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Perspectives on Sustainable Waste Management

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Abstract

Sustainable waste management is a goal that all societies must strive to maintain. Currently nearly 80% of global wastes are sent to landfill, with a significant amount lacking proper design or containment. The increased attention to environmental impacts of human activities and the increasing demand for energy and materials have resulted in a new perspective on waste streams. Use of waste streams for energy and materials recovery is becoming more prevalent, especially in developed regions of the world, such as Europe, the United States, and Japan. Although currently these efforts have a small impact on waste disposal, use of waste streams to extract value very likely will increase as society becomes more aware of the options available. This review presents an overview of waste management with a focus on following an expanded waste hierarchy to extract value specifically from municipal solid waste streams.

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INTRODUCTION

No existing process is 100 percent efficient or selective. Therefore, all processes will yield a residual or a by-product. If that by-product cannot be used in another process or has very low economic value, it is considered to be a waste that will ultimately need proper disposal. For example, a typical power plant producing electricity through a thermal cycle will have hot flue gas. The flue gas is vented to the atmosphere typically at 150°F to 200°F, with nearly 15% oxygen, 65% nitrogen, 10% carbon dioxide, and 10% water vapor (1). Although energy can be recovered from the hot gases and oxygen is a valuable gas, they are considered waste and thus vented to the atmosphere.

The same situation exists in complex systems, such as refineries and chemical plants. Many processes produce a by-product that is not valuable enough to recover and recycle back into the chemical process and is used only for its heating value, for example, refinery fuel gas. Refinery fuel gas, considered a waste chemical mix, is derived from the crude oil distillation process and is used to fuel boilers, heaters, and turbines. Extending this to the human consumption process, wastes are generated and therefore must be disposed of properly.

This review focuses on wastes generated by human activities, thus municipal solid waste (MSW), and presents the various management options worldwide. A brief history is followed by a discussion of MSW generation rates. Some specific information is given on characterization and categorization of the waste material. The globally accepted hierarchy of waste management is presented to set the stage for the various paths used to manage the waste streams. Finally, some information is provided on how a zero-waste society can be achieved, with an outlook for the future.

HISTORY

The human consumption process can generally be considered beginning with prehistoric populations gathering necessities for survival, such as food, clothing, and shelter. Materials that could not be used were discarded as waste. The consumption process has changed dramatically over time, resulting in a society predisposed toward the purchase or acquisition of goods in ever-increasing amounts. This has led to an unprecedented buildup of solid material stock that is turned over (i.e., used and discarded) at an alarming rate. **Figure 1** quantitatively shows this evolution. It is important to notice the stock that is accumulated in current society.

All streams have increased greatly, but for this review, the focus is on the solid waste streams and the stock. Because sewage and excreta are considered to be biodegradable and a necessary function of living, they must be managed and explored in a different context. However, for solid waste management, solutions exist to properly manage it in its entirety but are not being implemented for a variety of reasons. Whereas human turnover has increased by nearly an order of magnitude, increasing from 6 tonnes per capita per year (T/c/year) to 86 T/c/year, the solid wastes have increased by a factor of thirty, from approximately 0.1 to 3 T/c/year. The impact of this on human and environmental health is increasingly detrimental. Societies are struggling to properly manage the enormous solid waste generation rates, but they will only worsen. The stock has gone from essentially zero to nearly 260 T/c/year. Population and standard of living increases will only exacerbate this as the amount of stock increases proportionately. If this stock is not reused, it will become future solid waste.

WASTE GENERATION RATES

To understand the challenges of waste management, we must understand the enormous amounts of waste that are generated. Total worldwide MSW generation is estimated at 1.3 billion tons per year. The United States produces 621,000 tons per day, which is the highest in the world

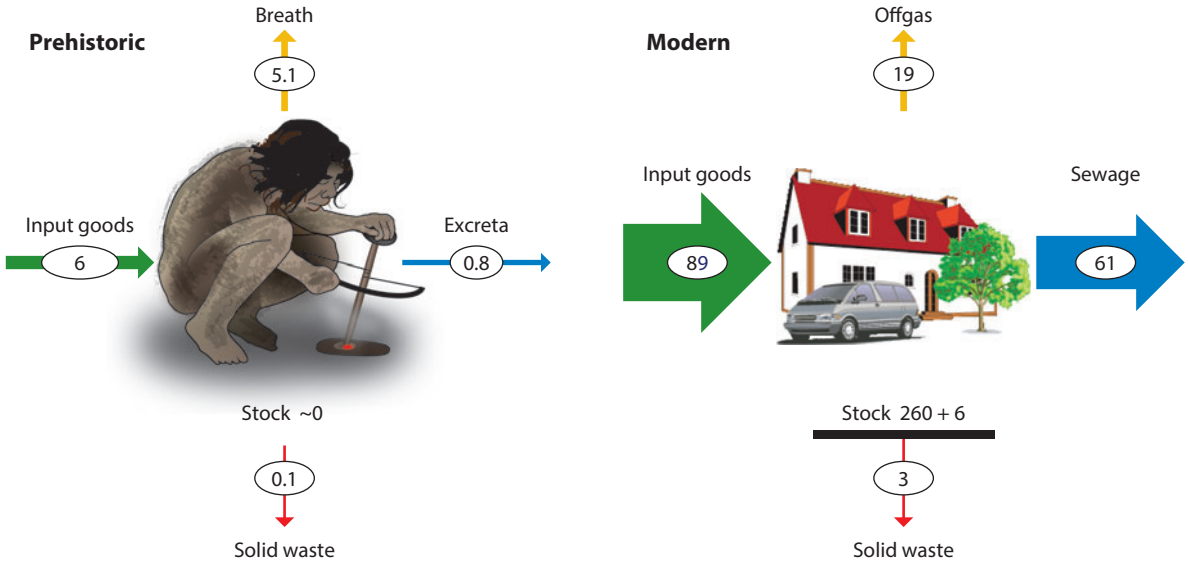

Figure 1

Input and output amounts for material utilization by humans (2).

and nearly seven times that of France. Typically the developed countries have the highest rates, but developing countries, such as Brazil, China, and India, have high rates owing to large urban population centers. For example, China produces nearly 521,000 tons of MSW per day, which is considered the second highest in the world (Worldwatch Institute). Therefore, population increase correlates with more waste generation, as mentioned in the introduction. **Figure 2** shows the waste generation rates in the United States from 1960 to 2011 as a total amount on the left ordinate and a per capita rate on the right ordinate. Total generation from 1990 to 2005 went from 208 to nearly 254 million tons, a 22% increase. But at the same time, the per capita generation rate increased by only 2.6%, from 4.57 to 4.69 lb/person/day.

It is also interesting that Japan, a nation that has been a world leader for several decades in waste reduction and recycling systems, in 1999 generated 53.7 million tons of MSW and combusted 40.3 million tons (3). On a per capita basis, the rate of MSW generation in Japan is nearly one-half of that in the United States. However, there is significant variability, ranging from approximately 2.5 lb/person/day for New York State to nearly 8 lb/person/day in Hawaii (4). Hawaii likely has such a high rate because most products must be imported to the island, whereas New York has a degree of manufacturing and obtains some efficiency via dense population areas. Therefore, packing, containment, and waste collection must be coordinated in the future to ensure high capture and recycle rates. **Figure 3** below shows the waste generation rate in lb/person/day against per capita income for the different states. It is interesting to see that there is no correlation; however, it appears there is a lower amount, slightly more than 2.0 lb/person/day. This may indicate that some base level of waste must be generated to live in a country with a high living standard. For example, it is known that waste generation rates are higher for wealthier nations; thus, it is generally accepted that higher standard of living (or per capita income) is positively correlated with higher waste generation rates. However, the data in **Figure 3** do not fully support this trend, because a waste generation rate of about 2.5 lb/person/day spans an income range of approximately $23,000 to $34,000/year. Although there are some outliers, the amount of waste generated clearly falls into a narrow band, between ~2.5 and 4.0 lb/person/day.

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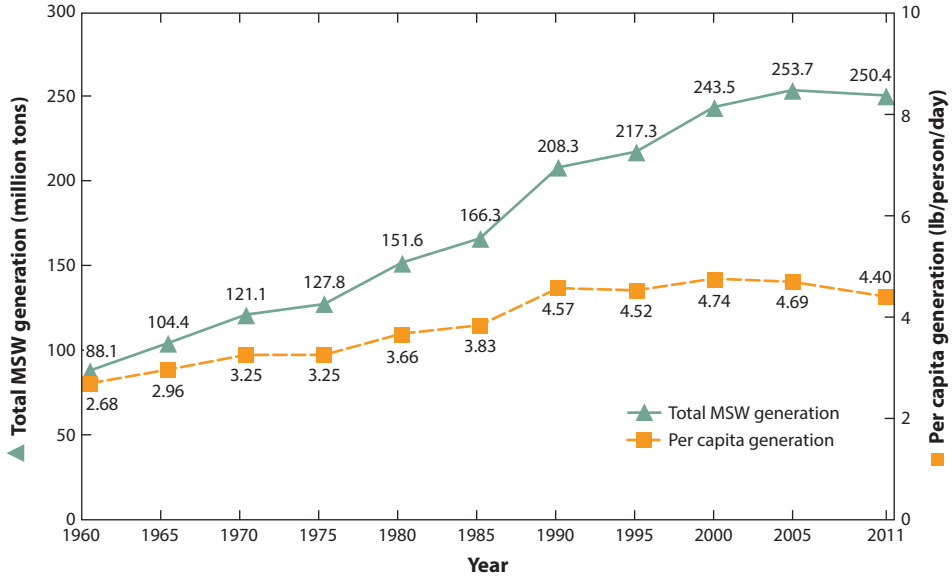

Figure 2

United States generation rates for municipal solid waste (MSW) from 1960 to 2011 (**http://www.epa.gov/epawaste/nonhaz/municipal/index.htm**).

Finally, MSW generation must be put into perspective with regard to streams that are commonly discussed as problematic on a worldwide scale. **Figure 4** presents the total metric tons of carbon dioxide, MSW, and nuclear waste generated in one year (**http://www.eia.gov/reports/**) on a semilog scale. The attention given to carbon dioxide and nuclear waste is far more intense than that given to MSW. However, it is evident that MSW is much larger than nuclear waste. Of course, a direct comparison cannot be made in terms of environmental impact and human health

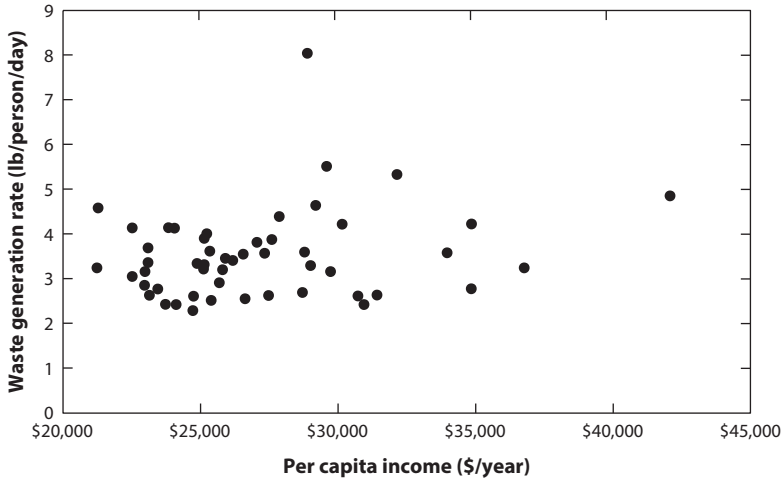

Figure 3

Waste generation rate compared with per capita income for each state in the United States.

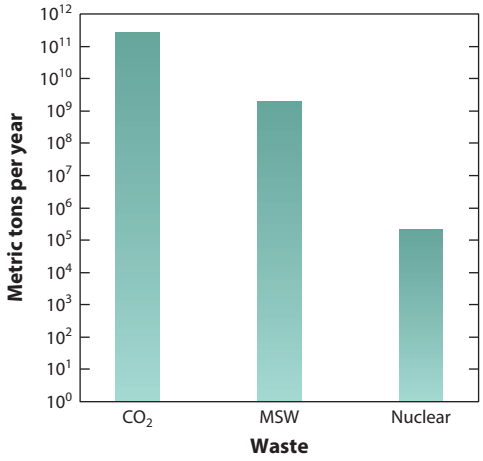

Figure 4

Comparison of major waste streams produced annually. Abbreviation: MSW, municipal solid waste.

risk. But if there is interest in reducing the environmental damage associated with waste streams, all large quantities must be considered.

CHARACTERIZATION OF WASTES

Waste streams are classified under many categories relating to their source or geographical boundaries, e.g., construction and demolition (C&D). However, definitions of medical waste vary between regulatory agencies, as well as from state to state. The US Environmental Protection Agency (EPA) Resource Conservation and Recovery Act (RCRA) Part 259 (1989) uses the following definition: "Medical waste is defined as any solid waste which is generated in diagnosis, treatment, or immunization of human beings or animals, in related research, biologicals production or testing" (5, p. 11). In addition, wastes fall into two overarching classifications: hazardous and nonhazardous. According to the RCRA, hazardous waste is defined as a solid waste that may pose a substantial present or potential hazard when treated, handled, stored, disposed of, or mismanaged. The hazard may arise from quantity or physical, chemical, or infectious characteristics. Except for variations in moisture content and organic fraction, primarily from food wastes, the compositions of wastes are remarkably similar on a global basis. Although there are many categories, only those with the most environmental impact are discussed briefly here.

Municipal Solid Waste

MSW is the common material or garbage that is discarded by the general public and collected through municipal or private haulers via curbside collection. This is typically the most heterogeneous mixture of waste streams because of the difficulty of enforcing current regulations. For example, alkaline batteries are composed primarily of common metals—steel, zinc, and manganese—and do not pose a health or environmental risk during normal use or disposal; however, small button batteries still contain some amounts of mercury and should not be discarded with household trash. **Table 1** shows the typical composition of MSW by world region.

As evidenced in **Table 1**, there is remarkable consistency with regard to food waste, paper, wood, plastics, and metal. Food waste is the largest source found in MSW, except for in southern

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Table 1 Composition of municipal solid waste global regions (6)

Region	Food waste	Paper/ cardboard	Wood	Textiles	Rubber/ leather	Plastic	Metal	Glass	Other
Asia									
Eastern Asia	26.2	18.8	3.5	3.5	1.0	14.3	2.7	3.1	7.4
South-central Asia	40.3	11.3	7.9	2.5	0.8	6.4	3.8	3.5	21.9
Southeastern Asia	43.5	12.9	9.9	2.7	0.9	7.2	3.3	4.0	16.3
Western Asia and Middle East	41.1	18.0	9.8	2.9	0.6	6.3	1.3	2.2	5.4
Africa									
Eastern Africa	53.9	7.7	7.0	1.7	1.1	5.5	1.8	2.3	11.6
Middle Africa	43.4	16.8	6.5	2.5		4.5	3.5	2.0	1.5
Northern Africa	51.1	16.5	2.0	2.5		4.5	3.5	2.0	1.5
Southern Africa	23.0	25.0	15.0						
Western Africa	40.4	9.8	4.4	1.0		3.0	1.0		
Europe									
Eastern Europe	30.1	21.8	7.5	4.7	1.4	6.2	3.6	10.0	14.6
Northern Europe	23.8	30.6	10.0	2.0		13.0	7.0	8.0	
Southern Europe	36.9	17.0	10.6						
Western Europe	24.2	27.5	11.0						
Oceania									
Australia and New Zealand	36.0	30.0	24.0						
Rest of Oceania	67.5	6.0	2.5						
America									
North America	33.9	23.2	6.2	3.9	1.4	8.5	4.6	6.5	9.8
Central America	43.8	13.7	13.5	2.6	1.8	6.7	2.6	3.7	12.3
South America	44.9	17.1	4.7	2.6	0.7	10.8	2.9	3.3	13.0
Caribbean	46.9	17.0	2.4	5.1	1.9	9.9	5.0	5.7	3.5

Africa and northern and western Europe, where food waste is, respectively, 2%, 3.3%, and 6.8% below the paper/cardboard category.

Construction and Demolition

C&D wastes are generated during new construction, renovation, and demolition of buildings, roads, and bridges. The typical composition differs significantly from MSW, as it is mostly building materials, such as concrete, wood, asphalt (from roads and roofing shingles), metals, and bricks. Owing to the collection infrastructure of C&D, waste can easily be transported to specially designed landfills because it consists of approximately 60% to 80% concrete and wood mixture (7).

Electronic Waste

Electronic wastes are generated through consumer products, such as computers, cellular telephones, and televisions. The electronic devices can contain up to 60 different elements, many of which are valuable, such as precious and special metals (e.g., gold, silver, platinum, and palladium), and some of which are hazardous (e.g., cadmium and lead). The printed circuit boards are

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composed primarily of plastic; however, they are impregnated with fire retardants that contain bromine, thus making them problematic.

Medical

US hospitals generate 6,600 tons of waste each day, and that number continues to grow with an aging and increasingly affluent population, greater accessibility to medical treatment, and an increase in the use of disposable products. Medical facilities generally use one of two methods or a combination thereof to treat their medical waste: incineration or autoclave sterilization followed by landfill.

Approximately 2–3% of medical waste must be incinerated owing to regulatory requirements and waste composition (6). However, anecdotal evidence shows that as much as 20–30% of all medical waste is treated by incineration. Most of the remaining waste is autoclaved and then landfilled. Autoclave sterilization is a process in which medical waste is exposed to steam under pressure for a specified period of time. The specified conditions have been established by testing protocols to achieve a desired level of sterilization to render the waste noninfectious before it is sent to a landfill. Autoclave sterilization typically offers a lower-cost waste treatment solution and may have environmental benefits, particularly if treated medical waste can be reused or recycled after sterilization. Incineration, performed in what are called hospital/medical/infectious waste incinerators, is a process where medical waste is combusted at high temperatures, yielding ash and combustion gases. The resulting ash is then sent to a landfill unless it is deemed hazardous owing to content such as heavy metals, at which point it must be disposed of as hazardous waste.

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HIERARCHY

Understanding the history, generation rates, and categories of solid waste provides a solid underpinning to propose practical management solutions. The current accepted best practice to manage solid wastes is embodied in **Figure 5**, the waste management hierarchy. This hierarchy has been developed based on minimizing environmental impacts of waste management procedures. The top of the pyramid indicates the best option with regard to minimal environmental impact. Seen in **Figure 5**, the top two tiers focus on avoiding waste disposal by reducing by-product or waste generation and reusing or repurposing materials, followed by recycling.

Once reduction, reuse, and recycling have been completed, the remaining waste must be disposed of. Therefore, the hierarchy can be viewed as reduction and disposal. **Figure 6** discriminates between the many disposal options of MSW, with preference given to methods that extract value from the potential energy and materials.

Composting

Composting is considered one of the superior options because the product can be used as soil conditioner/fertilizer. This has a beneficial effect on the overall environmental impact of a process, because the production of chemical fertilizers consumes chemicals and energy. For example, one metric ton (1,000 kg) of wet yard waste would yield a fertilizer with a 0.7-0.2-0.3 nitrogen-phosphorous-potassium (NPK) number, which is 51 times less effective on a nutrient-mass basis than a metric ton of synthetic fertilizer (4). Compost has other benefits, including increased soil organic matter and water-holding capacity and reduced pesticide requirements (9). However, composting works only for source-separated organics; otherwise, the contamination that results typically renders the product unusable. Importantly, if composting is done, anaerobic composting is preferable, because it produces a methane gas that can be captured and converted to heat or

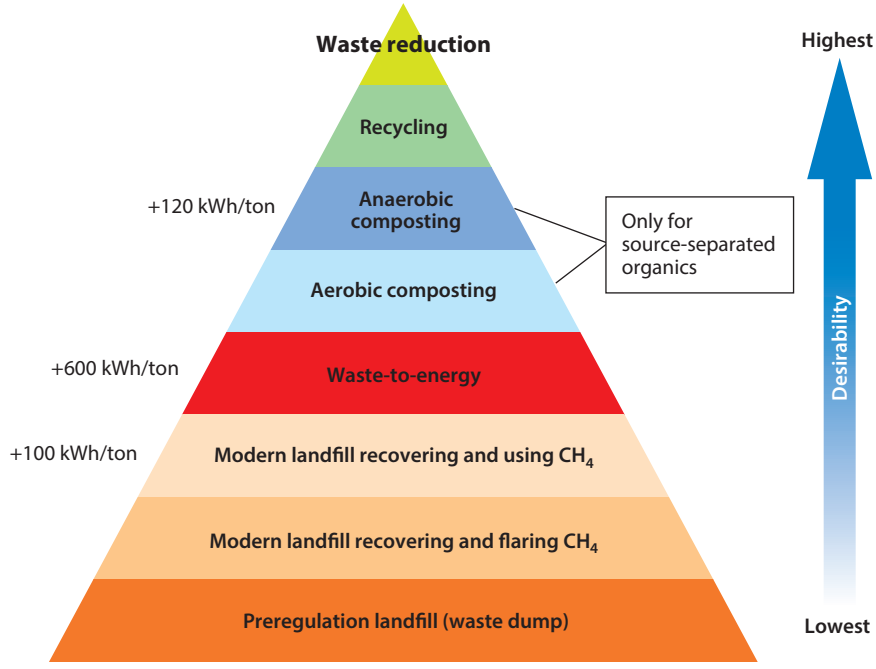

Figure 5

Waste management hierarchy (8).

electricity. If anaerobic composting is not possible, aerobic composting is the next best option, because it releases carbon dioxide, which has a significantly lower greenhouse gas impact compared to methane.

Thermal Conversion

Wastes that cannot be sufficiently separated and noncontaminated should then be processed via thermal conversion to extract the energy from the organics and recover the metals, typically referred to as waste-to-energy (WTE) or energy-from-waste systems. After reuse and recycle, only two methods can manage waste at the rate at which it is generated: burying MSW in landfills or thermally converting it in specially designed chambers at high temperatures. The heat generated by combustion or gasification is transferred to steam that can flow through a turbine to generate electricity, thus the WTE reference. This recycles the energy and the metals contained in the MSW, and most of the remaining ash by-product can be used beneficially for maintenance of landfills (in the United States) or for road and other construction purposes (in the European Union and Japan). WTE reduces the volume of MSW by 90%; if the remaining ash is reused, this is a nearly zero-waste solution. Importantly, WTE differs from incineration because of the energy-generation component.

The WTE industry worldwide has demonstrated safe, reliable use of combustion systems, as well as continually improving and developing new technologies, such as gasification, pyrolysis, and plasma processes, to produce myriad products from postrecycle waste streams. These range from grate combustion systems that produce heat and electricity to gasification processes that produce a synthesis gas (carbon monoxide and hydrogen), the building block to make liquid fuels–to–compact plasma systems that can do both. For example, Michigan currently has three

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combustion facilities (Detroit, Grand Rapids, and Jackson) processing 1,505,238 tons of MSW and producing 785,772 MWh of electricity and 483,727 tons of steam annually (10). This amounts to approximately 8% of the total MSW generated in Michigan, supplying nearly 1% of the electricity demand.

Currently, gasification facilities are being developed for MSW conversion, many of which are in the demonstration phase. Numerous summary reports and book chapters provide a wealth of information on gasification technologies that have been field tested as well as those that are still in development (11, 12). The typical size of gasification facilities targets 100 tons per day, nearly an order of magnitude smaller than combustion facilities. Recently, Covanta Energy announced the development of a gasification process called CLEERGAS (Covanta Low Emissions Energy Recovery Gasification). It is an atmospheric pressure, modified moving grate air gasifier that consists of partial combustion and gasification of as-received MSW and full combustion of the generated syngas in an adjoining combustion chamber. The unit processes approximately 350 tons of MSW per day, making it the largest gasifier system currently in operation.

Different thermal treatment technologies are being developed constantly, with new adaptations being tested and demonstrated at a very rapid pace. This review cannot cover the numerous systems that have been developed, tested, modified, and redeployed over the years; therefore, it is incumbent on the reader to stay current, as this is one of the most dynamic developing technology areas. The International Solid Waste Association, Earth Engineering Center of Columbia University, and City College of New York and journals such as *Waste Management World* and *Waste Management Research* are excellent sources for peer-reviewed, unbiased, quantitative information on gasification developments.

Although the field is quite vibrant, the thermal-conversion capacity of MSW is dominated by conventional combustion systems. **Figure 6** shows a summary of global operating systems in which the y-axis is on a log scale and the x-axis displays the different categories of thermal conversion processes. The categories are separated primarily by the operating temperature range or the range of oxidant (such as air or oxygen) used in the process. Therefore, combustion is the thermal breakdown of the wastes using excess oxidant (or air) compared with stoichiometric requirements and typically maintains an operating temperature between 1,200°C and 1,800°C. Gasification is the thermal breakdown of waste under oxygen-deficient conditions compared with stoichiometric requirements. This creates a gaseous product stream that contains mainly carbon monoxide and hydrogen or a synthesis gas and generally operates between 700°C and 1,000°C. Plasma gasification

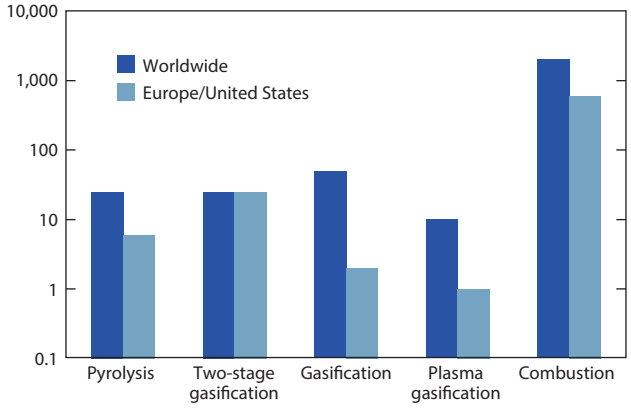

Figure 6

Comparison of thermal conversion systems (13).

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processes waste through a very-high-intensity electron arc, leading to temperatures greater than 2,000°C. Pyrolysis is the thermal breakdown of waste in the complete absence of oxidant (or air) to produce char, pyrolysis oil, and synthesis.

Figure 6 clearly shows the dominance of combustion systems, by nearly two orders of magnitude. The primary reason for this dominance is the use of excess oxidant from air and the production of fully oxidized gases, carbon dioxide, and water. In comparison, gasification systems strive to control the oxidation process by stopping the reactions at the partially oxidized gases of carbon monoxide and hydrogen. As discussed above, MSW is a highly heterogeneous mixture; therefore, the stoichiometric requirements to yield a synthesis gas change continuously. But a combustion system can be flooded with oxidant to fully oxidize the MSW, with the only drawback being a high volumetric flow of product gases that must be cleaned in air pollution–control systems.

Other than the throughput scale and the amount of oxidant used, the thermal conversion systems are similar in many ways. They all have a central hot box to break down the MSW into a product gas that enables the extraction of heat for power generation or transfer of heat for thermal use processes. The product gases must be cleaned, even the synthesis gas that is targeted for capture and possible usage, and they all produce some amount of emissions, albeit well below regulatory limits. **Figure 7** provides some emissions data for selected thermal conversion systems that have operated for a sufficient duration to enable analysis.

Because gasification, pyrolysis, and plasma technologies are still in development, the reporting of emissions data is difficult and many times not completely verified by independent assessment. **Figure 7** presents concentrations of selected emissions for commercial operations that convert MSW using thermal processes. Two important observations can be made from the data. One is that, as previously stated, all thermal conversion systems produce emissions. Second, for the categories shown, modern waste-to-energy combustion operations produce the lowest amount of emissions. Some of the data are provided by process suppliers, making them particularly significant for this comparison.

It should be stressed that combustion technology has advanced significantly with the implementation of the Clean Air Act (14), which has dramatically reduced all emissions. The EPA concluded that WTE now produces electricity with a lower environmental impact than almost any other source (15). Furthermore, according to the EPA and Intergovernmental Panel on

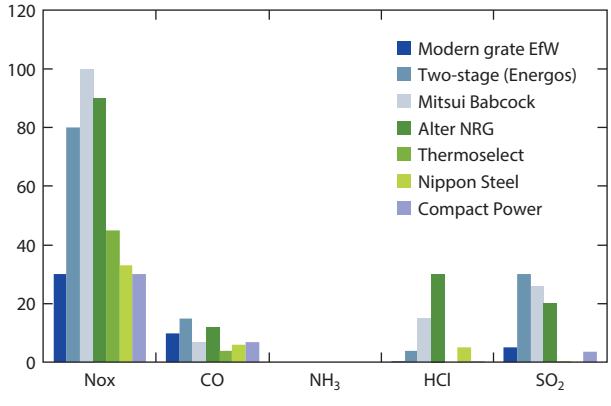

Figure 7

Emissions data for selected thermal conversion systems ranging from gasification to combustion (13). Abbreviation: EfW, energy from waste.

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Climate Change (IPCC) protocols, combustion of the biogenic fraction of MSW (approximately 65% of the carbon in MSW) does not result in additional greenhouse gas emissions.

Another beneficial effect of modern MSW combustion with energy recovery is material recovery. Using magnetic separators, the US WTE industry recovers and recycles more than 770,000 tons of ferrous scrap metal annually (16). At some facilities, nonferrous metals are also removed through the use of eddy current separators, which cause these materials to jump out of the remaining ash and into a recovery area. Metal processors sort this mixed metal into brass, aluminum, copper, and other base metals (17). The remaining ash can be used in the construction and maintenance of landfills and as an aggregate in construction (18, 19).

Landfill

Further down the waste hierarchy is management of waste by disposal in landfills. According to the US EPA, in 2011, 250 million tons of MSW were generated, with more than half (134.3 million tons) going to landfill. This is compared with approximately 35% of MSW being recycled and only 12% being disposed of using energy recovery technology. And it contrasts with the European Union, where 10 countries have less than 50% landfilling and others (Belgium, Denmark, Austria, Sweden, Germany, and the Netherlands) have achieved 5% or less landfilling. Encouragingly, nearly all EU member states have reduced their waste sent to landfill. **Figure 8** shows the progress made over a 10-year period in EU countries increasing their waste-diversion rates from landfills, with most waste going to recycling or WTE processing.

The extensive use of landfills in the United States is driven primarily by cost. The average cost to landfill MSW is approximately $30 per ton and is mainly a result of the abundance of unpopulated land areas in comparison to the European Union, where the fee is as high as €150 per ton in Sweden and nearly €140 per ton in Germany.

Figure 9 shows the distribution of landfills in the United States by region. The South and West contain nearly 73% of the landfills in the United States, whereas only 7% are located in the Northeast, the most populous portion of the country.

The least environmentally impactful method of landfilling is to dispose of MSW in modern landfills that have the capacity to capture and use the gases produced and completely contain and treat the leachate. Landfills decompose the MSW in a predominantly anaerobic environment, producing a usable gas consisting of approximately 50% methane and 50% carbon dioxide and having an energy value of approximately 500 Btu per cubic foot. Landfills are the largest human-generated source of methane emissions in the United States, and use of the gas provides multiple benefits. Because methane is both potent and short-lived, reducing methane emissions from MSW landfills is one of the best ways to achieve a near-term beneficial impact in mitigating global climate change. Currently, approximately 621 landfill gas–to-energy projects provide enough power for nearly 21,000 households, and another 400 projects could be developed. However, the US EPA estimates an order of magnitude more (530 additional) could turn their gas into energy, producing enough electricity to power 692,000 homes; thus, a large potential exists. Finally, there are efforts to convert landfill gas to liquid fuels to give a more widespread usage and distribution. The Hinkely Center for Solid and Hazardous Waste Management at the University of Florida has published a report (20) on the development of a tri-reforming process that includes CO_2 reforming, steam reforming, and partial oxidation of landfill gas. The product is a synthesis gas that is suitable for liquid fuel production using a Fischer-Tropsch method (20). Kohn et al. (21, 22) have also investigated the use of landfill gas reforming via autothermal operation, which introduces a limited amount of oxygen or air to provide the necessary heat energy to drive the heat-consuming reforming reactions. Additionally, impurities in landfill gas have been investigated to determine the

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Figure 8

Spiral graph of EU countries' landfill percentage of municipal solid waste for 2001 and 2010 (20).

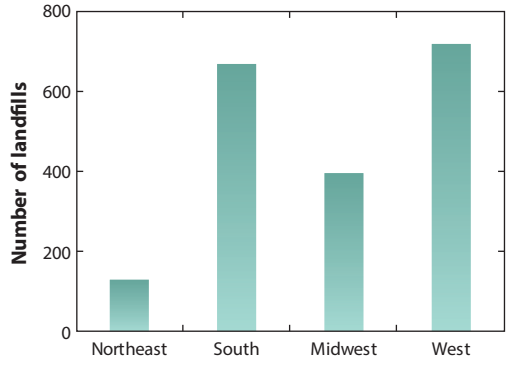

Figure 9

Distribution and number of landfills in the United States (21).

impacts on performance during the autothermal reforming of landfill gas. As better understanding and synthesis of new catalytic materials develop, more landfill gases are expected to be converted to liquid fuels, primarily for use in the transportation sector, which will encourage still more capture of landfill gas.

Although modern landfills are desired, not all landfills are the same. The modern sanitary landfills just discussed require a serious investment and effort to protect surface and ground water and to collect landfill gas and use it to generate energy, which results in an estimated disposal fee of nearly $100 per ton. However, numerous legacy landfills have rudimentary gas collection systems in place and do not have the desired energy content or high enough volumetric flow to justify energy recovery. These landfills are placed below the modern landfills on the hierarchy but are not the lowest because there is an attempt to reduce the environmental burden by converting the methane produced to carbon dioxide. Therefore, although there is no energy recovery, they reduce the release of methane into the atmosphere and the risk of a fire starting at the landfill.

On the lowest rung on the waste management hierarchy are waste dumps or unregulated landfills that have no provisions for gas capture or leachate treatment. Many times these waste sites are located in undeveloped regions of the world where economic output and standard of living are low. But even here a considerable amount of recycle occurs through scavengers that pick through the waste to recover anything of value. For example, one study looked at scavenging in Lagos, Nigeria, and the impact on the social and economic status of scavengers. The daily mean income of scavengers was 480.80 Naira. Although the scavengers were aware they were exposed to significant hazards, it was usually the only source of income. Interestingly, the study concluded that nearly 1,243 people were involved at one site, leading to a decent level of employment; thus, the outright banning of scavenging without rehabilitating the scavengers would constitute a social, economic, and security threat to the community (23).

CONCLUSIONS AND FUTURE TRENDS

The subject of waste management is an extensive, open-ended, changing one that is difficult to summarize even in an extensive review such as this. An attempt was made here to introduce some of the newest information and technical developments within waste management and address the increased attention given to conversion of wastes for energy or use of materials from the waste stream. There is an equally extensive body of knowledge on regulations, policy, and legal aspects of waste management that was not covered, as it would have led to a superficial review of too many subjects. Overall, there is a concerted movement in the waste field to extract and realize value from the different streams, especially the MSW streams. Concurrent with the increased awareness of value in wastes is the increased awareness of environmental impact on wastes. The development of the expanded hierarchy discussed here should provide a clear template for those interested in developing or understanding waste management solutions with the lowest environmental impact. It is imperative that the interested reader conduct an up-to-date follow-up to this review, as developments in the field are changing rapidly. Pertinent references were given throughout this article to provide the reader with a starting point for finding a wealth of information. General information can be found in some of the many magazines, newspapers, and internet sites; however, some recommended places to begin research are given below.

To the author's best knowledge, the following sites are considered some of the best for finding unbiased, peer-reviewed reports and literature on the subject of MSW management and conversion. A few excellent internet sites are The Earth Engineering Center at Columbia University and City College of New York (**www.seas.columbia.edu/earth/** & **www.eec-ccny.org/**), the Hinkely Center for Solid and Hazardous Waste (**www.hinkleycenter.org**), the International

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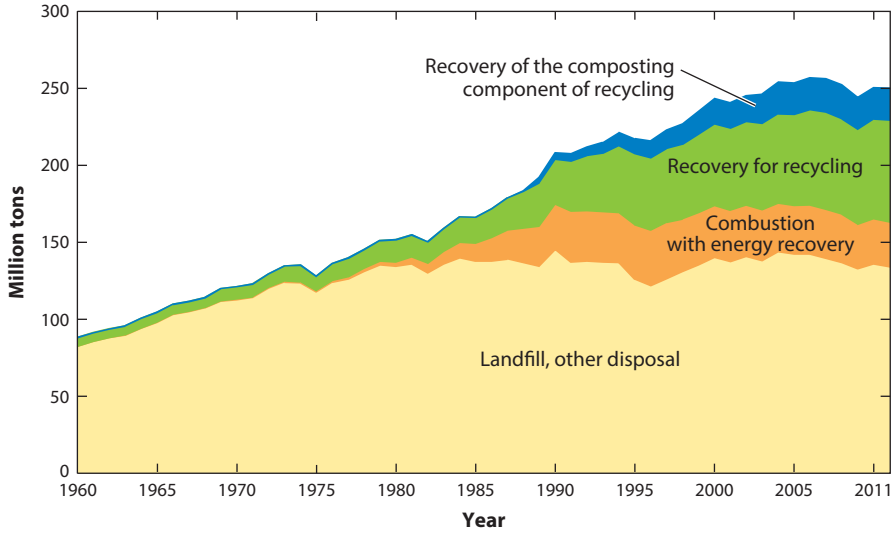

Figure 10

Municipal solid waste management from 1960 to 2012 (21).

Solid Waste Association (**www.iswa.org**), and the American Society of Mechanical Engineers Materials and Energy Recovery Division (**www.asme.org**). Many journals have waste management articles, but the following journals have been found to be most useful in terms of targeting technical developments in waste valorization: *Waste and Biomass Valorization* (Springer), *Waste Management & Research* (International Solid Waste Association), and *Waste Management* (Elsevier). Finally, two excellent conference series that provide up-to-date, technical, peer-reviewed presentations are the WasteEng Conference Series and the International Thermal Treatment Technology (IT3) Conference.

Future trends appear to point toward waste streams, especially MSW, being viewed as valuable. In addition, as source separation increases owing to public concern and awareness of the environment, waste streams will become more homogeneous. **Figure 10** clearly shows that although the amount of waste generation has increased, the amount of landfilling during that same time has remained constant.

Particularly staring around 1975, we saw the onset of combustion with energy recovery (i.e., WTE), and in 1985, recovery of the composting component of recycling began to come online. All this occurred while recovery for recycling increased, indicating that these recovery technologies, from composting to combustion, are completely compatible with recycling efforts and have collectively allowed the amount of landfilling to remain constant, at nearly 125 million tons, while waste generation has increased nearly 65% from 1975 to 2012.

DISCLOSURE STATEMENT

The author is a member of the American Society of Mechanical Engineers Material and Energy Recovery Division and has held the position of Division Chairman from 2013–2014. In addition, the author has several patents pertaining to gasification technology.

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Contents

Plans and Detours
James Wei 1

Simulating the Flow of Entangled Polymers
Yuichi Masubuchi 11

Modeling Chemoresponsive Polymer Gels
Olga Kuksenok, Debabrata Deb, Pratyush Dayal, and Anna C. Balazs 35

Atmospheric Emissions and Air Quality Impacts from Natural Gas Production and Use
David T. Allen 55

Manipulating Crystallization with Molecular Additives
Alexander G. Shtukenberg, Stephanie S. Lee, Bart Kahr, and Michael D. Ward 77

Advances in Mixed-Integer Programming Methods for Chemical Production Scheduling
Sara Velez and Christos T. Maravelias 97

Population Balance Modeling: Current Status and Future Prospects
Doraiswami Ramkrishna and Meenesh R. Singh 123

Energy Supply Chain Optimization of Hybrid Feedstock Processes: A Review
Josephine A. Elia and Christodoulos A. Floudas 147

Dynamics of Colloidal Glasses and Gels
Yogesh M. Joshi 181

Rheology of Non-Brownian Suspensions
Morton M. Denn and Jeffrey F. Morris 203

Factors Affecting the Rheology and Processability of Highly Filled Suspensions
Dilhan M. Kalyon and Seda Aktaş 229

Continuous-Flow Differential Mobility Analysis of Nanoparticles and Biomolecules
Richard C. Flagan 255

From Stealthy Polymersomes and Filomicelles to "Self" Peptide-Nanoparticles for Cancer Therapy
Núria Sancho Oltra, Praful Nair, and Dennis E. Discher 281

Carbon Capture Simulation Initiative: A Case Study in Multiscale Modeling and New Challenges
David C. Miller, Madhava Syamlal, David S. Mebane, Curt Storlie, Debangsu Bhattacharyya, Nikolaos V. Sahinidis, Deb Agarwal, Charles Tong, Stephen E. Zitney, Avik Sarkar, Xin Sun, Sankaran Sundaresan, Emily Ryan, Dave Engel, and Crystal Dale 301

Downhole Fluid Analysis and Asphaltene Science for Petroleum Reservoir Evaluation
Oliver C. Mullins, Andrew E. Pomerantz, Julian Y. Zuo, and Chengli Dong 325

Biocatalysts for Natural Product Biosynthesis
Nidhi Tibrewal and Yi Tang 347

Entangled Polymer Dynamics in Equilibrium and Flow Modeled Through Slip Links
Jay D. Schieber and Marat Andreev 367

Progress and Challenges in Control of Chemical Processes
Jay H. Lee and Jong Min Lee 383

Force-Field Parameters from the SAFT-γ Equation of State for Use in Coarse-Grained Molecular Simulations
Erich A. Müller and George Jackson 405

Electrochemical Energy Engineering: A New Frontier of Chemical Engineering Innovation
Shuang Gu, Bingjun Xu, and Yushan Yan 429

A New Toolbox for Assessing Single Cells
Konstantinos Tsioris, Alexis J. Torres, Thomas B. Douce, and J. Christopher Love 455

Advancing Adsorption and Membrane Separation Processes for the Gigaton Carbon Capture Challenge
Jennifer Wilcox, Reza Haghpanah, Erik C. Rupp, Jiajun He, and Kyoungjin Lee 479

Toward the Directed Self-Assembly of Engineered Tissues
Victor D. Varner and Celeste M. Nelson 507

Ionic Liquids in Pharmaceutical Applications
I.M. Marrucho, L.C. Branco, and L.P.N. Rebelo 527

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Perspectives on Sustainable Waste Management
Marco J. Castaldi 547

Experimental and Theoretical Methods in Kinetic Studies of Heterogeneously Catalyzed Reactions
Marie-Françoise Reyniers and Guy B. Marin 563

Indexes

Cumulative Index of Contributing Authors, Volumes 1–5 595

Cumulative Index of Article Titles, Volumes 1–5 598

Errata

An online log of corrections to *Annual Review of Chemical and Biomolecular Engineering* articles may be found at http://www.annualreviews.org/errata/chembioeng

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