11 The Disposal of Municipal Solid Wastes

Abstract

The publication of Rachel Carson's *Silent Spring* (1962) stimulated eventual worldwide interest in the environment, leading to the founding of the United Nations Environmental Programme (UNEP) and the inauguration of national environmental ministries, agencies or laws world-wide.

Solid wastes management involves waste reduction, reuse and recycling, composting, incineration with or without energy recovery, and landfilling.

Modern incinerators scrub the flue gases of incineration to reduce the harmful components. Newer methods of treating wastes include plasma arc gasification, in which waste is treated at very high temperatures and pressures, melting the waste into a nontoxic dross and yielding a fuel, syngas, for generating electricity. Pyrolysis operates at about 430°C. Supercritical water oxidation (SCWO) is the destruction technology for organic compounds and toxic materials at very high temperature and pressure, converting them to carbon dioxide, hydrogen to water, and chlorine atoms to chloride ion.

Keywords

Municipal solid wastes • Environment and development • Waste management • Incineration • Landfills • Plasma gasification • Composts • Energy from waste • Recycling • Reuse • Supercritical water oxidation • Pyrolysis

11.1 The Nature of Wastes in General

Wastes are unwanted materials or outcomes resulting from *a particular* human activity. The fact that a material or outcome is a waste in a particular activity does not render that material or outcome totally unwanted for all other activities. Indeed what is waste under one condition may be the corner stone of activity in another. Thus molasses is a waste material in sugar manufacture, but it is a major input in the manufacture of many fermentation products such as antibiotics. Similarly, farm trash such as corn cobs, wastes from corn growing, may be the basis for improving soil qualities through composting.

Wastes differ in nature and weight according to the activities which generate them. Thus wastes by weight were highest in construction and manufacturing, followed by mining and by municipal activities, agriculture in the European Union (EU) in 2002. (Anonymous 2005).

The nature of the wastes generated in any society or country clearly relates to the economic activity of that society. Thus, although wastes from construction and manufacturing are expected to be heavier by their

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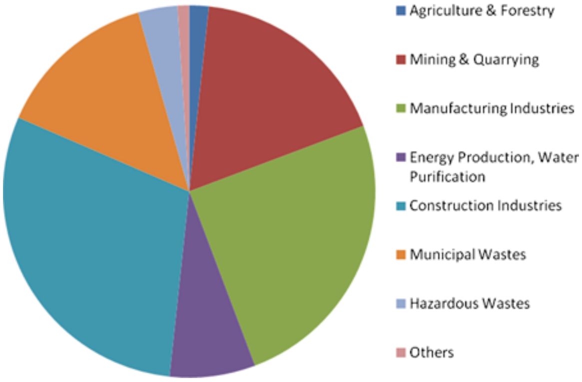

Fig. 11.1 Wastes generated in the European Union (EU), by activity, in 2002 (Pie chart generated from data in Anonymous 2005)

nature than those from agriculture, Fig. 11.1 can be interpreted to mean that more activities go on in construction and industry than in agriculture; since agricultural wastes are at the bottom of the chart, while manufacturing and construction are at the top. It can also be interpreted to mean that Western Europe is more of a manufacturing region and that its agriculture is very efficient, yielding little wastes, since, comparatively, so little agricultural waste is produced.

Municipal Solid Waste (MSW) is waste collected by, or on behalf of, a local authority. It comprises mostly household waste, but it may include some commercial and industrial wastes. European Union legislation require the pretreatment, including presorting, of waste before it is sent to landfill (Anonymous 2009a).

11.2 The World-Wide Development of Interest in the Environment

Although the environment has influenced human affairs from as early as the seventh century AD (see Table 11.1), the earliest country in modern times to develop a concerted government (please also see Section 7.3.2 on oil spills) interest on the environment is the USA in the 1970s. This followed the public interest generated by *Silent Spring*, a book by Rachel Carson (1962), which documented the detrimental effects of pesticides on the environment, particularly on birds; the book stated that the insecticide DDT had been the cause of thinner egg shells, resulting in reproductive problems for the birds. It also criticized the chemical industry for spreading disinformation and government officials for uncritically accepting industry claims. *Silent Spring*, published in 1962, led to widespread public concerns on pesticide use and the pollution of the environment.

The immense public interest in these concerns regarding environmental pollution eventually led to the creation of the US Environmental Protection Agency (US EPA) on December 2, 1970 to consolidate in one agency a variety of federal research, monitoring, standard-setting, and enforcement activities to ensure environmental protection. From regulating auto emissions to banning the use of DDT; from cleaning up toxic waste to protecting the ozone layer; from increasing recycling to revitalizing inner-city brown fields, the US EPA's achievements have resulted in cleaner air, purer water, and better protected land (Anonymous 2010a).

The EPA submitted the Agency's *2006–2011 Strategic Plan* to Congress on September 29, 2006 as required under the Government Performance and Results Act (GPRA) of 1993. This revised *Strategic Plan* maintains the five goals that were described in the *2003–2008 Strategic Plan*, but reflects a sharpened focus on achieving more measurable environmental results.

The five goals are Clean Air and Global Climate Change, Clean and Safe Water, Land Preservation and Restoration, Healthy Communities and Ecosystems, and Compliance and Environmental Stewardship. The *Strategic Plan* serves as the Agency's road map and guides it in establishing the annual goals that need to be met along the way. It helps provide a basis from which the organization can focus on the highest priority environmental issues and ensure that taxpayer dollars are used effectively. The EPA produces numerous data on environmental affairs in the US.

11.2.1 The Stockholm Conference, 1972: Beginning of World-Wide Interest in the Protection of the Environment

Today, almost all (if not all) countries of the world have legislation, a Department, a Ministry, an Agency or such-like body whose function is the protection of the environment. This is as a result of the Conference on the Human Environment, held in Stockholm, Sweden, June 5–16, 1972 (also called the Stockholm Conference), the first of a series of world environmental conferences, to be held on a 10-yearly basis.

Table 11.1 Timeline of history of environmentalism (Modified from www.public.iastate.edu/~sws/enviro%20and%20society and http://en.wikipedia.org/wiki/Timeline_of_history_of_environmentalism, Anonymous 2010a, b). A listing of events that have shaped humanity's perspective on the environment, human induced disasters, environmentalists that have had a positive influence, and environmental legislation

Pre-twentieth century	
Seventh century: AD 676	Cuthbert of Lindisfarne enacts protection legislation for birds on the Farne islands (Northumberland, UK)
Fourteenth century: AD 1366	City of Paris forces butchers to dispose of animal wastes outside the city (Ponting); similar laws would be disputed in Philadelphia and New York nearly 400 years later
Fourteenth century: AD 1388	British Parliament passes an act forbidding the throwing of filth and garbage into ditches, rivers and waters. City of Cambridge also passes the first urban sanitary laws in England
Fifteenth century: AD 1420–1427	Madeira islands : destruction of the laurisilva forest, by fire that burnt for 7 years.
Seventeenth century: AD 1609	Hugo Grotius publishes *Mare Liberum* (The Free sea) with arguments for the new principle that the sea was international territory and all nations were free to use it for seafaring trade. The ensuing debate had the British empire and France claim sovereignty over territorial waters to the distance within which cannon range could effectively protect it, the three mile (5 km) limit
Seventeenth century: AD 1690	US Colonial Governor, William Penn requires Pennsylvania settlers to preserve 1-acre (4,000 m^2) of trees for every 5 acres cleared
Eighteenth century: AD 1720	In India, hundreds of Bishnois Hindus of Khejadali go to their deaths trying to protect trees from the Maharaja of Jodhpur, who needed wood to fuel the lime kilns for cement to build his palace
Eighteenth century: AD 1739	Benjamin Franklin and neighbors petition Pennsylvania Assembly to stop waste dumping and remove tanneries from Philadelphia's commercial district
Eighteenth century: AD 1748	Jared Eliot, clergyman and physician, writes *Essays on Field Husbandry in New England* promoting soil conservation
Eighteenth century: AD 1762–1769	Philadelphia committee led by Benjamin Franklin attempts to regulate waste disposal and water pollution
Nineteenth century: AD 1820	World human population reached one billion
Nineteenth century: AD 1828	Carl Sprengel formulates the Law of the Minimum stating that economic growth is limited not by the total of resources available, but by the scarcest resource
Nineteenth century: AD 1845	First use of the term "carrying capacity" in a report by the US Secretary of State to the Senate
Nineteenth century: AD 1860	*Henry David Thoreau* delivers an address to the Middlesex (Massachusetts) Agricultural Society, entitled "The Succession of Forest Trees," in which he analyzes aspects of what later came to be understood as forest ecology and urges farmers to plant trees in natural patterns of succession
Nineteenth century: AD 1862	John Ruskin publishes *Unto This Last*, which contains a proto-environmental indictment of the effects of unrestricted industrial expansion on both human beings and the natural world. The book influences Mahatma Gandhi, William Morris and Patrick Geddes
Nineteenth century: AD 1866	The term Ecology is coined (in German as Oekologie by Ernst Heinrich Philipp August Haeckel (*1834–1919*) in his Generelle Morphologie der Organismen. Haeckel was an anatomist, zoologist, and field naturalist appointed professor of zoology at the Zoological Institute, Jena, in 1865
Nineteenth century: AD 1872	The term acid rain is coined by Robert Angus Smith in the book *Air and Rain*
Nineteenth century: AD 1872	German graduate student Othmar Zeidler first synthesizes DDT, later to be used as an insecticide
Nineteenth century: AD 1876	British River Pollution Control Act makes it illegal to dump sewage into a stream
Nineteenth century: AD 1895	Sewage cleanup in London means the return of some fish species (grilse, whitebait, flounder, eel, smelt) to the River Thames
Twentieth century	
1900s	
AD 1902	George Washington Carver writes *How to Build Up Worn Out Soils*
	7300 ha of land in the Lake District of the Andes foothills in Patagonia are donated by Francisco Moreno as the first park, Nahuel Huapi National Park, in what eventually becomes the National Park System of Argentina

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Table 11.1 (continued)

AD 1905	The term smog is coined by Henry Antoine Des Voeux in a London meeting to express concern over air pollution
	San Francisco earthquake and subsequent fires destroy much of the city
AD 1909	US President Theodore Roosevelt convenes the North American Conservation Conference, held in Washington, D.C. and attended by representatives of Canada, Newfoundland, Mexico, and the United States
1910s	
AD 1910	Scientific American reports alcohol-gasoline anti-knock blend is "universally" expected to be the fuel of the future
	Spanish Flu kills between 50 and 100 million people worldwide
1920s	
1921	Thomas Midgley discovers lead components to be an efficient antiknock agent in gasoline engines. In spite of the well known toxic effects, lead was in ubiquitous use. First banned from use in Japan 1986
1928	Thomas Midgley develops chlorofluorocarbons (CFC's) as a nontoxic refrigerant. The first warnings of damage to stratospheric ozone were published by Molina and Rowland 1974. They shared the 1995 Nobel Prize for Chemistry for their work
1929	The Swann Chemical Company develops polychlorinated biphenyls (PCBs) for transformer coolant use. Research in the 1960s revealed PCBs to be potent carcinogens. Banned from production in the US 1976, probably one million tonnes of PCBs were manufactured in total globally
1930s	
1930	World human population reached two billion
1933	First legislation on Animal rights adopted, Germany
1939	The insecticidal properties of DDT discovered by Paul Hermann Müller, who was awarded the 1948 Nobel Prize in Physiology and Medicine for his efforts. The first ban on its use came in 1970
1940s	
1949	First known dioxin exposure incident, in a Nitro, West Virginia herbicide production plant. Extensively used during the Vietnam War 1961–1971 as Agent Orange. Production ban in the US on some component from 1970
1950s	
1951	World Meteorological Organization (WMO) established by the United Nations
1954	The first nuclear power plant to generate electricity for a power grid started operations at Obninsk, Soviet union on 27 June
1956	Minamata disease, a neurological syndrome caused by severe mercury poisoning
1957	The first substantial nuclear accident happened on 10 October 1957 in Windscale, England
1960s	
1960	World human population reached three billion
1961	World Wildlife Fund (WWF) registered as a charitable trust in Morges, Switzerland, an international organization for the conservation, research and restoration of the natural environment
1962	Rachel Carson publishes *Silent Spring*
1969	National Environmental Policy Act including the first requirements on Environmental impact assessment
1970s	
1970	Earth Day – April 22, millions of people gather in the United States for the first Earth day organized by Gaylord Nelson, former senator of Wisconsin, and Denis Hayes, Harvard graduate student
	US Environmental Protection Agency (USEPA) established

(continued)

Table 11.1 (continued)

1971	The international environmental organization Greenpeace founded in Vancouver, Canada. Greenpeace has later developed national and regional offices in 41 countries worldwide
	Friends of the earth founded
	International Institute for Environment and Development established in London, UK. One offshoot is the World Resources Institute with its biannual report *World resources* since 1984
1972	The conference on the human environment, held in Stockholm, Sweden 5–16 June, the first of a series of world environmental conferences, to be held on a 10-yearly basis
	United Nations Environment Programme founded as a result of the Stockholm conference
	The Club of Rome publishes its report Limits to Growth, which has sold 30 million copies in more than 30 translations, making it the best selling environmental book in world history
	In the US Clean Water Act
	First photograph of the whole illuminated Earth taken from space, Apollo 17, resulting in the famous “Blue Marble” photograph, said to have been at least partly responsible for launching the modern environmental movement
1973	OPEC announces oil embargo against United States
	World Conservation Union (IUCN) meeting drafts the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES)
1974	Chlorofluorocarbons are first hypothesized to cause ozone thinning.
	World human population reached four billion
1976	Dioxin accidental release in Seveso, Italy on 10 July, killing animals and traumatizing the population
1977	Surface Mining Control and Reclamation Act (US)
1978	Brominated flame-retardants replaces PCBs as the major chemical flame retardant. Swedish scientists noticed these substances to be accumulating in human breast milk 1998. First ban on use in the EU 2004
1979	Three Mile Island, worst nuclear power accident in US history
1980s	
1980	Superfund (Comprehensive Environmental Response, Compensation, and Liability Act or CERCLA)
1982	United Nations Convention on the Law of the Sea (UNCLOS) is signed on December the 10th at Montego Bay. Part XII of which significantly developed port-state control of pollution from ships
1983	Dr. Gro Harlem Brundtland, the first woman prime minister of Norway, as chairperson of UN World Commission on Environment and Development; UNCED coined the ‘sustainable development’.
1984	Bhopal disaster in the Indian state of Madhya Pradesh (Methyl isocyanate leakage
1986	Chernobyl, world’s worst nuclear power accident occurs at a plant in Ukraine.
1987	World human population reached five billion
	The report of the Brundtland Commission, our common future on sustainable development, is published
1988	Ocean Dumping Ban Act (US)
	Intergovernmental Panel on Climate Change (IPCC) was established by two United Nations organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to assess the “risk of human-induced climate change”
1989	Exxon Valdez creates largest oil spill in US history (see also Table 7.11)
	Montreal Protocol on substances that deplete the ozone layer entered into force on January 1. Since then, it has undergone five revisions, in 1990 (London)
1990s	
1990	European Environment Agency was established by EEC Regulation 1210/1990 and became operational in 1994. It is headquartered in Copenhagen, Denmark
1991	World’s worst oil spill (820,000 tones) occurs January 23, 1991 in the Persian Gulf (Kuwait) during war with Iraq

(continued)

Table 11.1 (continued)

1992	The Earth Summit, held in Rio de Janeiro from June 3 to June 14, was unprecedented for a United Nations conference, in terms of both its size and the scope of its concerns; Global warming major issue in Rio
	United Nations Framework Convention on Climate Change opened for signature on 9 May ahead of the Earth Summit in Rio de Janeiro
	The international convention on biological diversity opened for signature on 5 June in connection with the Earth Summit in Rio de Janeiro
	World Ocean Day began on 8 June at the Earth summit in Rio de Janeiro
	The metaphor ecological footprint is coined by William Rees
1993	The Great Flood of 1993 was one of the most destructive floods in United States history involving the Missouri and Mississippi river valleys
1994	United Nations Convention to Combat Desertification
	The first genetically modified food crop released to the market. It remains a strongly controversial environmental issue.
1996	Western Shield, a wildlife conservation project is started in Western Australia, and through successful work has taken several species off of the state, national, and international (IUCN) Endangered species lists
1997	Kyoto Protocol was negotiated in Kyoto, Japan in December. It is actually an amendment to the United Nations Framework Convention on Climate Change (UNFCCC). Countries that ratify this protocol commit to reduce their emissions of carbon dioxide and five other greenhouse gases
1999	World human population reached six billion
Twenty-first century	
2001	USA rejects the Kyoto Protocol
2002	Earth Summit, held in Johannesburg a United Nations conference; Focused for first time on problems of developing countries; a commitment to halve the number of people in the world who lack basic sanitation by 2015
2003	The world's largest reservoir, the Three Gorges Dam begins filling 1 June
	European Heat Wave resulting in the premature deaths of at least 35,000 people
2004	Earthquake causes large tsunamis in the Indian Ocean, killing nearly a quarter of a million people
	The Kyoto Protocol came into force on February 16 following ratification by Russia on November 18, 2004
2005	Hurricanes Katrina, Rita, and Wilma cause widespread destruction and environmental harm to coastal communities in the US Gulf Coast region, including numerous oil spills
2006	Former U.S. vice president Al Gore releases *An Inconvenient Truth*, a documentary that describes global warming. The next year, Gore is awarded the Nobel Peace Prize (jointly with the Intergovernmental Panel for Climate Change) for this and related effort
	World human population reached 6.5 billion
2007	The IPCC release the IPCC Fourth Assessment Report.
2009	The Energy Action Coalition hosted the second national youth climate conference to be held at the Washington Convention Center from February 27 to March 2, 2009. The conference aims to attract more than 10,000 students and young people and will include a Lobby Day
2010	The Gulf of Mexico oil spill (also known as Deepwater Horizon oil spill and the BP oil spill) resulted from a sea-floor oil gusher and flowed for 3 months before being capped on July 15, 2010, but not before 4.9 million barrels or 205.8 million gallons of crude oil had gushed from it. With 627,000 tonnes of crude oil, this would appear to be the largest spill in history, second only to the Lakeview Gusher, California, USA, March 1910 – September, 1911 which spilled 1,230,000 tonnes

This first major environmental (1972) conference of the United Nations was a watershed in the development of international environmental politics and was held at the initiative of the government of Sweden. Attended by the representatives of 113 countries, 19 inter-governmental agencies, and more than 400 inter-governmental and nongovernmental organizations, it is widely recognized as the beginning of modern political and public awareness of global environmental problems. It has been suggested that at least three achievements are the lasting legacy of the Stockholm United Nations Conference on the Environment and Development (UNCED): The creation of the UN Environment Programme (UNEP), the call for cooperation to reduce marine pollution, and the establishment of a global monitoring network have been cited as of especially lasting significance. The third aspect, the establishment of a global monitoring network can be seen, notwithstanding other more specific resolutions, to be the impetus for the world-wide establishment of environmental protection agencies by national governments around the world (Anonymous 2010c). The initiative with the EPA in the US, a well-developed economy, has been discussed above. To illustrate this world-wide interest in the environment at governmental level, brief discussions of the development of governmental interest in environmental protection in two economically developed areas of the world, namely the European Union and Japan, and two developing countries, Ghana and Egypt will be undertaken.

11.2.2 Environmental Regulation in the European Union

The 32-member European Union has as its environment-regulating body, the European Environment Agency (EEA), which is headquartered in Copenhagen, Denmark. The regulation establishing the EEA was adopted by the European Union in 1990 and it came into force in late 1993 with the following as its functions:

- To help the [EU] Community and its member countries make informed decisions about improving the environment, integrating environmental considerations into economic policies and moving toward sustainability
- To coordinate the European environment information and observation network (Anonymous 2010d)

11.2.3 Environmental Regulations in Japan

In Japan, with a population of about 130 million, environmental pollution has accompanied industrialization since the Meiji period (1868–1912). One of the earliest cases was the copper poisoning caused by drainage beginning as early as 1878. During the 20 years since the establishment of the Environment Agency in 1971, the environmental situation at the national and global levels has undergone substantial changes. At the national level, notable achievements have been made in combating severe pollution during the period of high economic growth.

Current Japanese environmental policy and regulations were the consequence of a number of environmental disasters in the 1950s and 1960s. One of the most famous was the *Minamata disease* episode in which there were many casualties from eating fish which had been contaminated by methyl mercury.

In the 1990s, Japan's environmental legislation was further tightened and in 1993, the government reorganized the environment law system and passed the *Basic Environment Law* and related laws. The law includes restriction of industrial emissions, restriction of products, restriction of wastes, improvement of energy conservation, promotion of recycling, restriction of land utilization, arrangement of environmental pollution control programs, relief of victims, and provision for sanctions. The Environment Agency was elevated to a full-fledged Ministry of the Environment in 2001.

Japan has of recent taken a much more proactive approach to waste management. As a signatory of the *Kyoto Protocol*, and host of the 1997 conference which created it, Japan is under treaty obligations to reduce its carbon dioxide emissions level by 6% less than the level in 1990, and to take other steps related to curbing climate change (Anonymous 2010e).

11.2.4 Governmental Regulation of the Environment in Ghana

In Ghana, which is in west Africa with a population of about 24 million, the central governmental environmental body is the Ghana Environmental Protection Agency (EPA). Its history began at a time of growing world-wide concern on the dangers posed to the environment through human activities and which prompted the United Nations to convene the conference in Stockholm on the Human Environment, in June 1972. An outcome of this meeting was the establishment of the United Nations Environmental Program (UNEP). The decision of the Ghana Government to establish an Environmental Protection Council was a direct outcome of recommendations of the Stockholm Conference. Prior to that, the National Committee on the Human Environment was formed by the Ministry of Foreign Affairs in 1971 as a result of concern expressed by the Economic Commission for Africa and the Organization of African Unity regarding the need to conserve and protect Africa's natural resources.

On 23rd May 1973, the government of Ghana announced its decision to establish an Environmental Protection Commission; the government soon renamed it the Environmental Protection Council. In 1994, it was transformed into an Agency by the Environmental Protection Agency Act, 1994 (Act 490). The EPA became a corporate body with powers to sue and be sued. It was also given the responsibility of regulating the environment and ensuring the implementation of government policies on the environment.

The Ghana EPA's objectives are to:

- Create awareness to mainstream environment into the development process at the national, regional, district, and community levels;
- Ensure that the implementation of environmental policy and planning are integrated and consistent with the country's desire for effective, long-term maintenance of environmental quality;
- Ensure environmentally sound and efficient use of both renewable and nonrenewable resources in the process of national development;
- Guide development to prevent, reduce, and as far as possible, eliminate pollution and actions that lower the quality of life;
- To apply the legal processes in a fair, equitable manner to ensure responsible environmental behavior in the country;
- Continuously improve EPA's performance to meet changing environmental trends and community aspirations;
- Encourage and reward a commitment by all EPA staff to a culture based on continuous improvement and on working in partnership with all members of the Ghanaian community (Anonymous 2010f).

11.2.5 Egypt's Environmental Affairs Agency

The other developing country, Egypt, is an Arab country in the Mediterranean region of North Africa with a population of about 80 million. Egypt had participated in the Conference on the Human Environment, Stockholm, 1972 and had indeed proposed with the overwhelming support of participating countries including the USA, Sweden, Germany, and many others for a Second United Nations Conference on the Human Environment within 5 years in Egypt. (Anonymous 2010g). Although this was not implemented, it showed that Egypt was fully in the spirit of the conference.

Environmental matters are handled in Egypt by the Egyptian Environmental Affairs Agency (EEAA) officially launched in 1982 by a Presidential Decree No. 631 of the year 1982. Its existence was formalized in 1994 by a decree issued by the Agency's Executive Head.

In June 1997, a Ministry of State for Environmental Affairs (MSEA) was created. The MSEA has focused, in close collaboration with the national and international development partners, on defining environmental policies, setting priorities and implementing initiatives within a context of sustainable development. MSEA and EEAA are the highest authority in Egypt responsible for promoting and protecting the environment, and coordinating adequate responses to these issues.

The functions of the EEAA are to:

(a) Prepare the draft laws concerning the Environment
(b) Implement the experimental projects
(c) Prepare the Environmental Training and Planning Policy
(d) Draft the necessary norms and standards to ensure that the environment is not polluted
(e) Formulate the basis and procedures for the assessment of environmental impacts of projects
(f) Supervise the Environmental Protection and Development Fund (Anonymous 2010g).

11.3 Nature of Municipal Solid Wastes

Municipal Sold Wastes (MSW), also known as trash or garbage, include everyday items such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries.

Items such as construction and demolition debris, municipal wastewater treatment sludges, and nonhazardous industrial wastes are not generally included in those described as MSW.

According to the US EPA, in 2005, United States residents, businesses, and institutions produced more than 245 million tons of MSW, which is approximately 4.5 lb of waste per person per day. About one third of MSW in that year was made up of paper and paper board (34%), followed by yard trimmings (13%), and food scraps and plastics (about 12% each). (Fig. 11.1). (Anonymous 2004, 2005).

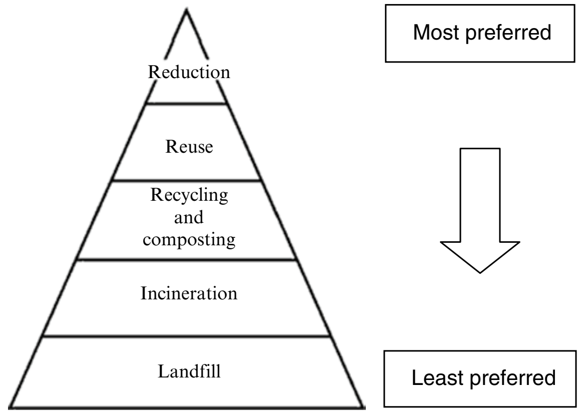


Fig. 11.2 Diagram illustrating alternative methods of treating wastes in an integrated waste management system

11.3.1 Integrated Solid Waste Management

Integrated waste management involves a series of activities dealing with solid wastes including storage, sorting, collection, transportation, and alternative treatment procedures designed to minimize the adverse effect of solid wastes on the environment and/or on human health (Anonymous (2004). The alternative procedures, in the generally accepted hierarchy of preferences, beginning with the most desirable, include the following:

- Making every effort to reduce wastes in the first place
- Reusing materials
- Recycling them
- Making composts of degradable waste components
- Incinerating the materials with or without recovery of energy or burial of the materials in landfills (see Fig. 11.2)

Which of the above alternatives is adopted in terms of the actual procedure and the order of the procedure, in any society, municipality, state, country, or regional organization of countries depends on the following:

- *Economic affordability*, i.e., the costs of waste management systems are acceptable to all sectors of the community served, including householders, commerce, industry, institutions, and government;
- *Social acceptability* in which the waste management system adopted not only meets the needs of the local community, but also reflects the values and priorities of that society; and
- *Environmental effectiveness* which ensures that the overall environmental burdens of managing waste are reduced, both in terms of consumption of resources (including energy) and the reduction of emissions to air, water, and land (Anonymous 2004).

The management of wastes includes its collection, transportation, processing, recycling or disposal, and monitoring of waste materials. Waste management is undertaken for one or more of the following reasons: To reduce the adverse effect of their accumulation on human health, avoid the physical deterioration of the environment for aesthetic considerations, or to recover resources.

Waste management may involve solid, liquid, gaseous, or radioactive substances, each of which requires a different approach and techniques. What method or approach is adopted depends on the economic capability of the country or community, within the same country whether it is urban or rural and whether the wastes relate domestic or industrial activities.

It now seems generally accepted by the US EPA, the EU's EEA, and environmental regulatory bodies around the world that in the concept of a hierarchy of waste management options, the most desirable option is to prevent waste in the first place (see Fig. 11.2) and the least desirable option is to dispose of the waste with no recovery of either materials and/or energy. Between these two extremes, there is a variety of waste treatment options that may be used as part of a waste management strategy to recover materials (e.g., furniture reuse, glass recycling, or organic waste composting) or generate energy from the wastes (e.g., through incineration, or digesting biodegradable wastes to produce usable gases). In order to reduce the uncontrollable amounts of green house gases emitted to the atmosphere, some countries and regional

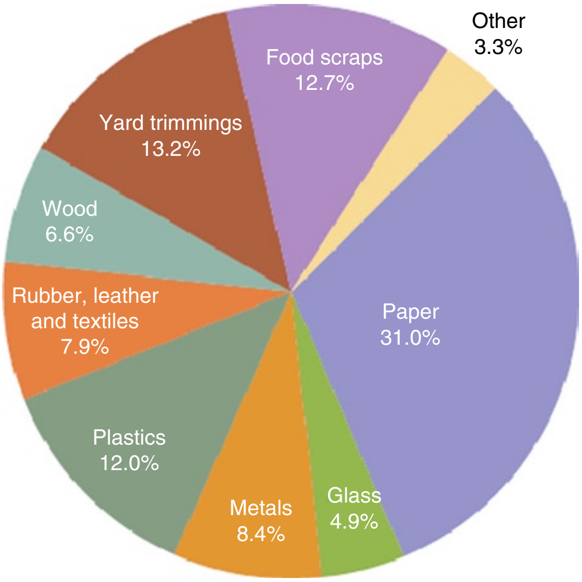


Fig. 11.3 Total municipal solid waste (by materials) generated in the US in 2008 (250) million tons) before recycling (From USEPA: http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf, Anonymous 2009a)

governmental organizations, for example, the EU, now limit the amount of biodegradable municipal waste (BMW) sent for disposal in landfill.

The generally accepted integrated waste management hierarchy includes the following four components, listed in order of preference:

1. Source reduction
2. Recycling
3. Incineration with energy recovery
4. Disposal through:
   (a) Composting
   (b) Landfilling
   (c) Incineration without energy recovery

Although EPA encourages the use of the top of the hierarchy whenever possible, all four components remain important within an integrated waste management system (Fig. 11.3).

11.3.1.1 Source Reduction

Perhaps the best slogan to describe source reduction is "Eliminate waste before it is created". Source reduction (also sometimes termed "waste prevention") deals with the design, manufacture, purchase, or use of materials or products designed to reduce the amount of waste generated; it includes reuse of second-hand products, waste elimination, repairing broken-down items instead of buying new ones, encouraging consumers to avoid using disposable products (such as disposable cutlery), designing products to be refillable or reusable (such as cotton instead of plastic shopping bags), package reduction and substitution, and designing products that use less material to achieve the same purpose. Source reduction is at the top of the solid waste management hierarchy because it is generally superior to both recycling and disposal from an environmental and economic perspective. Source reduction is a pro-active, practical way to preempt the need to collect, process, and/or dispose of trash and recyclables by preventing their generation. Practices such as grass cycling, backyard composting, two-sided copying of paper, and transport packaging reduction by industry have yielded substantial benefits through source reduction. It has many environmental benefits: It prevents emissions of many greenhouse gases, reduces pollutants, saves energy, conserves resources, and reduces the need for new landfills and incinerators (Anonymous 2004).

11.3.1.2 Recycling

Recycling is passing a substance through a system that enables that substance to be reused; it enables the reprocessing of materials into new products. In waste recycling, waste materials are collected, sorted, separated, and those to be reused are cleaned-up.

Recycling waste means that fewer new products and consumables need to be produced, and thus raw materials are saved and energy consumption is reduced. Recycling generally prevents the waste of potentially useful materials, reduces the consumption of raw materials and reduces energy usage, and hence greenhouse gas emissions, compared to new production. Recycling, including composting, diverted 79 million tons of material away from disposal in 2005, up from 15 million tons in 1980, when the recycle rate was just 10% and 90% of MSW was being combusted with energy recovery or disposed of by landfilling. Typical materials that are recycled include batteries, recycled at a rate of 99%, paper and paperboard at 50%, and yard trimmings at 62%. These materials and others may be recycled through curbside programs, drop-off centers, buy-back programs, and deposit systems.

Recycling prevents the emission of many greenhouse gases and water pollutants, saves energy, supplies valuable raw materials to industry, creates jobs, stimulates the development of greener technologies,

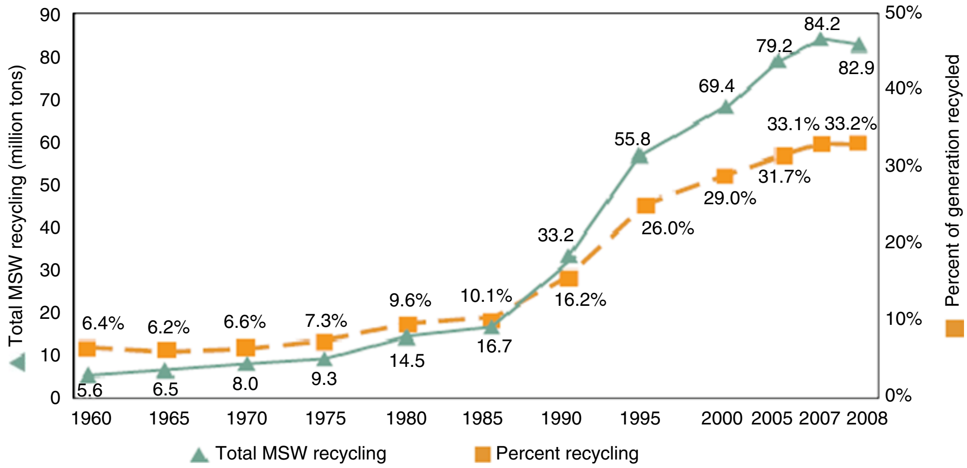


Fig. 11.4 Recycling rates in the US, 1960–2008 (From *municipal solid wastes in the US* http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf, Anonymous 2009a)

conserves resources for our children's future, and reduces the need for new landfills and combustors.

Recycling also helps reduce greenhouse gas emissions that affect global climate. In 1996, recycling of solid waste in the United States prevented the release of 33 million tons of carbon into the air, roughly the amount emitted annually by 25 million cars. The recycling rate has been rising steadily in the US and in 2005 had reached about 32% (see Fig. 11.4).

A breakdown of the rates of recycling of various items is given in Table 11.2, from where it will be seen that the most widely recovered items were nonferrous metals (69%), rubber and leather (11%), paper and paper board (55%), steel (38%), plastics (7%) and wood (10%).

Around the world, many of the waste items recycled are paper, glass jars and bottles (especially from hotels since most drinks are put in bottles), plastics and metals such as aluminum cans. There are usually three bottle banks, one for each color of glass: clear, green, and brown.

With regard to bottles in many parts of the world, they are collected in bottle banks from where they are sent for recycling.

Plastics make up a large amount of waste, since they are available in numerous forms especially for packaging. There are two main types of plastic: thermoplastics, which are the most common; and thermosetts. Thermoplastics melt when heated and can therefore be remolded. This enables thermoplastics to be recycled relatively easily. Plastic waste tends to be sorted by hand, either at a materials recycling facility or the householder can separate it.

The metals recycled come from iron and steel and aluminum. Most of this waste comes from scrap vehicles, cookers, fridges, and other kitchen appliances. It is mainly made up of aluminum drinks cans and tin-plated steel food cans. Aluminum is an expensive metal and can therefore produce high incomes for recycling schemes. Copper, zinc, and lead are also recycled in the UK.

Many countries also rethread tires and reuse them. For example, every year in the UK, between 25 and 30 million scrap tyres are generated. Approximately 21% of these tyres are retreaded and reused. The old tread is ground off the tyre and replaced with a new tread. However, about half of all used tyres are dumped in landfill sites throughout the country; other tyres may be incinerated.

11.3.1.3 Incineration with Energy Recovery

Scrubbing the (flue) gas released during incineration of pollutants

The incineration of wastes is the combustion of wastes. Modern incinerators used in economically developed countries such as in the EU and the USA are designed to avoid or minimize the short-comings of the older incinerators.

Modern incinerators generally burn MSW and the heat produced is used to boil water to produce steam which in turn drives turbines for the production of electricity. This, in the parlance of modern energy

Table 11.2 Generation and Recovery of Materials in MSW, 2008 in the US. (From http://www.epa.gov/wastes/nonhaz/municipal/pubs/msw2008rpt.pdf, Anonymous, 2009)

Material	Weight generated	Weight recovered	Recovery as %age of generation
Paper and glass			
Paper and board	77.42	42.94	55.50%
Glass	12.15	2.81	23.10%
Metals			
Steel	15.68	5.29	33.70%
Aluminum	3.41	0.72	21.10%
Other nonferrous metals	1.76	1.21	68.80%
Total metals	**20.85**	**7.22**	**34.60%**
Plastics	30.05	2.12	7.10%
Rubber and leather	7.41	1.06	14.30%
Textiles	12.31	1.89	15.30%
Wood	16.39	1.58	9.60%
Other materials	4.50	1.15	25.60%
Total materials in products	**181.14**	**60.77**	**33.50%**
Other wastes			
Food	31.79	0.80	2.50%
Yard trimmings	32.90	21.30	64.70%
Miscellaneous inorganic wastes	3.78	Negligible	Negligible
Total other wastes	**68.47**	**22.10**	**32.30%**
Total municipal solid wastes	**249.61**	**82.67**	**33.20%**

generation is Waste-to-Energy (WtE) or Energy-from-Waste (EfW) activity.

When MSW and other materials are ordinarily burnt, the composition of combustion gas flue gas (i.e., the gas coming off the chimney or pipe leading the gases into the atmosphere) will depend on the composition of the material being burnt. In general, the flue gas from burning MSW will be contain 66% nitrogen, CO_2, some O_2 water vapor, as well as materials regarded as pollutants: Particulate matter, carbon monoxide, oxides of nitrogen and sulfur, as well as hydrochloric acid, which make solutions of the flue gas acidic. Other items which may be found in flue gas are heavy metals, dioxins, and furans (Anonymous 2010h).

Modern incinerators have facilities which ameliorate the problems of the older ones by passing the flue gas through scrubbers which remove the pollutants. There are many different types of scrubbing arrangements depending on the components of flue gases. In some, particles are removed by passing the gas through special filters where the particles, including those of heavy metals such as mercury, are captured by electrostatic attraction; the sulfur dioxide present in the flue gas is then passed through $CaCO_3$, which neutralizes the sulfurous acid yielding $CaSO_4$. Nitrogen oxides are treated either by modifications to the combustion process to prevent their formation, or by high temperature or catalytic reaction with ammonia or urea; in both cases, the objective is to produce nitrogen gas.

In the first stage of one scrubber, the Van Roll Flue Gas Scrubber, scrub water is sprayed into the hot flue gases. As it vaporizes, it cools the gas stream to about 70°C. The scrub water washes coarse particulate matter out of the flue gases and absorbs most of the HCl. This stage also handles the absorption of the HCl and the removal of mercury. In the second stage, the gases pass through a packed bed stage in countercurrent to the scrub water, which cools them to about 60°C. The remaining pollutants, such as HCl and HF, are absorbed with good efficiency here, while heavy metal vapors condense to aerosols. If necessary, sodium hydroxide may be added at this stage to further remove any sulfur dioxide. In the third stage, aerosols and submicron dust particles generated in the cooling and absorption stage are collected. The flue gases pass a manifold of ring jets which are part of a multiple venturi configuration that subdivides the gas stream in order to boost separation efficiency. Controlled water supply makes it possible to hold a constant pressure drop and thus a constant removal efficiency over a wide range of loads. The ring jet also offers high efficiency in collecting gaseous contaminants such as sulfur dioxide. After passing through another demister, the flue gases – now free of all pollutants in gas, particulate, and aerosol forms – are routed to the stack or to a downstream process stage, for example, the carbon entrainment process. The scrubber stages can be combined in any way to achieve an optimal solution for individual requirements (Anonymous 2009b, 2010h).

Controversy over the health effects of incineration

Inspite of the scrubbing of the flue gases, it was still claimed in a report by the UK Society for Ecological Medicine *The Health Effects of Waste Incinerators* (Thompson and Anthony 2008) that "incinerator emissions are a major source of fine particulates, of toxic metals and of more than 200 organic chemicals, including known carcinogens, mutagens, and hormone disrupters. Emissions also contain other unidentified compounds whose potential for harm is as yet unknown, as was once the case with dioxins. Since the nature of waste is continually changing, so is the chemical nature of the incinerator emissions and therefore the potential for adverse health effects." The report concluded thus:

> Recent research, including that relating to fine and ultrafine particulates, the costs of incineration, together with research investigating non-standard emissions from incinerators, has demonstrated that the hazards of incineration are greater than previously realised. The accumulated evidence on the health risks of incinerators is simply too strong to ignore and their use cannot be justified now that better, cheaper and far less hazardous methods of waste disposal have become available. We therefore conclude that *no more incinerators should be approved*. (My italics).

However another report on *The Impact on Health of Emissions to Air from Municipal Waste Incinerators*, published by the British Government's Health Protection Agency a year later, disputes these findings and concludes that modern, well managed incinerators make only a small contribution to local concentrations of air pollutants and any such small additions, if they have any effects on health at all, "are likely to be very small and not detectable."

Modern and Emerging (and Safer?) Methods of the Thermal Treating of MSW

Some of the newer and emerging technologies which may obviate the negative aspects of incineration are: Plasma gasification, pyrolysis, supercritical water oxidation, and Sonophotochemical Oxidation. They are sometimes called Advanced Thermal Technologies or Alternative Conversion Technologies.

1. Plasma arc gasification (also called plasma pyrolysis)

   Very hot plasma is formed by ionized gas in a strong electrical arc with the power ranging from 2 to 20 MW and temperatures ranging from 2,000°C to 6,000°C. An example in nature is lightning, capable of producing temperatures exceeding 6,980°C. A gasifier vessel utilizes plasma torches operating at 5,540°C which is about the surface temperature of the Sun. In such high temperature, all waste constituents, including metals, toxic materials, silicon, etc. are totally melted forming nontoxic dross. Plastic, biological and chemical compounds, toxic gases yield complete dissociation into simpler gases mainly H_2 and CO_2. The resulting gas mixture is called synthesis gas or syngas and is itself a fuel. When municipal solid waste is subjected to this intense heat within the vessel, the waste's molecular bonds break down into elemental components. The process results in elemental destruction of waste and hazardous materials. Gasification is a method for extracting energy from many different types of organic materials; the minimum temperature for it to occur is 1,500°C. Simpler gases, mainly H_2 can be used as ecological fuel to generate heat energy and electrical energy decreasing significantly the cost of plasma formation and waste utilization. Regained metals from dissociation process can safely return to metallurgic industry, and slag can be used as an additive to road and construction materials. The utilization of municipal waste using this method does not cause the emission of foul odors and does not produce a harmful ash, which is something that normally takes place in an incinerating plant.

   Some of the advantages of plasma technology are as follows:

   (a) Plasma method can be used on any type of waste (hazardous, toxic, or lethal) because of the very high temperatures which disassociate molecular bonds.
   (b) Plasma waste utilization method takes place in a close system, without releasing ashes, waste

remnants, dusts, and toxic gases into environment. Regained metals return to metallurgic industry and created slag is used as an additive to road construction materials. Nontoxic gases, which are created, are stored in special containers (gas cylinders) and used as fuel and energy creators.

(c) The ratio of the reduction in volume after waste is treated by plasma is about 300:1, whereas with conventional incineration, it is only about 5:1, because a large quantity of ash is produced.
(d) Plasma technology allows converting large quantities of municipal waste in the range of 10–500 tons a day.
(e) This method of waste reduction is the only method available to stabilize electronic waste, which does not undergo biodegradation.
(f) The costs of using plasma technology are significantly low (as low as $40/ton or less) when the value of the products made because of it are included; the costs of using conventional incineration are in the range of $100/ton.
(g) Contaminates in slag and gases created during plasma utilization with elements such as mercury, cadmium, sulfur, SO_2, HCl, dioxins, selenium, chromium, lead, barium, arsenic, radioactive elements are strictly controlled by usage of special water or dry scrubbers and filters. Using this method, elements released are considerably minimized below environmental standards. The remainder of the pollutants sink into glassy slag and can be treated further in a closed system, which is a major distinction to conventional incineration.
(h) The ashes that are formed as a result of conventional incineration can be further burned down using plasma technology to make them harmless.
(i) Contemporary plasma converters are computer controlled, safe, quiet, and can be stationary or mobile; incinerators are always stationary.
(j) Plasma waste utilization will improve public health and safely achieve total and irreversible destruction of hazardous and toxic compounds, lethal viruses, bacteria, and prions that are dangerous to human health (Kowalski and Kopinski 2010).

In addition syngas, which is produced with this technology has the following advantages:

(k) Syngas has also to be scrubbed as is the case with incineration flue gas; however, the volume of syngas is much less than that of flue gas.
(l) Electric power may be generated in engines and gas turbines, which are much cheaper and more efficient than the steam cycle used in incineration
(m) No product of incineration has the versatility of syngas, which can not only produce electricity but also other chemicals, including other fuels.

2. Pyrolysis

Pyrolysis come from two Greek words (pyros = fire; lysis = breakdown) i.e., breakdown by heat. Pyrolysis is the thermal decomposition of large molecules when heated in the absence of oxygen at temperatures over 500°C. One of the products of this process is pyrolysis oil which has the potential to be a low-cost transport fuel with low greenhouse gas emissions when derived from waste. Pyrolysis typically occurs under pressure and at operating temperatures above 430°C. In practice, it is not possible to achieve a completely oxygen-free atmosphere; on account of this, in any pyrolysis system, a small amount of oxidation occurs.

Pyrolysis is a special case of thermolysis, and is most commonly used for organic materials, then being one of the processes involved in charring. The pyrolysis of wood, which starts at 200–300°C, and in general, pyrolysis of organic substances produces gas and liquid products and leaves a solid residue richer in carbon content.

Pyrolysis is used in the chemical industry, for example, to produce charcoal, activated carbon, methanol, and other chemicals from wood, to convert ethylene dichloride into vinyl chloride to make PVC, to produce coke from coal, to convert biomass into syngas, to turn waste into safely disposable substances, and for transforming medium-weight hydrocarbons from oil into lighter ones like gasoline. These specialized uses of pyrolysis are called by various names, such as dry distillation, destructive distillation, or cracking.

Pyrolysis also plays an important role in several cooking procedures, such as baking, frying, grilling, and caramelizing.

Pyrolysis is usually the first chemical reaction that occurs in the burning of many solid organic fuels, like wood, cloth, and paper, and also of some kinds of plastic. In a wood fire, the visible flames are not due to combustion of the wood itself, but rather of the gases released by its pyrolysis; whereas the flame-less burning of embers is the combustion of the solid residue (charcoal) left behind by it.

3. Supercritical water decomposition (hydrothermal monophasic oxidation)
Supercritical water oxidation (SCWO) is the destruction technology for organic compounds and toxic wastes using the unique properties of water in supercritical condition that is high temperature and pressure (above 374°C and 22 MPa). In supercritical water, organic materials, such as chlorinated organic compounds, are quickly oxidized and decomposed with oxidants. Carbon in the organic compounds is converted to carbon dioxide, hydrogen to water, and chlorine atoms to chloride ion.

A supercritical (SC) fluid is defined as a substance that is at conditions of temperature and pressure that are above its vapor-liquid critical point. At supercritical conditions, a fluid does not behave entirely as a liquid or as a gas, but somewhere in between. The properties of supercritical fluids combine the solvating powers of liquids with the diffusivities of gases. The critical point for water is at 3740 C, (70SoF) and 218 atm, (22 MPa, 3,191 psi). The changes in the properties of water once supercriticality has been reached are remarkable. The familiar, polar liquid with its high dielectric constant of 78.5 changes to an almost nonpolar fluid with a value of less than five, approaching that of ambient hexane at 1.8. The density of SCW is found to decrease to around 0.15 g/ml, depending upon conditions. SCW possesses properties which enable it to become miscible with organic molecules and with gases.

Gases including oxygen and organic compounds are completely soluble in supercritical water and become a single phase. Such single phase contact under high density and high temperature allows rapid and almost complete oxidation reaction. Quite high destruction efficiencies for various compounds have been demonstrated.

SCWO is a high temperature and pressure technology that uses the properties of supercritical water in the destruction of organic compounds and toxic wastes. Under SC conditions, the oxidation reactions occur in a homogeneous phase where carbon is converted to carbon dioxide, hydrogen to water, nitrogen-containing substances to nitrogen, and sulfur-containing substances to sulfuric acid. An important factor in the context of this application of SCWO is that the reactions are exothermic and the process can become thermally self-sustaining if the appropriate concentration of oxidizable substances is present. SCW is known to be highly effective at rapidly oxidizing organic matter, for example, aqueous waste streams. Its application to the complete destruction of hazardous and toxic wastes has been extensively studied (Hamley et al. 2001).

4. Combinative sonochemical oxidations of pollutants in water
Sonic and ultra-sonic sound waves in combination with oxidative methods are receiving growing attention as ways of destroying pollutants in water. Some processes have combined sonochemical methods with UV or chemical oxidants such as hydrogen peroxide, H_2O_2, ozone O_3 with some degree of success. It appears to be a method which may find application in special circumstances (see Adewuyi 2005).

MSW can be directly combusted in waste-to-energy facilities to generate electricity. Because no new fuel sources are used other than the waste that would otherwise be sent to landfills, MSW is often considered a renewable power source (see Table 11.3). Although MSW consists mainly of renewable resources such as food, paper, and wood products, it also includes nonrenewable materials derived from fossil fuels, such as tires and plastics.

At the power plant, MSW is unloaded from collection trucks and shredded or processed to ease handling. Recyclable materials are separated out, and the remaining waste is fed into a combustion chamber to be burned. The heat released from burning the MSW is used to produce steam, which turns a steam turbine to generate electricity. Over one-fifth of the US municipal solid waste incinerators use refuse derived fuel (RDF); the United States has about 89 operational MSW-fired power generation plants, generating approximately 2,500 MW, or about 0.3% of total national power generation. However, because construction costs of new plants have increased, economic factors have limited new construction.

The combustion of MSW reduces MSW waste streams, reducing the creation of new landfills. MSW combustion creates a solid waste called ash,

Table 11.3 Generation, materials recovery, composting, combustion with energy recovery, and discards of MSW, 1960–2008 (in millions of tons) in the US (From USEPA: Municipal solid waste generation, recycling, and disposal in the United States: Facts and Figures for 2008 http://www.epa.gov/osw/nonhaz/municipal/pubs/msw2008rpt.pdf, Anonymous 2009a)

Activity	1960	1970	1980	1990	2000	2003	2005	2007	2008
Generation	88.1	121.1	151.6	205.2	239.1	242.2	249.7	254.6	249.6
Recovery for recycling	5.6	8.0	14.5	29.0	52.9	55.6	58.6	62.5	60.8
Recovery for composting[a]	Negligible	Negligible	Negligible	4.2	16.5	19.1	20.6	21.7	22.1
Total materials recovery	5.6	8.0	14.5	33.2	69.4	74.7	79.2	84.2	82.9
Combustion with energy recovery[b]	0.0	0.4	2.7	29.7	33.7	33.1	31.6	32.0	31.6
Discards to landfill, other disposal[c]	82.5	112.7	134.4	142.3	136.0	134.4	138.9	138.4	135.1

[a] Composting of yard trimmings, food scraps, and other MSW organic material. Does not include backyard composting
[b] Includes combustion of MSW in mass burn or refuse-derived fuel form, and combustion with energy recovery of source separated materials in MSW (e.g., wood pallets, tire-derived fuel)
[c] Discards after recovery minus combustion with energy recovery. Discards include combustion without energy recovery

which may contain any of the elements that were originally present in the waste. MSW power plants reduce the need for landfill capacity because disposal of MSW ash requires less land area than does unprocessed MSW. However, because ash and other residues from MSW operations may contain toxic materials, the power plant wastes must be tested regularly to assure that the wastes are safely disposed of, so as to prevent toxic substances from migrating into ground-water supplies.

Under current regulations, MSW ash must be sampled and analyzed regularly to determine whether it is hazardous or not. Hazardous ash must be managed and disposed of as hazardous waste. Depending on state and local restrictions, nonhazardous ash may be disposed of in a MSW landfill or recycled for use in roads, parking lots, or daily covering for sanitary landfills.

A variety of pollution control technologies significantly reduce the gases emitted into the air, including scrubbers, devices that use a liquid spray to neutralize acid gases and filters, that remove tiny ash particles.

5. Disposal through composting, landfilling or combustion without energy generation

11.3.1.4 Composting

Composting is the aerobic decomposition of organic materials by microorganisms under controlled conditions. During composting, the microorganisms consume O_2 while subsisting on organic matter (Fig. 11.3). Active composting generates considerable heat, large quantities of CO_2, and water vapor. The CO_2 and water losses can amount to half the weight of the initial materials, thereby reducing the volume and mass of the final product.

There are three stages in the composting process: Preprocessing, processing and post-processing.

Preprocessing

These are steps which enable the optimization of the composting process and include the following:

Sorting the feedstock material and removing materials that are difficult or impossible to compost such as woody stems.

Reducing the particle size of the feedstock. In large scale composting, machinery exist which chop the material into desirable particle sizes. Particle size reduction increases the surface area to volume ratio of the feedstock materials and this facilitates decomposition by increasing the area exposed to microorganisms. A balance must be drawn between the size which will increase the surface and that may increase compaction of the material and hence limit the free flow of air within the pile (Fig. 11.5).

Optimizing composting conditions. To enhance composting, the materials need to be adjusted for the optimal conditions of moisture content, carbon-to-nitrogen (C:N) ratio, and acidity/alkalinity (pH) (see Table 11.4).

Mixing. Mixing entails either blending certain ingredients with feedstock materials or combining different types of feedstock materials together; for example, bulking agents (such as wood chips) are often added to feedstock materials that have a fine particle size (such as grass).

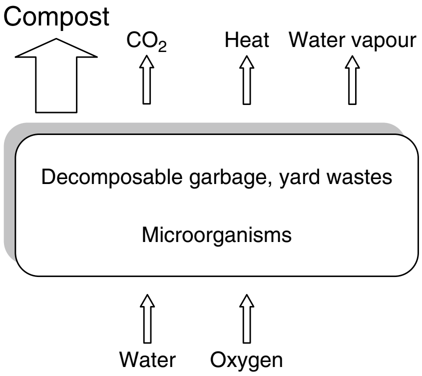


Fig. 11.5 Schematic diagram depicting the composting process

Table 11.4 Optimum conditions for composting (Modified from Palmisano and Barlaz 1998)

Condition	Reasonable range	Preferred range
Carbon:nitrogen (C:N) ratio	20:1–40:1	25:1–30:1
Moisture content	40–65%	50–60%
Oxygen concentration	Greater 5%	Much greater than 5%
Particle size (diameter, in.)	1/8–1/2	Variable
pH	5.5–9.0	6.5–8.0
Temperature (°F)	110–150	130–140

Compost Processing Conditions

Processing methods are chosen to enhance the rapid decomposition of the materials and to minimize negative effects, such as odor release and leachate runoff. Maximum conditions are provided for the decomposition of the composting feed stock.

(a) *Oxygen and aeration*
A minimum oxygen concentration of 5% within the pore spaces of the compost is necessary for aerobic composting. Oxygen levels within the windrows or piles may be replenished by turning the materials over; in large scale composting, this may be done by a front-end loader, or by means of special compost turner.

(b) *C:N ratio*
Carbon (C), nitrogen (N), phosphorous (P), and potassium (K) are the primary nutrients required by the microorganisms in composting. An appropriate C:N ratio usually ensures that the other required nutrients are present in adequate amounts. Raw materials are blended to provide a C:N ratio of 25:1 to 30:1. For C:N ratios below 20:1, the available carbon is fully utilized without stabilizing all of the nitrogen which can lead to the production of excess ammonia and unpleasant odors. For C:N ratios above 40:1, not enough N is available for the growth of microorganisms and the composting process slows dramatically.

(c) *Moisture*
Composting materials should be maintained within a range of 40–65% moisture. Water displaces much of the air in the pore spaces of the composting materials when the moisture content is above 65%. This limits air movement and leads to anaerobic conditions. Moisture content generally decreases as composting proceeds; therefore, water may need to be added to the compost. As a rule of thumb, the materials are too wet if water can be squeezed out of a handful and too dry if the handful does not feel moist to the touch.

(d) *Particle size*
The rate of aerobic decomposition increases with smaller particle size. Smaller particles, however, may reduce the effectiveness of oxygen movement within the pile. Optimum composting conditions are usually obtained with particle sizes ranging from 1/8 to 2 in. average diameter.

(e) *Temperature*
Composting will essentially take place within two temperature ranges: Mesophilic (10–35°C) and Thermophilic (over 45°C). The thermophilic temperatures are desirable because they destroy more pathogens, weed seeds, and fly larvae in the composting materials.

(f) *Time*
The length of time required to transform raw materials into compost depends upon the factors listed above. In general, the active decomposition period may be between 3 and 4 months.

Compost Post Processing or the Curing Stage

When the compost material no longer releases heat, it has entered the curing stage; curing stage begins. The curing stage of compost usually lasts for about a month. Curing occurs at mesophilic temperatures. Curing piles undergo slow decomposition; care must be taken during this period so that these piles do not become anaerobic. The C:N ratio of finished compost should not be greater than 20:1. C:N ratios that are too low can result in phytotoxins being emitted when composts are used. Compost becomes dry and crumbly in texture.

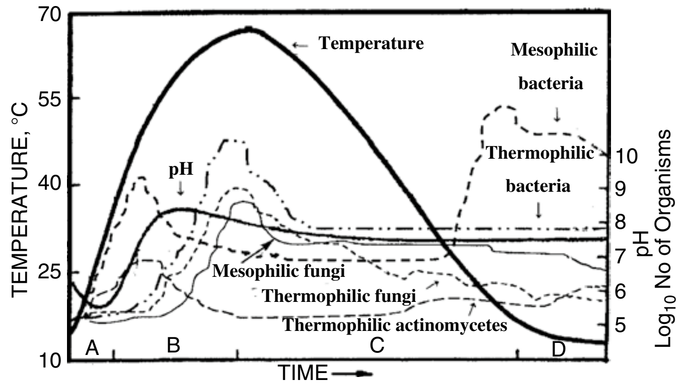


Fig. 11.6 Microbial groups dominant at each temperature regime during composting (Modified from Palmisano and Barlaz 1998)
Stages in the production of compost: A, mesophilic stage; B, thermophilic stage; C, cooling stage; D, maturation stage

When the curing stage is complete, the compost is considered "stabilized" or "mature". Any further microbial decomposition will occur very slowly.

Microbiology of Composting

Composting proceeds through a succession of non-actinomycete mesophilic bacteria, followed by actinomycetes, then fungi; the simplest substrates are metabolized quickly, while substrates which are more complex or difficult to metabolize remain. In the composting of grass straw, the sugars from cell wall polysaccharides are degraded initially, while the less available cellulose is decomposed in the latter stages of composting.

In the first stage of composting (see "A" in Fig. 11.6), the temperature rises from ambient into the thermophilic range. Mesophilic bacterial populations, (mainly non-actinomycete) multiply very rapidly utilizing simple and readily available substrates.

The activity of the mesophilic organisms (non-actinomycete bacteria followed by mesophilic fungi) generates heat which is retained within the compost pile. As the temperature rises to about 45°C, mesophilic populations die off and thermophilic bacterial populations begin to flourish (B in Fig. 11.6). Thermophilic non-actinomycete bacteria, thermophilic fungi, and thermophilic actinomycete in that order become dominant.

In the third stage (see "C" in Fig. 11.6), the temperature drops as the activity by thermophilic declines because they have used up available food in the compost.

In the fourth and final stage (see "D" in Fig. 11.6), the curing stage, the temperature once again returns to the ambient and mesophilic bacteria increase, sometimes even beyond their initial original numbers. The mesophilic fungal and actinomycete populations gradually attack the more complex materials such as cellulose and lignin. Overall, microbial activity drops progressively to very low rates,

Some of the mesophilic bacteria encountered in compost are *Alcaligenes faecalis*, *Bacillus brevis*, *B. circulans* complex. Among the thermophilic bacteria are: *Bacillus subtilis*, *B. polymyxa*, *B. pumilus*, *B. sphaericus*, *and B. licheniformis*, *B. stearothermophilus*, *B. acidocaldarius*, *and B. schleglii*, *B. circulans complex types i and ii*, and *B. subtilis*.

Mesophilic actinomycetes include *Actinobifida chromogena*, *Microbispora bispora*, *Micropolyspora faeni*, *Nocardia* sp., and *Streptomyces rectus*, while some thermophilic actinomycetes are *Thermomonospora* sp., and *Thermoactinomyces vulgaris*

Mesophilic fungi include: *Absidia corymbifer*, *A. ramose*, *Mortierella turficola Mucor miehe*, *M. pusillus*, and *Rhizomucor* sp., while thermophilic fungi are *Aspergillus fumigatus*, *Chaetomium thermophile*, *Humicola lanuginosa*, *Mucor pusillus*, *Thermoascus aurantiacus*, *and Torula thermophila*. Of these, only *Chaetomium thermophile* has been found to be cellulolytic.

11.3.1.5 Landfills Used in the Disposal of MSW

An MSW landfill is not simply a hole in the ground where refuse is dumped. Rather it is a carefully engineered structure built into the ground (where a natural valley exists) or on top of the ground (if the terrain is flat) in which trash is isolated from the surrounding environment, especially groundwater, but also from rain and the surrounding air. This isolation is accomplished with a daily covering of compacted soil over the day's trash and a bottom liner of clay or specially designed thick plastic material. Some authors designate landfalls using clay as sanitary landfill and those using a synthetic (plastic) liner as Municipal solid waste (MSW) landfill. Many factors must be considered and taken into account before the construction of a landfill occurs. After construction, many steps must be taken for it to continue to function well (Anonymous 2010i).

A number of other types of landfills exist. For example, special landfills can be used to reclaim land from the oceans, rivers, or swamps; the materials dumped therein are usually building materials. Some special landfills are also used for disposing of industrial wastes. Hazardous waste landfills are waste disposal units constructed to specific design criteria and which receive hazardous wastes. These landfills are generally constructed to securely hold materials which are regarded as injurious to human health such as radioactive wastes. Inert waste landfills are units which receive wastes that are chemically and physically stable and do not undergo decomposition, including bricks, concrete sand etc. Dumps are simple un-engineered depositories which store various materials and have no facility for leachate and water contamination control. They are not common, are often used in rural areas. Some authorities do not allow their use.

In this section, the discussion will be on landfills used in the disposal of domestic wastes or municipal solid wastes (MSW).

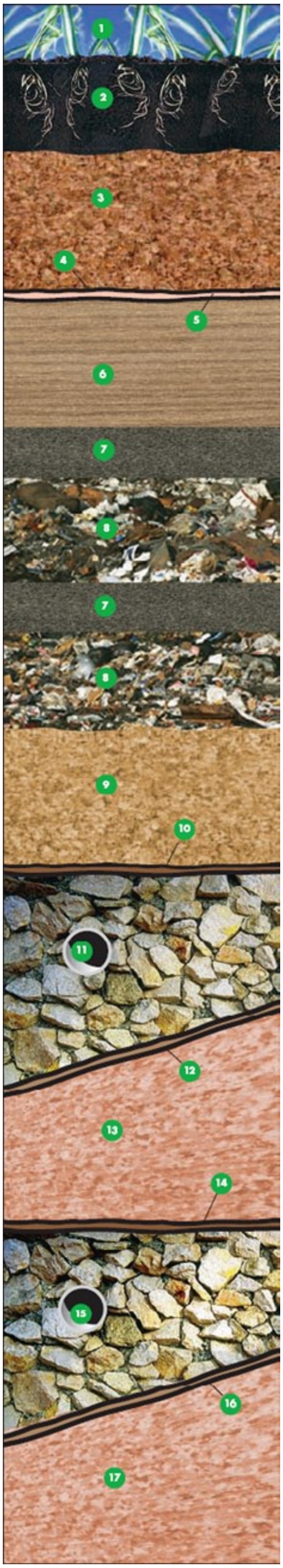
Factors to be Considered in Planning an MSW Landfill

1. *Approval by the appropriate government authority*
   The world over, there are regulations that govern where a landfill can be placed and how it can operate. Permission must therefore be sought from the appropriate authority. In the United States, taking care of trash and building landfills are local government responsibilities and are built by city or other local government authorities. However, a few privately established and operated landfills do exist. Before a city, other local government authority, or private entrepreneurs can build a landfill, an environmental impact assessment (EIA) or study must be carried out to determine the availability of the other factors.
2. *The nature of the underlying soil and bedrock*
   The nature of the underlying soil and bedrock must be determined. The rocks should be as impervious and watertight as possible to prevent any leakage from reaching groundwater. It must not be cracked so as to be sure that leachates from the landfill do not enter the underground water. The site should not be near mines or quarries because these structures frequently contact the groundwater supply. It must finally be possible to sink wells at various points around the site to monitor the groundwater or to capture any escaping wastes.
3. *There must be sufficient land for the landfill and the activities associated with it*
   Although the actual landfill is at the center stage of the landfill establishment, the essential support services and activities must also be present. These include runoff access roads, collection ponds, leachate collection ponds, drop-off stations, areas for borrowing soil, and 50- to 100-foot buffer areas etc. These ancillary activities take up three to four times more space than the actual landfill and must be taken into account when a landfill is being planned.
4. *The flow of water over the area must be studied*
   It is necessary to study the flow of water so as to ensure that excess water from the landfill does not drain into to neighboring property or vice versa. Similarly, the landfill should not be close to rivers, streams, or wetlands so that any potential leakage from the landfill does not enter the groundwater or watershed.
5. *The ground water should be as low as possible*
   The level of the underground water table should be as low as possible so that leachates from the landfill do not easily enter the ground water.
6. *Avoidance of wild life or historical locations*
   The landfill should not be located near areas important to wild life such as nesting areas of local or migrating birds or fisheries. Similarly, it should not be located near any sites containing any historical or archaeological artifacts.

Parts of a Landfill

Figure 11.7 is a vertical section of a generalized landfill reproduced with the permission of Waste Management Inc. of Houston, Texas, USA; the description of parts of a landfill which follows below are based on the legend of the generalized landfill and is used with the permission of Waste Management Inc.

The parts of a landfill may be divided into: The protective cover (A); the moisture barrier cap (B); working



landfill (C); leachate collection system (D); ground water protection base (E); monitoring liner system (F); secondary protection base (G). The details of the various parts of a landfill are in Parts A to G of Fig. 11.5. The aspects of landfills and their ancillary activities dealing with ground water, surface water, and methane gas monitoring are discussed in Fig. 11.8 (Anonymous 2010i).

(A) **Protective Cover**

1. *Grass and flower cover*
   As portions of the landfill are completed, they are planted over with native grass and shrubs, no trees whose roots will penetrate deep are included. The vegetation is aesthetically pleasing and helps prevent erosion. It will resemble an open space with rolling hills of wild flowers.
2. *Top soil*
   This provides the root system with support and nutrients for the vegetation growing on the erstwhile landfill.
3. *Soil, sand, and gravel*
   This protects the liner system from direct rain and borrowing animals and provides additional moisture retention to help support the plant on the top soil.

(B) **Moisture Barrier Cap**

4. *Filtering system*
   A fabric composed of felt-like plastic acts as a filtration system. The geotext prevents the overlying soil and small particles from clogging the underlying drainage system. High density polyethylene geo net is a heavy plastic with large mesh-like openings. The geo net allows liquid to flow away from the landfill and helps prevent the infiltration of rain water.
5. *Plastic shield*
   High density polyethylene liner shields the landfill from liquid penetration.
6. *Clay shield*
   When the landfill reaches its permitted height, a minimum of 18 in. layer of re-compacted clay is placed over the garbage. This liner is another system which provides an excellent

Fig. 11.7 Vertical section of a generalized landfill (From http://tontitown.wm.com/documents/tontitown_landfill_anatomy.pdf. With the kind permission of Waste Management Inc., Texas, Houston)

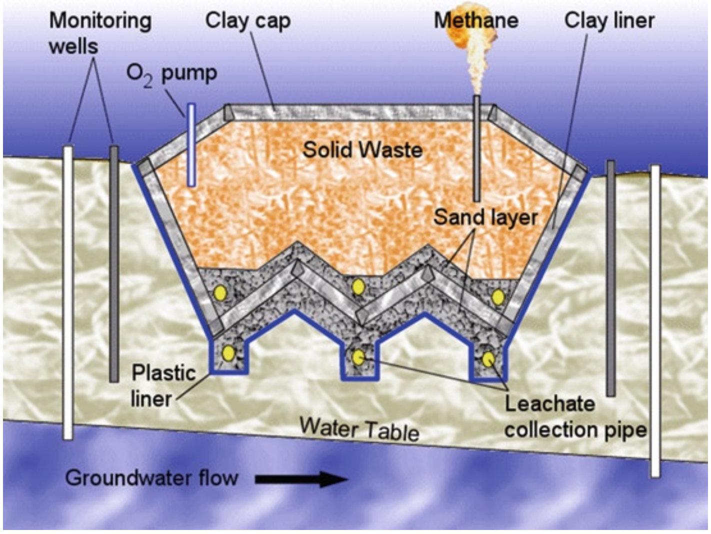


Fig. 11.8 A composite figure of a landfill showing a cell and accompanying landfill activities (From Anonymous 2010j) *Note:* (a) There are pipes for sampling the ground water around the landfill for contamination from the landfill. (b) The bottom of the landfill is slanted to facilitate the drainage of the leachates to the pipes located at the bottom of the landfill. (c) The methane (landfill gas) is being flared, although many modern landfills have facilities for collecting the gas and using it for generating electricity, for heating homes. (d) The ground water is slanting, and some way from the bottom of the landfill

barrier against rainwater infiltration; it also keeps out gas (and hence odors) and vermin.

(C) **Working Landfill**

7. *Daily cover*

   At the end of each working day, garbage is covered with a 6–12 in. layer of soil. Daily cover reduces odors, blowing litter, and helps deter scavengers.

8. *Garbage*

   In compliance with the requirement of most authorities, as garbage arrives it is compacted in layers within a small area known as a *cell* to reduce the volume consumed within the landfill. It helps to control odors, stop the refuse from scattering and keeps off rats and other vermin. Perhaps, the most precious commodity and overriding problem in a landfill is air space. The amount of space is directly related to the capacity and usable life of the landfill. To increase the space, trash is compacted into cells that contain only 1 day's trash (see Fig. 11.6). In one landfill, a cell is approximately 50 ft long by 50 ft wide by 14 ft high (15.25 m × 15.25 m × 4.26 m). The amount of trash within the cell is 2,500 ton and is compressed at 1,500 lb per cubic yard using heavy equipment (tractors, bulldozers, rollers, and graders) that go over the mound of trash several times. Once the cell is made, it is covered with 6 in of soil and compacted further. Cells are arranged in rows and layers of adjoining cells known as *lifts*. As a further way of conserving space, bulky materials, such as carpets, mattresses, foam, and yard waste, are excluded from most landfill.

(D) **Leachate Collection System**

Leachates consist of water which enter the landfill during rainfall or formed as a result of biological activity within the landfill. As the water percolates through the trash, it picks up contaminants (organic and inorganic chemicals, metals, biological waste products of decomposition) and is typically acidic. The function of the leachate collection system is to control the flow of leachates so that it can be properly removed from the landfill and treated.

9. *Sand and gravel*

   A 12-inch layer of sand and/or gravel provides protection for a layer of thick plastic mesh (called a geonet) which collects leachate and allows it to drain by gravity to the leachate collecting pipe system.

10. *Filtering (geotextile) system*
A blanket of nonwoven geotextile fabric, composed of felt-like plastic is placed below the gravel. This porous material allows liquid to flow downward while preventing fine particles from clogging and blocking the drainage and collection systems. Underneath, a geo net made of felt-like plastic diverts made of mesh-like plastic diverts the leachate toward the underlying collection pipes and a low-lying sump.
11. *Collection system*
Six-inch perforated PVC perforated plastic pipes surrounded by a bed of porous rock/and sand directs the leachate to the lowest part of each disposal cell. The liquid is conveyed via the leachate collection system to a sump located at the lowest point of each disposal cell. When a small amount of the liquid has built up, a pump automatically removes the liquid from the landfill to specially designed storage tanks or pond, where they are tested for acceptable levels of various chemicals (biological and chemical oxygen demands, organic chemicals, pH, calcium, magnesium, iron, sulfate, and chloride) and allowed to settle. After testing, the leachate must be treated like any other sewage/wastewater; the treatment may occur on-site or off-site at approved wastewater treatment plants.

(E) **Ground Water Protection Base**

12. *The HDPE plastic (geomembrane) shield*
The primary bottom shield consists of two components. First is a man-made synthetic thick high density polyethylene liner, the geomembrane, which is used in MSW landfills and consists of a thick (30–100 mm) type of durable, puncture-resistant synthetic plastic, polyethylene, polyvinylchloride, high-density polyethylene (HDPE). It is impermeable, and highly resistant, to chemicals which might be present in the liquids leaving the landfill (i.e., leachates) as well as gases emanating therefrom. This plastic is also called the bottom liner and is key to the achievement of the purpose of the landfill which is to keep the refuse or any items emanating from it from entering the environment. The plastic liner may also be surrounded on either side by a fabric mat (geotextile mat) that will help to keep the plastic liner from tearing or puncturing from the nearby rock and gravel layers.
The second part of the ground water base is the clay shield described in 13.
13. *Clay shield*
The shield consists of a minimum of 24 in. of compacted clay. It is the second component of the primary liner system and provides added environmental protection, preventing leachates and gas from entering the environment from the landfill.

(F) **Monitoring Liner System**

14. *Protection against clogging of the monitoring layer*
A blanket of geotextile fabric composed of felt-like plastic fibers is laid below the primary ground water protection base. Underneath, a geonet of mesh-like plastic is used to permit any liquids movement. These materials, collectively, prevent the fine clay particles from clogging the monitoring layer below.
15. *Collection system*
Perforated plastic pipes surrounded by a bed of porous rock and/or sand at the lowest point of the liner system. This feature is used to measure the performance of the liner system and groundwater protection base. Regular monitoring is performed to ensure the integrity of the landfill components.

(G) **Secondary Protection Base**

16. *HPDE plastic shield*
The secondary bottom liner consists of two components. First is a man-made synthetic 60 mil high density polyethylene liner, impermeable to liquids. The second is the clay shield described in 17 below.
17. *Clay shield*
The second component of the secondary bottom liner is a minimum of 24 in. of re-compacted clay. The clay and the synthetic liner located above it provide an added measure of environmental protection.

Operation of a Landfill

Landfills are used differently in different localities, including different countries. In some, MSW is dumped into landfills without much possessing, and no attempt is made to recover recyclable items. In

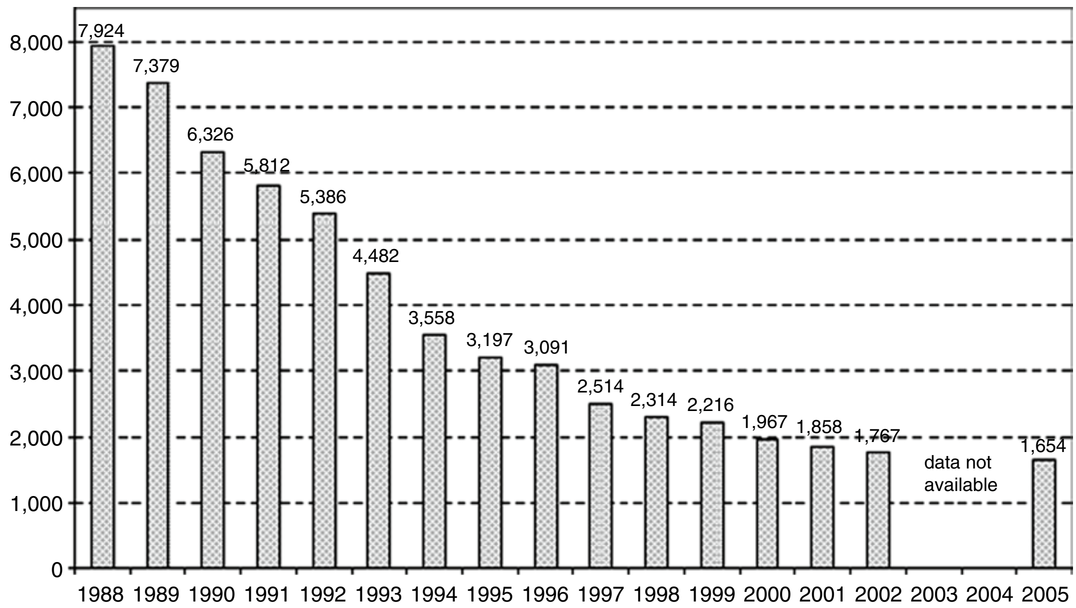


Fig. 11.9 Number of landfills in the US. 1988–2005 (From Municipal Solid Waste in the United States: *2005 Facts And Figures*. U.S. EPA www.epa.gov/osw. Accessed at on Monday, June 11, 2007, Anonymous 2006)

others, the items taken to a landfill would have passed through other activities (see Fig. 11.7). In general, in the USA, the items taken to a landfill are the recalcitrant ones which are left over; the MSW has been subjected to other treatments. Consequently, the number of landfills in the USA has been declining (see Fig. 11.9). In a similar vein, in recent years, some countries, such as Germany, Austria, and Switzerland, have banned the disposal of untreated waste in landfills. In these countries, only the ashes from incineration or the stabilized output of mechanical biological treatment plants may still be deposited.

Problems of Landfills

Major concerns in a landfill include the following, which routine operations are designed to take care of.

(a) *Leachate collection and treatment and/or removal*
Leachate is liquid generated from moisture brought in with the waste, from rainfall which percolates into the landfill, and from the waste decomposition processes. It contains dissolved and insoluble chemicals. A network of perforated pipes within the landfill collects the leachate, which then is pumped to a treatment plant, where it may be treated on site for reuse (e.g., to control dust) or may be piped to a treatment plant for safe disposal.

(b) *Checking for leachate leakage*
Many landfills have wells located around them at appropriate depths and are sampled on a daily basis to determine if leachates from the landfills are escaping into underground waters.

(c) *Control of odors, flies, and vermin*
At the end of each day's operation, bulldozers spread and compact the MSW and further compacts at least 6 in. of earth over all of the waste. The daily cover prevents the emergence of flies and other insects, and controls odors, blowing litter, and the infiltration of rainfall. The compacting also limits hiding places for rats and other vermin.

(d) *Control of gases released from the landfill*
As a result of anaerobic decomposition in the landfills (see below), gases, methane, and carbon dioxide, are released. A series of perforated pipes connected to vacuum blowers collects and removes the gas to be burned off or used to generate electricity in a gas turbine.

Gas monitoring wells are placed all around the site, and sampled frequently, to make certain that there is no migration of the gas beyond the site boundaries as gas leakages have been known to cause explosions around landfills.

(e) *Drainage and Erosion Control*
The landfill must be constructed with graded decks to ensure proper drainage and prevent flooding.

(f) *Closure and Post-Closure Care Requirements for Municipal Solid Waste Landfills*
The EPA requires that when a landfill is closed, it must have a final cover which:

1. Has a permeability less than or equal to the permeability of any bottom liner system or natural subsoils present, using an infiltration material that contains a minimum 18-inches of earthen material
2. Minimizes erosion of the final cover by the use of an erosion layer that contains a of minimum 6-inches of earthen material that is capable of sustaining native plant growth

After closure, the EPA has the following post-closure requirements which must be observed for 30 years, although this period may be shortened:

1. Maintaining the integrity and effectiveness of any final cover, including making repairs to the cover as necessary to correct the effects of settlement, subsidence, erosion, or other events, and preventing run-on and run-off from eroding or otherwise damaging the final cover
2. Maintaining and operating the leachate collection system
3. Monitoring for possible the ground water contamination
4. Maintaining and operating the gas monitoring system

11.4 Anaerobic Breakdown of Organic Matter in Landfills (and Aquatic Sediments)

Anaerobic activity by microorganisms is usually indicated by offensive odors due to H_2S, CH_4, amines, and skatoles.

Methanogenesis or biomethanation is the formation of methane, also known as marsh gas by microorganisms. Methanogens, microorganisms capable of producing methane, are found only among Archaea (see Chap. 2). Recently, it has been demonstrated that leaf tissues of living plants emit methane, although the mechanism by which such methane production occurs is, as yet, unknown.

Methanogens belong to the Domain Archaea that produce methane as a metabolic byproduct in anoxic (anaerobic) conditions. Methanogens are the most common and widely dispersed of the Archaea being found in anoxic sediments and swamps, lakes, marshes, paddy fields, landfills, hydrothermal vents, and sewage works as well as in the rumen of cattle, sheep and camels, the cecae of horses and rabbits, the large intestine of dogs and humans, and in the hindgut of insects such as termites and cockroaches. In marine sediments, biomethanation is generally confined to where sulfates are depleted, below the top layers. Ecologically, methanogens play the vital role in anaerobic environments of removing excess hydrogen and fermentation products that have been produced by other forms of anaerobic respiration (see Fig. 11.10).

Methanogens typically thrive in environments in which all other electron acceptors (such as oxygen, nitrate, sulfate, and trivalent iron) have been depleted. Most methanogens grow on CO_2 and H_2 as their sole energy source. There are a few exceptions which only metabolize acetate, or reduce methanol with H_2, or use methylamine and methanol (see Table 11.5).

For the majority that reduce CO_2 to CH_4, there are a few key coenzymes they need; coenzyme bound C_1-intermediates Methanofuran (MFR), tetrahydromethanopterin (H_4MPT), and coenzyme M (H-S-CoM). Other key coenzymes worth noting are F_{420} and *N*-7-mercaptoheptanoyl-*O*-phospho-L-threonine (H-S-HTP). Coenzyme F_{420} acts analogously to a quinone in electron transfer sequences by accepting the H^+ ions from the electron donor and supplying them to the electron acceptor. The other coenzyme, H-S-HTP, does the same task as F_{420} only in the last step of methanogenesis from CO_2 and H_2 (Fig. 11.11).

11.4.1 Some Properties of Methanogens

Seventeen genera of methanogenic Archaea exist (see Table 11.6). They have a few peculiarities (Anonymous 2010k).

(a) *Shapes*
Two shapes, rods and coccoid, seem to dominate the methanogens. Some examples of rod shaped cells include *Methanobacterium* spp. and *Methanopyrus*

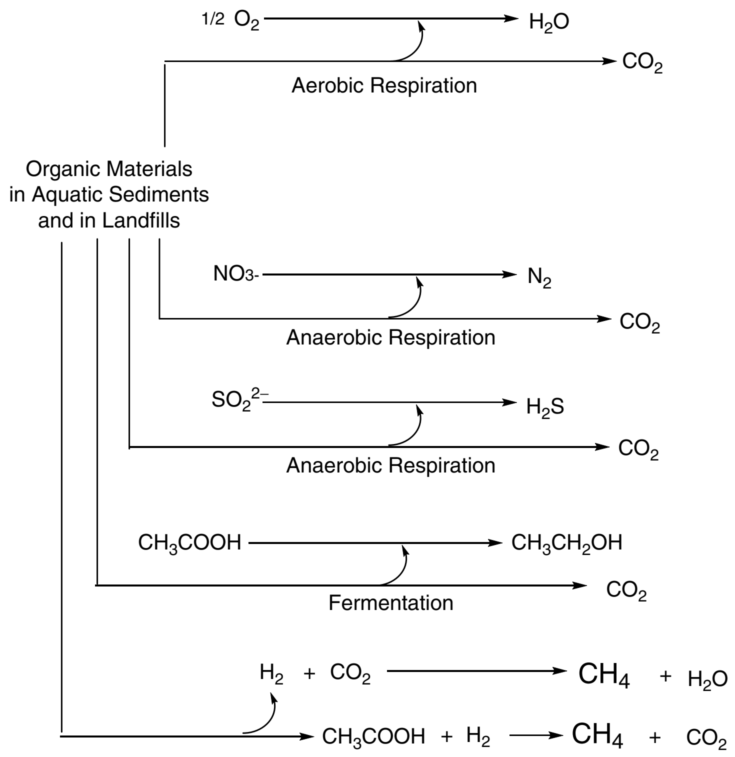


Fig. 11.10 Breakdown of organic matter in the anaerobic regimes of landfill and aquatic sediments

Table 11.5 Some substrates utilized by methanogens (Modified from Rehm and Reed 2008)

CO_2+H_2	Carbon dioxide + hydrogen gas
$HCOO^-$	Formate
$CO+H_2$	Carbon monoxide + Hydrogen gas
CH_3OH	Methanol
CH_3NH^{3+}	Methylamine
$(CH_3)2NH^{2+}$	Dimethylamine
$(CH_3)3NH^+$	Trimethylamine
CH_3SH	Mehtylmercaptan
$(CH_3)2S$	Dimethylsulphide
CH_3COO^-	Acetate

kandleri. Examples of the coccoid methanogens include species from *Methanococcus* and *Methanosphaera* to name a few. *Methanoculleus* and *Methanogenium* are coccoid as well but are irregularly shaped, possibly due to S-layers not being so strongly bonded like other wall structures. Methanogens are not just limited to these shapes, but include a plate shaped genus *Methanoplanus*, *Methanospirillum* that are long thin spirals, and *Methanosarcina* that are cluster of round cells.

(b) *Lack of mureins in their cell walls*
Methanogens lack murein typical of bacteria (eubacteria), but some contain pseudomurein, which can only be distinguished from its bacteria counterpart through chemical analysis. Those methanogens that do not possess pseudomurein have at least one paracrystalline array (S-layer). An S-layer is made up of proteins that fit together in an array like jigsaw pieces that do not covalently bind to one another, in contrast to a cell wall that is one giant covalent bond. Also, some methanogens have S-layer proteins that are glycosylated, which could increase stability, while others do not (e.g., *Methanococcus* spp).

(c) *Ecological distribution in Extreme environments*
Methanogens are found in extreme environments: from the hot vents in the ocean floor to the polar ice to hot springs.

11.4.2 Landfill Gas

Landfill gas is the gas released from landfills. The gas produced by landfills contains about 50% each of methane (CH_4) and carbon dioxide (CO_2). Methane is a

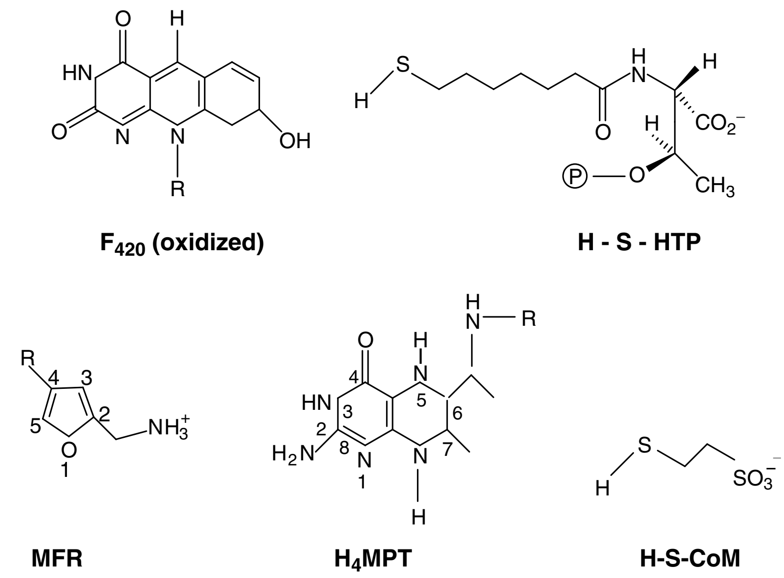


Fig. 11.11 Some coenzymes peculiar to methanogens (From DiMarco et al. 1990. With permission)

Table 11.6 Methanogenic genera among the archeae (Modified from http://www.earthlife.net/prokaryotes/euryarchaeota.html, and http://en.wikipedia.org/wiki/Methanogen, Anonymous 2010i)

Methanogenic archaea	Number of species	Cell morphology	Example
Methanobacterium	19	Long rods	*Methanobacterium bryantii*
Methanobrevibacter	7	Short rods	*Methanobrevibacter ruminantium*
Methanosphaera	2	Cocci	*Methanosphaera stadtmanae*
Methanothermus	2	Rods	*Methanothermus fervidus*
Methanococcus	11	Irregular cocci	*Methanococcus deltae*
Methanomicrobium	2	Short rods	*Methanomicrobium mobile*
Methanogenium	11	Irregular cocci	*Methanogenium frigidum*
Methanospirillium	1	Sprilla	*Methanospirillium hungatei*
Methanoplanus	3	Plate-like	*Methanoplanus limicola*

greenhouse gas and has 25 times more heat trapping potential than carbon dioxide (CO_2). However, methane is only present in the atmosphere at concentrations around 1,800 parts per billion (as opposed to CO2's 385 ppm).

There are many factors that determine how much landfill gas, including the valuable methane, a given landfill will produce. The most important factors for predicting the quality of the landfill methane that will be produced over the lifetime of a landfill are:

1. Waste composition
   The more organic waste present in a landfill, the more landfill gas (e.g., carbon dioxide, methane, nitrogen, and hydrogen sulfide) is produced by the bacteria during decomposition. The more chemicals disposed of in the landfill, the more likely non-methane organic compounds (NMOCs) will be produced either through volatilization or chemical reactions.
2. Age of refuse
   Generally, more recently buried waste (i.e., waste buried less than 10 years) produces more landfill gas through bacterial decomposition, volatilization, and chemical reactions than does others.
3. Moisture content
   The presence of moisture in a landfill increases gas production because it encourages bacterial

decomposition. Moisture may also promote chemical reactions that produce gases.

4. Temperature
   As the landfill's temperature rises, bacterial activity increases, resulting in increased gas production. Increased temperature may also increase rates of volatilization and chemical reactions.

11.4.2.1 Landfill Methane Capture Technology

The basic process behind capturing the methane that is emitted by landfills is to place a cap on it (see the operation of a landfill), using a variety of different materials based in part on the waste contents of the landfill, to block the direct emissions of methane into the atmosphere. A common landfill gas capture system is made up of an arrangement of vertical wells and horizontal collectors, usually placed after the landfill has been capped, that is used to direct the flow of the gas This common type of collection is known as a "passive gas collection system" and the collection wells can be installed during the initial construction of the landfill or after the landfill is permanently closed.

In the other method, the "active gas collection system", a series of pumps move the gas to collection wells and through a series of low-pressure chambers to help direct and control the flow of the gas. The active gas collection method is more expensive than the passive version, but the ability to control the flow rate of gas, coupled with the ability to have multiple collection wells, helps to make the active gas collection system an economically viable option for many landfills. There are nearly 500 landfills in the United States that are capturing methane and either burning it for electricity generation or flaring it, which converts the methane into carbon dioxide, which has a lower global warming potential than methane.

11.5 Options for Municipal Solid Wastes Management

Several options exist for the disposal of wastes and what is adopted in any community, municipal, state or country, depends much on the economic status of the unit. As seen in Fig. 11.8, MSW can be sorted into seven categories: Yard trimmings, food scraps, paper and paper board, metals, glass, plastics and wood. The first two, yard trimmings and food scraps, may be composted, while the other five may recycled and used for manufacturing. The compost is used as soil amendment or organic manure in agriculture, while any materials not decomposable is either sent to the landfill or incinerated.

The non-decomposable and/or nonrecyclable remnants of the recycled materials among paper, metals, glass, plastics, and wood are sent to the landfill or for incineration, depending on their nature.

The breakdown of organic materials in the landfill leads to methane release which can be used to produce electricity. The leachate from the landfill must be carefully managed to prevent it from getting into ground water.

All seven categories of MSW may however be incinerated; sometimes, the heat generated from the incineration may be used to generate electricity. The ash generated from the incineration is sent to the landfill (Fig. 11.12).

The disposal of wastes (solid or sewage) costs money and the community must not only have the means to pay for the service, but must also be willing to pay for it.

When the various options are arranged in descending order of desirability, the order would be:

1. Source reduction
2. Recycling
3. Incineration with energy recovery
4. Disposal through:
   (a) Incineration
   (b) Landfilling
   (c) Incineration without energy recovery

The more affluent a society is, the more likely it is that the options it will select will be nearer to the top of the list. Many developing countries, for example, do not have the resources to establish the type of well-engineered landfills described above, or to invest in the infrastructure to generate electricity from combusted MSW. They end up simply combusting the wastes, or just dumping them in dumpsites to be collected and buried or incinerated at a latter date (see Bassey et al. 2006).

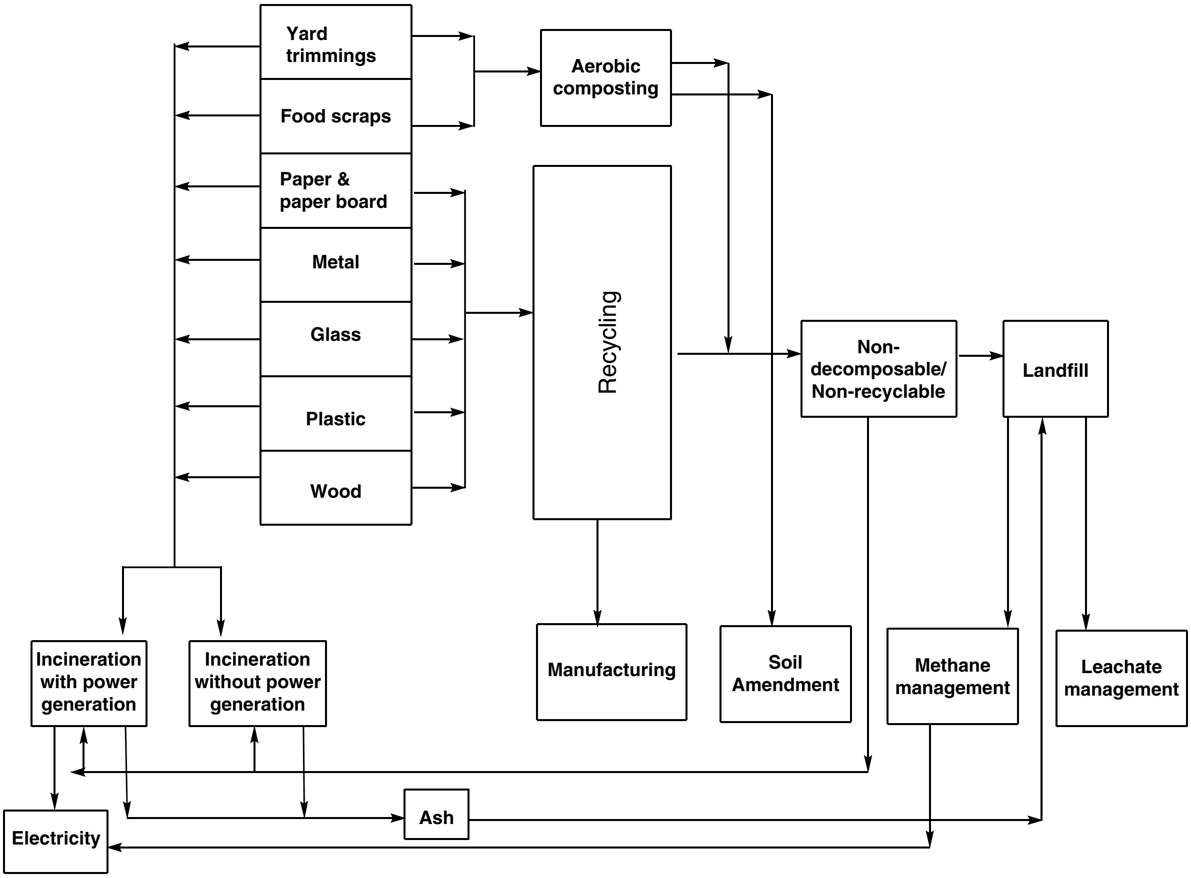


Fig. 11.12 Options for managing municipal solid wastes

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