotoxic constituents such as hydrogen sulfide, methane, and ethylene might arise. The reduced soil conditions and poor soil aeration could adversely affect plant growth and root development.

Another study, reported in the J.R. Science News in November 2001, indicates hormone concentrations in composted animal manure of 13 and 16 ppb of testosterone and estrogen, respectively.

Dry, dusty compost may cause healthy individuals to experience eye, skin, or respirator irritation, which can be reduced with appropriate protective gear (Mitchell, 1997a).

5. CONCLUSIONS

Environmentally sound methods of disposing of vast quantities of organic wastes generated by municipalities, agricultural farming, animal agriculture, logging, and industries has been a hot issue in recent decades. Past practices of lagooning and surface applying the wastes without treatment has led to surface and groundwater contamination, air pollution, and has presented other health and safety concerns. Landfilling of the wastes has reduced contamination but has placed a burden on shrinking landfill space. Many cities have passed legislation banning "clean wastes" such as yard trimmings from landfills to conserve landfill space. Furthermore, many landfill operators have banned wastewater sludges from landfills, making alternative disposal options such as land application and composting more attractive.

Composting has become the preferred management practice for most diverted yard waste (Haug, 1993) and is being investigated for use with many other wastes. Composting of organic wastes has become a principal method of waste reduction, disposal, and reuse because it produces a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land (Haug, 1993). Composting also reduces greenhouse gas emissions (Daigle et al., 1989).

Generally, most compost has a pH in the neutral range, organic matter content in the 30% to 60% range, moisture content in the 30% to 50% range, and higher values of N, P, K, and salts than typical agricultural soils. Some composts (especially compost derived from MSW) typically has higher levels of trace metals, especially Cu, Zn, and Pb, which can cause accumulation problems in soils with repeated applications (He et al., 1992).

The addition of compost to soil changes the chemical and physical properties of the soil. In general, compost addition improves soil structure by reducing the bulk density, increasing the permeability, and increasing aggregate stability. These improvements reduce erosion (Kreft, 1987; Tester, 1990) and increase the water holding capacity of soils (Kreft, 1987). There is also evidence that compost addition improves drought resistance (USCC, 1996). Khaleel et al. (1981) reports that compost amendment improved soil physical properties, increased availability of soil nutrients, microbial population and its activity, reduced the incidence of soil nematodes and other pathogens (Gallardo & Nogales, 1987), and increased crop yields (Roe et al., 1993). Compost addition may also aid in the capacity of the soil to bind heavy metals by altering soil chemistry, including pH and CEC (USCC, 1996).

Compost has been used for turf establishment, remediation of contaminated soils, as a liner or cover for landfills, for erosion control, to reduce the need for chemical fertilizers and herbicides, and as a soil conditioner.

Erosion is a naturally occurring process that is exacerbated by new construction and road building. As such, many state DOTs and the United States Department of Transportation have initiated studies to combat erosion along roadsides. Much of this research has been geared toward the use of compost for erosion control, as a soil conditioner, and for added nutrients. Research indicates that compost amendment generally decreases soil erodibility.

Potential problems with compost use include quality, nutrient loss through erosion and leaching, accumulation of heavy metals, and the introduction of high salt levels.

BIBLIOGRAPHY

On-line Sources

City of Lincoln, Nebraska on-line Website. (2002). Retrieved 1/22/02 from http://www.ci.lincoln.ne.us/city/pworks/waste/recycle/g&l/results.htm

Cox, D., Bezdicek, D., & Fauci, M. (2001). Effects of compost, coal ash, and straw amendments on restoring the quality of eroded Palouse soil. Published on-line in *Biology & Fertility of Soils*. Retrieved 5/7/02 from http://link.springer-ny.com/lings/s…0335/paper/s003740000335ch110.html

Neibling, H., & Robertson, L. (1997). *Scheduling the last irrigation on cereals*. Boise, ID: University of Idaho Cooperative Extension System and Agricultural Experiment Station.

Texas A&M University online information databank. (2002). Retrieved 1/22/02 from http://tomgreen-ext. ext.tamu.edu/mg/soilwat.htm

Texas A&M University online databank. (2002). Retrieved 1/22/02 from http://interactive.usask.ca/skinteractive/modules/agriculture/soils/soilphys/index.html

Urban soils. (2002). City: Washington State University. Retrieved 1/22/02 from http://www.puyallup.wsu.edu/soilmgmt/UrbanSoils.htm

Books and Journal Articles

Adeoye, G.O., Sridhar, M.K.C., & Mohammed, O.E. (1994). Poultry waste management for crop production: Nigerian experience. *Waste Management & Research*, 12, 165-172.

Aggelides, S.M., & Londra, P.A. (2000). Effects of compost produced from town wastes and sewage sludge on the physical properties of a loamy and a clay soil. *Bioresource Technology*, 71, 253-259.

Albiach, R., et al. (2001). Organic matter components and aggregate stability after the application of different amendments to a horticultural soil. *Bioresource Technology*, 76, 125-129.

Alexander, R. (2001, June). Tapping potential for compost use in highway applications. *Biocycle*, 57-60.

Alexander, R. (2002, April). National specifications for highway use of compost. *Biocycle*, 74-77.

Bauer, A., & Black, A.L. (1992). Organic carbon effects on AWC of three soil textural groups. *Soil Science Society of America Journal*, 56, 248-254.

Benson, C.H., & Othman, M.A. (1993). Hydraulic and mechanical characteristics of a compacted MSW compost. *Waste Management & Research*, 11, 127-142.

Bernal et al. (1992). Effects of the application of pig slurry on some physico-chemical and physical properties of calcareous soils. *Bioresource Technology* 42, 233-239.

Block, D. (1999, September). Composting for erosion control in Texas. *Biocycle*, 40-41.

Block, D. (2000, January). Controlling erosion from highway projects. *Biocycle*, 59-62.

Bouyoucos, G.J. (1938). *Effect of organic matter on the WHC and the wilting point of mineral soils* (Scientific Paper No. 336). Michigan Agricultural Experiment Station.

Bresson, L.M., et al. (2001). Soil surface structure stabilization by MSW compost application. *Soil Science Society of America Journal*, 65, 1804-1811.

Browning, G.M. (1941). *Relation of field capacity to moisture equivalent in soils of West Virginia* (Scientific Paper No. 265). West Virginia Agricultural Experiment Station.

Buchanan, M. & Gliessman, S.R. (1991, December). How compost fertilization affects soil nitrogen and crop yield. *Biocycle*. 72-77.

Canet, R., et al. (2000, December). Analyzing chemical properties of MSW composts. *Biocycle*, 72-76.

Christensen, T.H. (1983). Leaching from land disposed municipal compost: 2. Nitrogen. *Waste Management & Research* 1, 115-125.

Christensen, T.H. (1983). Leaching from land disposed municipal compost: 3. Inorganic ions. *Waste Management & Research* 2, 63-74.

Christensen, T.H. & Nielsen, C.W. (1983). Leaching from land disposed municipal composts: 1. Organic matter. *Waste Management & Research* 1, 83-94.

Christensen, T.H. & Tjell, J. (1984). Leaching from land disposed municipal compost: 4. Heavy metals. *Waste Management & Research* 2, 347-357.

Cole, M. (1997, November). Compost: Right stuff to manufacture topsoil. *Biocycle*, 61-63.

Colman, E.A. (1946). *A laboratory procedure for determining field capacity of soils*. USDA: Author.

Craul, P.J., & Switzenbaum, M.S. (1996). Developing biosolids compost specifications. *Biocycle*, 37, 44-47.

Cross, O.E., Mazurack, A.P., & Chesnin, L. (1973). Animal waste utilization for pollution abatement. *Transactions of the ASAE,* 16, 160-163.

Cuevas, G., et al. (2000). Composted MSW effects on soil properties and native vegetation in a degraded semiarid shrubland. *Compost Science & Utilization*, 8, 303-309.

Daigle et al. (1989). One solution of two problems. In: Overend, R.P. & Jeglum, J. (eds). Proceedings of peat and peatlands. Symposium 89, International Peat Society, 6-10 August 1989, Quebec, Canada, 64-66.

Darmody, R.G., et al. (1983). Municipal sewage sludge compost-amended soils: Some spatiotemporal treatment effects. *Journal of Environmental Quality*, 12, 231-236.

de Bertoldi, M., Sequi, P., Lemmes, B., & Papi, T. (Eds.) (1996). *The science of composting.* Glasgow: Blackie Academic and Professional.

Demars, K., Long, R., & Ives, J. (2001, November). Using woody materials for erosion control. *Biocycle*, 43-45.

Diaz et al. (1977). *Public Health Aspects of Composting Combined Refuse and Sludge and of the Leachates Therefrom.* Berkeley, CA, U.S.A.: College of Engineering, University of California.

Diaz, L.F. & Trezek, G.J. (1979). Chemical characteristics of leachate from refuse-sludge compost. *Compost Science Land Utilization* 20(2), 27-30.

Diaz-Marcote, I., & Polo, A. (1996). Evolution of the physical and chemical properties of soil with the application of MSW compost. *Journal of Solid Waste Technology & Management*, 23, 101-106.

Diop, A.M. (1999). Sustainable agriculture: New paradigms and old practices? Increased production with management of organic inputs in Senegal. *Environment, Development & Sustainability*, 1, 285-296.

Eghball, B., & Gilley, J.E. (2001). Phosphorus risk assessment index evaluation using runoff measurements. *Journal of Soil and Water Conservation*, 56, 202-206.

Eghball, B., & Gilley, J.E. (1999). Phosphorus and nitrogen in runoff following beef cattle manure or compost application. *Journal of Environmental Quality*, 28, 1201-1210.

Epstein, E. (1974). Effect of sewage sludge on some soil physical properties. *Journal of Environmental Quality* 4, 139-142.

Epstein, E., Taylor, J.M., & Chaney, R.L. (1976). Effects of sewage sludge and sludge compost applied to soil on some soil physical and chemical properties. *Journal of Environmental Quality*, 5, 422-426.

Fernandez et al. (1987). Handling of municipal solid waste residuals. In: 7th National Conference on Agriculture and the Environment. Seville, Spain.

Freeman, T.M., & Cawthon, D.L. (1999). Use of composted dairy cattle biomass, poultry litter and municipal biosolids as greenhouse growth media. *Compost Science & Utilization*, 7, 66-71.

Gallardo, F. & Nogales, R. (1987). Effects of the application of town refuse compost on the soil-plant system. *Biol. Wastes* 19, 35-63.

Giusquiani, P.L., Marucchini, C., & Businelli, M. (1987). Chemical properties of soils amended with compost of urban waste. *Plant & Soil*, 109, 73-78.

Goldstein, N. (2002). Erosion control research update. *Biocycle*, 43, 78-82.

Gouin, F.R. (1991, August). The need for compost quality standards. *Biocycle*, 44-47.

Gupta, S.C., Dowdy, R.H., & Larson, W.E. (1977). Hydraulic and thermal properties of a sandy soil as influenced by incorporation of sewage sludge. *Soil Science Society of America Journal*, 41, 01-605.

Haan, S. de (1979). Chemical composition of drainage water from sewage sludges used as plant substrates. In *Treatment and Use of Sewage Sludge, 1st European Symposium, Cadarache 13-15 February 1979* (Proceedings, 1981). Brussels, Belgium: Commission of the European Communities.

Hafez, A.A.R. (1974). Comparative changes in soil-physical properties induced by admixtures of manures from various domestic animals. *Soil Science*, 188, 53-59.

Hamilton Manufacturing, Inc. (1999). *Evaluation of hydroseeding with compost additive.* Recycling Technology Assistance Partnership: Author.

Harrison, R.B., et al. (1997). *Field test of compost amendment to reduce nutrient runoff*. Seattle: University of Washington College of Forest Resources.

Haug, R.T. (1993). *The Practical Handbook of Compost Engineering*. Boca Raton: Lewis Publishers, 1993.

He, X.T., Traina, S.J., & Logan, T.J. (1992). Chemical properties of municipal solid waste composts. *Journal of Environmental Quality*, 21, 318-329.

Henry, G., & Bush, D. (1996). Applying yard trimmings compost to Florida highways. *Biocycle*, 53-54.

Henry, S.T., & White, R.K. (1993). Composting broiler litter from two management systems. *Transactions of the ASAE*, 36, 873-877.

Hernando, S., Lobo, M.C., & Polo, A. (1989). Effect of the application of municipal refuse compost on the physical and chemical properties of a soil. *The Science of the Total Environment*, 81/82, 589-596.

Hill, J.N.S., & Sumner, M.E. (1967). Effect of bulk density on moisture characteristics of soils. *Soil Science*, 103, 234-238.

Hortensine, C.C. & Rothwell, D.F. (1973). Pelletized municipal refuse compost as a soil amendment and nutrient source for sorghum. *Journal of environmental Quality* 2, 343-345.

Huberty, M.R. (1936). Effect of soil characteristics on plant development in relation to water conservation. *Soil Science Society of America Proceedings*, 1, 439-446.

Inbar, Y., Hadar, Y., & Chen, Y. (1993). Recycling of cattle manure: The composting process and characterization of maturity. *Journal of Environmental Quality*, 22, 857-863.

Inman, J.C., et al. (1982). Nitrogen and phosphorus movement in compost amended soils. *Journal of Environmental Quality*, 11, 529-532.

Jamison, V.C., & Kroth, E.M. (1958). Available moisture storage capacity in relation to textural composition and organic matter content of several Missouri soils. *Soil Science Society of America Proceedings*, 22, 189-192.

Khaleel, K., Reddy, K.R., & Overcash, M.R. (1981). Changes in soil physical properties due to organic waste applications: A review. *Journal of Environmental Quality*, 10, 133-141.

Klute, A. (1986). Water retention: Laboratory methods. In: A. Klute (ed.) 2nd ed. *Methods of Soil Analysis.* Part 1. American Society of Agronomy, Madison, WI, 635-651.

Kreft, S. (1987). *Soil physical properties as influenced by the addition of municipal compost*. M.S. Thesis. University of Minnesota, St. Paul, Minnesota.

Long, F.L. (1979). Runoff water quality as affected by surface applied dairy cattle manure. *Journal of Environmental Quality*, 8, 215-218.

Long, F.L., Lund, Z.F., & Hermanson, R.E. (1975). Effect of soil incorporated dairy cattle manure on runoff water quality and soil properties. *Journal of Environmental Quality*, 4, 163-166.

Mamo, M., et al. (2000). The effect of MSW compost application on soil water and water stress in irrigated corn. *Compost Science & Utilization*, 8, 236-246.

Mamo, M., Rosen, C.J., & Halbach, T.R. (1999). Nitrogen availability and leaching from soil amended with MSW compost. *Journal of Environmental Quality*, 28, 1074-1082.

Mathers, A.C., Stewart, B.A., & Thomas, J.D. (1977). Manure effects on water intake and runoff quality from irrigated grain sorghum plots. *Soil Science Society of America Journal*, 41, 782-785.

Mays, D.A., Terman, G.L., & Duggan, J.C. (1973). Municipal compost: Effects on crop yields and soil properties. *Journal of Environmental Quality*, 2, 89-92.

Mbagwu, J.S.C. (1992). Improving the productivity of a degraded ultisol in Nigeria using organic and inorganic amendments. Part 2. Changes in physical properties. *Bioresource Technology* 42, 167-175.

McConnell, D.B., Shiralipour, A., & Smith, W.H. (1993, April). Compost application improves soil properties. *Biocycle*, 61-63.

Mitchell, D. (1997a, March). *Compost utilization by departments of transportation in the United States*. Gainsville: University of Florida Cooperative Extension, FlDOT, USDOT.

Mitchell, D. (1997b, July). State transportation departments expand compost use. *Biocycle*, 75-80.

Mitchell, D. (1997c, August). State highway departments find it pays to use compost. *Biocycle*, 67-72.

Naeth, M.A., et al. (1991). WHC of litter and soil organic matter in mixed prairie and fescue grassland ecosystems of Alberta, Canada. *Journal of Range Management*, 44, 13-17.

Ortega et al. (1981). Modification in the porosity of soil with the addition of composted urban waste. *An. Edafol. Agrobiol.* 40, 1735-1747.

Pagliai, M., et al. (1981). Effects of sewage sludges and composts on soil porosity and aggregation. *Journal of Environmental Quality*, 10, 556-561.

Pare, T., et al. (1998). Tranformations of C and N during composting of animal manure and shredded paper. *Biological Fertility of Soils*, 26, 173-178.

Roe et al. (1993). Utilization of MSW compost and other organic mulches on commercial vegetable crops. *Compost Science and Utilization,* 1(3), 73-84.

Sommerfeldt, T.G., & Chang, C. (1985). Changes in soil physical properties under annual applications of feedlot manure and different tillage practices. *Soil Science Society of America Journal*, 49, 983-987.

Sommerfeldt, T.G., & Chang, C. (1986). Soil-water properties as affected by twelve annual applications of cattle feedlot manure. *Soil Science Society of America Journal*, 51, 7-9.

Spomer, L.A. (1975). Small soil containers as experimental tools: Soil water relations. *Comm. Soil Sci. and Plant Analysis*, 6, 21-26.

Tester, C.F. (1990). Organic amendment effects on physical and chemical properties of a sandy soil. *Soil Science Society of America Journal*, 54, 827-831.

Tiarks, A.E., Mazurak, A.P., & Chesnin, L. (1974). Physical and chemical properties of soil associated with heavy applications of manure from cattle feedlots. *Soil Science Society of America Journal*, 38, 826-830.

Tietjen, C., & Hart, S.A. (1969). Compost for agricultural land? *J. Sanitary Engineering Div. Proc. ASCE*, Vol. 95, No. Sa 2, 269-287.

Unger, P.W., & Stewart, B.A. (1974). Feedlot waste effects on soil conditions and water evaporation. *Soil Science Society of America Journal*, 38, 954-957.

USCC (1996). *Field guide to compost use*. United States Composting Council.

USEPA (1997). *Innovative uses of compost: Erosion control, turf remediation and landscaping*. United States Environmental Protection Agency: Author.

Veihmeyer, F.J., & Hendrickson, A.H. (1971). The moisture equivalent as a measure of the field capacity of soils. *Soil Science*, 32, 181-193.

Villar, M.C., et al. (1993). Physical and chemical characterization of four composted urban refuses. *Bioresource Technology*, 45, 105-113.

Walker, J.M., & O'Donnell, M.J. (1991, August). Comparative assessment of MSW compost characteristics. *Biocycle*, 65-69.

Wischmeier, W.H., & Mannering, J.V. (1969). Relation of soil properties to its erodibility. *Soil Science Society of America Journal*, 33, 131-137.

Wu, L., Ma, L.Q., & Martinez, G.A. (2000). Comparison of methods for evaluating stability and maturity of biosolids compost. *Journal of Environmental Quality*, 29, 424-429.

Zaccheo, P., Ricca, G., & Crippa, L. (2002). Organic matter characterization of composts from different feedstocks. *Compost Science & Utilization*, 10, 29-38.

Zinati, G.M., Li, Y.C., & Bryan, H.H. (2001). Utilization of compost increases organic carbon and its humin, humic and fulvic acid fractions in calcareous soil. *Compost Science & Utilization*, 9, 156-162.

Composting cuts manure's toxic legacy. (2001, November). *J.R. Science News*, 160, 285.

Specifying compost use in highway erosion control. (2000, April). *Biocycle*, 65-66.

Transportation department uses more residuals for highway landscaping. (1997, May). *Biocycle*, 38.