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# Solid Waste Treatment as a High-Priority and Low-Cost Alternative for Greenhouse Gas Mitigation

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ABSTRACT / The increased concern about environmental problems caused by inadequate waste management, as well as the concern about global warming, promotes actions toward a sustainable management of the organic fraction of the waste. Landfills, the most common means to dispose of municipal solid waste (MSW), lead to the conversion of the organic waste to biogas, containing about 50% methane, a very active greenhouse gas (GHG). One unit of methane has a global warming potential of 21 computed for a 100-year horizon or 56 computed for 20 years. The waste sector in Israel contributes 13% of total greenhouse gases (GHG) emissions for a time horizon of 100 years (for a time horizon of 20 years, the waste sector contribution equals to more than 25% of total GHG emissions). The ultimate goal is to minimize the amount of methane ($CH_4$) by converting it to $CO_2$. This can be achieved by physicochemical means (e.g., landfill gas flare, incineration) or by biological processes (e.g., composting, anaerobic digestion). Since the waste in Israel has a high organic material content, it was found that the most cost-effective means to treat the degradable organic components is by aerobic composting (investment of less than US$ 10 to reduce emission of one ton $CO_2$ equivalent per year). Another benefit of this technology is the ability to implement it within a short period. The suggested approach, which should be implemented especially in developing countries, could reduce a significant amount of GHG at relatively low cost and short time. The development of a national policy for proper waste treatment can be a significant means to abate GHG emissions in the short term, enabling a gain in time to develop other means for the long run. In addition, the use of $CO_2$ quotas will credit the waste sector and will promote profitable *proper* waste management.

The threatening global climate change calls for international efforts to reduce emissions of greenhouse gases (GHG), mostly $CO_2$, $CH_4$, and $N_2O$. The extent to which the emissions of different GHG contribute to the global warming are calculated in $CO_2$ equivalents ($CO_2$ eq.), using the global warming potential (GWP) of the different gases as proposed by the International Panel on Climatic Change (IPCC 1995, 1996). Since different GHG have different efficiencies in heat adsorption and different lifetimes in the atmosphere, the GWP for every gas depends on the chosen planned time horizon. The GWP of $CH_4$ for a time horizon of 20 years is 56 (compared with $CO_2$ over the same period of time) and 21 for 100 years. The Kyoto Protocol of 1997, signed by more than 60 countries (Morrissey and Justus 1999), calls for specific steps to be taken by the different parties involved. The developed countries (contributing about 80% of global GHG emissions) that have signed the protocol have committed to reduce $CO_2$ eq. by an average of 5.2% by 2008–2012 as compared with 1990 emissions. This commitment calls for a reduction plan in consultation with all target groups including, among others, the country's starting point and basic inventory (Bohringer and others 1998), time for implementation, time horizon of the anticipated effect, technologic feasibility, and costs. It was estimated (Weyant 1993) that reduction costs could go as high as 2.5% ± 1% of world GDP, a significant part of the world economy and a very significant expense for less developed nations. A global effort is devoted to the development of means to reduce GHG emissions.

The range of alternatives to mitigate GHG emissions is rather wide, yet several drawbacks should be noted. For example, the use of renewable energy sources demands research and development and high investments; this solution is anticipated to play a significant role in the long term. Changes and improvements in the industry and power plants demand technological

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changes as well as a supply of alternative fuels (e.g., natural gas). Changes in transportation and in energy demand in residential and commercial buildings are associated with social changes as well as massive investments. These examples demonstrate the urgent need for short- and medium-term solutions, as well as the need for cost-effective ones.

The waste sector in Israel contributes 13% of total $CO_2$ eq. emitted in Israel (Avnimelech 1999) for the 100-year time range. This significant contribution is due to the fact that most of the waste, containing a high percentage of degradable organic material, is being landfilled without any methane recovery. It is expected that changing the technology of waste treatment could lead to a substantial GHG reduction with relatively low marginal costs and within a short time. In addition, better waste management is associated with other environmental benefits, i.e., reduction of surface waterbody and groundwater contamination, preventing waste of land and resources, etc. The time gained by the changes in waste management practices could be devoted to the development of alternative innovative solutions. We believe that the principals demonstrated here are relevant worldwide and could be implemented in other countries as well.

## Role of Waste Sector in GHG Emissions Inventory

The total annual emissions of GHG in Israel, according to IPCC (1995) mass balance guidelines, are 62 million tons (Mt) $CO_2$ eq. (Koch and Dayan 1998). Of this, actual $CO_2$ emissions are 51 Mt/yr; $CH_4$ (methane) was estimated to contribute 8.9 Mt $CO_2$ eq./yr for the 100-year time horizon, where 7.8 Mt is due to solid waste and 200 kt are from wastewater treatment (the remaining contribution of $CH_4$ is related to the agricultural sector); $N_2O$ makes up 2 Mt $CO_2$ eq./yr.

MSW in Israel contains 72% (on weight basis) degradable organic material, including food waste, yard waste, disposable diapers, and paper products (IEB 1997). Most of the MSW in Israel is disposed of in landfills. Such values are typical for many other countries where fresh, unpacked organic food is common. Degradation of organic matter in landfills is an anaerobic process, leading to the generation of biogas (landfill gas, LFG) containing roughly 50%–60% methane ($CH_4$) and 40%–50% $CO_2$ (EPA 1989). Factors such as waste composition, physical factors (i.e., moisture content, pH, temperature) and waste disposal practices (i.e., waste compaction) are the most significant factors influencing methane generation in landfills.

The contribution of the waste sector, 7.8 Mt $CO_2$ eq. for the 100-year time horizon, comprises 13% of the total $CO_2$ eq. emitted in Israel. According to the IPCC guidelines, the GWP for methane is 21; nevertheless, using the GWP of 56 for the 20-year time horizon makes the waste sector a contributor of more than 25% of the emissions. This point is very important and will be discussed shortly.

It is reasonable to combine the contribution of MSW with that of sewage sludge, since the later could be treated using the same means as MSW. The annual contribution of wastewater treatment plants is equivalent annually to 200 Kt $CO_2$ eq. for a 100-year horizon factor, i.e., 0.5% of all GHG emissions. It should be noted that the potential addition of this sector could go as high as 1.2 Mt of $CO_2$ eq. The significant difference is due to the fact that not all 6 million inhabitants of Israel are connected to central sewage treatment plants and not all domestic wastewater and sludge is being treated.

Wastes could be treated by several means, such as landfilling, composting, incineration, anaerobic degradation, and recycling. A summary of the means and effects of different waste management alternatives that lead to GHG emissions mitigation is given in the appendix. Different waste management alternatives could lead to a significant decrease of GHG emissions. In order to reduce GHG emissions, the aim is to convert $CH_4$ to $CO_2$ (e.g., by incineration). It should be noted that some of the methods could be applied to the entire amount of the waste (incineration or landfilling) and in some methods only the organic part of the waste could be treated (e.g., composting, anaerobic digestion). In addition, each method has other benefits (e.g., crop yield increase due to compost use) and drawbacks (e.g., possible $N_2O$ emissions in incineration plants, presence of heavy metals and other impurities in the compost). Some of these benefits have direct influence on GHG emissions and they are stated, qualitatively, in Table A in the appendix. Full conversion of $CH_4$ to $CO_2$ will reduce the GHG emissions from the waste sector to 2.3 Mt, comprising only 4% of total emitted GHG, as compared to the present 13%.

## Economic Evaluation of GHG Emission Abatement and Alternatives Assessment

There is a need to assess the environmental, economic, and social aspects of the alternatives to manage waste in order to abate GHG. The assessment will not concentrate solely on the amount of $CO_2$ eq. mitigated, but also on local conditions such as availability of land, waste composition, feasibility of implementation of each alternative, direct and environmental costs etc.

Table 1. Investment cost estimates for GHG mitigation from MSW[a]

| Alternative | Size of typical plant (t/day) | Plants needed ($N$) | Investment per plant (US$$10^6$)[b] | Total investment (US$$10^6$) | Investment costs of reduction (US$/ton $CO_2$ eq.) | Annualized costs (15 yr) (US$/ton $CO_2$ eq.) |
|---|---|---|---|---|---|---|
| Landfilling + LFG flare 50% collection efficiency | 400 | 7 | 2[(1)] | 14 | 18 | 1.21 |
| Landfilling + LFG collection and energy recovery 50% efficiency | 400 | 7 | 5[(1)] | 35 | 45 | 3.02 |
| Incineration | 500 | 6 | 50[(2)] | 300 | 194 | 12.94 |
| Aerobic composting 90% efficiency | 250 | 12 | 1[(3)] | 12 | 9 | 0.58 |
| Anaerobic digestion | 500 | 6 | 10[(3)] | 60 | 39 | 2.59 |

[a]Calculated for a representative city (1.7 million inhabitants) producing 3000 tons MSW per day (1 Mt/yr) for 100 years; emission factor of 21. The plant sizes were chosen following different performance efficiencies. In each alternative, the total investment was calculated according to the number of plants needed to treat all waste produced.

[b]Sources: [(1)]EPA, 1997b; [(2)]Coopers & Lybrand, 1996; [(3)]commercial entrepreneurs engaged in waste management in Israel that asked specifically not to be identified.

(Ayalon and others 1999). The chosen integrated waste management should deliver both economic and environmental sustainability.

In order to appraise the abatement costs of GHG emissions, the investment cost of each alternative was evaluated. Operating and maintenance (O&M) costs were not included in this valuation because they are site specific, highly variable, and a function of factors such as salaries, transportation, insurance rates, taxes and prices obtained for recyclables or energy sales, etc. It should be noted that there is a rough correlation between investment costs and O&M costs. As a rule of thumb, O&M represent ca. 40% of the costs of landfilling (Glebs 1989) and 35%–40% of incineration cost (excluding revenues from energy sales).

Table 1 summarizes the investment costs for each alternative (given as US dollars of investment for a metropolitan region producing 1 Mt of waste per year). Investments required to abate 1 ton of $CO_2$ eq. were calculated using $CH_4$ multiplying factor of 21 for the time horizon of 100 years.

The investment to reduce one ton of $CO_2$ eq. by collecting and burning the LFG in landfills is rather low, less than US$ 20, and more than twice that for a system containing energy recovery (EPA 1997a,b). Yet, these systems can recover only 40%–90% of the emitted gas (White and others 1995). Incineration of MSW is the most effective technology, yet the investment is the highest. Another potential energy recovery system is anaerobic digestion (AD), producing both biogas and compost. Systems containing energy recovery devices are credited for selling energy. For example, selling electricity at $0.05/kWh will reduce the tipping fee (TF) at the gate of an incineration plant by $9.4/ton of waste (Enosh Consultants Ltd. 1996); at an AD plant by $3.5/ton (de Laclos and others 1997), and at a landfill that recovers energy from LFG by $1.6/ton (DOE 1993). The investment required to reduce a ton of $CO_2$ eq. by aerobic composting, using the windrow technology, is the lowest, but the efficiency of this method to reduce GHG emission is high. Therefore, the lowest cost alternative to mitigate GHG emissions from the waste sector in Israel is to construct composting plants. In this option, all organic waste will be processed, some of the materials (i.e., paper, plastics, etc.) will be recycled, and only the nonrecyclable waste that does not produce GHG will be landfilled. By adopting an integrated waste management approach, a reduction of 8%–9% of total GHG emissions could be achieved at reasonable costs.

As discussed before, the contribution of the waste sector to GHG emissions for the time horizon of 20 years is more than 25%. In order to assess the costs of GHG mitigation for a time horizon of 20 years, we have recalculated investment costs (presented in Table 1) using multiplying factor of 56 (Table 2).

It can be seen that the annualized abatement costs of $CO_2$ eq. emissions are reduced significantly, and in all waste management alternatives except incineration, they are US$1/ton $CO_2$ and under. This presentation

Table 2. Investment costs estimates for GHG mitigation from MSW[a]

| Alternative | Efficiency of $CH_4$ reduction (%) | Investment costs of reduction (US$/ton $CO_2$ eq.) | Annualized costs (15 yr) (US$/ton $CO_2$ eq.) |
|---|---|---|---|
| Landfilling with LFG flare | 50 | 6 | 0.41 |
| Landfilling with energy recovery | 50 | 16 | 1.03 |
| Incineration | 100 | 67 | 4.43 |
| Aerobic composting | 90 | 3 | 0.21 |
| Anaerobic digestion | 100 | 13 | 0.9 |

[a]Calculated for a representative city producing 3000 tons MSW per day (1 million tons per year) for 20 years; emission factor of 56.

emphasizes the fact that proper waste treatment can be the most significant means to abate GHG emissions in the short term, enabling one 'buy time' and develop other means for the long run.

## External Credits Related to GHG Emission Abatement

As discussed above, some of the alternatives of waste management can produce energy and be credited for selling it. In addition, an external credit should be given to these plants since they are replacing $CO_2$ emissions from conventional power plants. In the present analysis these plants are not credited for it. Our calculations show (Table 1) that the annualized costs of reducing 1 ton $CO_2$ eq. from landfills by collecting and recovering energy from methane are US$3, similar to the US$2.75–5.5/ton of $CO_2$ abated (Augenstein 1997). The annualized costs needed to reduce 1 ton of $CO_2$ eq. by a LFG flare or aerobic or anaerobic composting plants are even lower.

A world market for trading $CO_2$ emission permits among countries is presently proposed. The details of a potential trading system as well as the price of these permits have yet to be negotiated at an international level (Bertram 1996, Cansier and Krumm 1997). The anticipated advantages of this mechanism over other approaches are its potential to minimize the costs of achieving a given level of GHG abatement and its certainty in meeting emission targets. A simulation model to assess the influence of carbon dioxide emission permit prices on welfare costs of several European countries was based on a tradable carbon permit price of US$ 8.4–13.13/ton (for the year 2000) up to US$182–235 (for the year 2020) (Bohringer and others 1998). It can be seen clearly that this mechanism will encourage the waste sector that will be credited by the value of the GHG emission reduced. This mechanism will encourage investments in alternatives such as flaring LFG or composting, regardless of any political decision. Furthermore, producing energy from waste not only reduces the need to produce energy from conventional resources, it can also reduce the need to buy carbon permits and even create available credits for sale. For example, the avoided emissions of $CO_2$ by energy recovery from LFG, anaerobic digestion, and incineration are 23.5, 50.1 and 137.6 kg $CO_2$ eq./ton of waste, respectively (Table A in the appendix). By using a value of US$100/ton carbon (i.e., US$27.5/ton $CO_2$ eq.), the benefits from the above alternatives are US$ 0.64$, US$ 1.37, and US$ 3.78/ton of waste, respectively, or 0.8 cents/kWh in each of these alternatives.

## Discussion and Conclusions

Increased concerns about global warming, as well as awarenes of the environmental problems caused by inadequate waste management in developing countries, provide an important additional rational for a sustainable management of the organic fraction of the waste. This international concern is the major driving force in recent legislation in Europe to reduce the amount of biodegradable organic fraction of waste entering landfills (EU 1996, Petersen 1997), with Germany leading (Stegmann 1997), as well as in several states in the United States (Friesen 1999).

The investments required to abate GHG emissions from other sectors (e.g., switch from coal to natural gas in power stations, clean and renewable energy sources, improved energy production and industrial processes, improvements in transportation) are very high and a long time period is needed for their implementation. Reducing GHG emission by proper treatment of waste is cheaper than the above-mentioned alternatives, and it is even cheaper than the price of carbon permits (if an emission trading mechanism is available). Therefore, on a national basis, there is a clear incentive to invest in these infrastructures and even possibly create available permits for international trade. One can visualize the financing of waste treatment facilities by the industry or the industrial countries, based upon transfer of emission permits. Expeditious reduction in the waste sector is needed for an immediate transition period as an immediate solution enabling the development of long-range environmental changes in other sectors. The major effects of these steps are aimed at a short to medium transition period. This fact justifies the evaluation based on a 20-year time horizon (instead of the conservative time range of 100 years).

It was found that by comparing the alternatives within the waste sector, the most cost-effective alternative to reduce GHG emissions from MSW is to compost it aerobically. The composting option does not require high investments, produces a product that can be readily utilized by the agricultural sector, and seems to be an available interim solution to mitigate GHG emission by most countries. In addition, the composting option carries a positive credit for the production of compost, an efficient soil amendment, especially in arid, semiarid, and other impoverished soils. A consistent 10%–20% yield increase over and above the yield obtained with normal fertilizer additions was found following the addition of compost (Avnimelech 1995). It should be emphasized that quality compost that is to be used freely for gardening and sustainable farming has to be free of glass, heavy metals, and other hazardous materials. In order to get clean compost, source separation is required. This requires a suitable infrastructure and the use of two different containers at home and at the curb, followed by massive public education. It should be emphasized, however, that stricter regulations regarding open composting plants and demand for closed ones might change the overall picture and call for further studies. The approach presented here calls for expanding these efforts, especially in the developing countries, characterized by a high organic matter fraction in the MSW. Assuming that changes in the waste sector are publicly and politically accepted and technically feasible, the time needed for implementation is short and the effect is significant.

Judging from the Israeli case study, it may be assumed that a concentrated effort in this direction may reduce national GHG emissions by about 10%. This seems to be an achievable and affordable short and medium range alternative that deserves concentrated national and international effort. The dominant effect of MSW on GHG emissions and global climate change calls for intensive scientific, economic, and political efforts in order to minimize the emissions from this sector. The benefits from proper waste management will not only contribute significantly to the reduction of GHG emissions, but it will play a significant role in other environmental areas, such as sustainable management of the waste as well as resource conservation. Reducing GHG emission by proper waste management is not the only means, but is the most available and feasible one. Further technological and scientific efforts should be devoted to the development of other sustainable, long-term solutions.

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## Appendix: Summary of Means and Effects of Different Waste Management Alternatives Leading to GHG Emissions Mitigation

Known and commercially available methods for waste management are listed in Table A. Indirect effects are listed in addition to the direct effects. The direct abatement is achieved through the conversion of methane to $CO_2$. Indirect effects, positive or negative, are, for example, reducing electricity production in conventional power plants, increasing carbon sequestration in the soil or producing GHG by hauling waste for long distances. Some of the indirect, external effects were quantified (e.g., avoided emissions from conventional energy sources); others are given only in qualitative terms (e.g., carbon sequestration).

The present situation in Israel, where about 90% of the waste generated in 1996 was landfilled, without any extraction of LFG, serves as the reference point. Extraction and burning of LFG reduces the emissions of methane, yet recovery rate efficiencies vary from 40% to 90% (White and others 1995, Meadows and others 1997). In our analysis we assumed 50% LFG collection efficiency. When LFG is used for energy production, $CO_2$ emission is further reduced indirectly due to the production of electricity and replacement of the equivalent $CO_2$ emissions from conventional power plants. It was estimated (DOE 1993) that 80 kWh could be produced from 1 ton of MSW, equivalent to 23.5 kg $CO_2$ emitted from a conventional power plant. It was estimated (Meadows and others 1997) that by the year 2025, only 40%–50% of LFG will be collected in North America, Western Europe, and Oceania and just 10% in developing countries. These figures emphasize the need to implement other waste management technologies in order to achieve a more significant reduction in GHG mitigation.

A very effective means to reduce GHG emissions is to incinerate the waste. This process is assumed to convert all carbon to $CO_2$ and thus to reduce GHG emissions to only 4% of Israel's national emissions inventory. In cases where energy is recovered, it was assumed (Enosh Consultants Ltd 1996) that 1 ton of Israeli waste will produce 468 kWh and thus the process is further credited by 138 kg $CO_2$ for avoiding electricity production in conventional power plants.

The third group of options is to compost the waste, either by using aerobic (Epstein 1997, Haug 1993) or anaerobic process and subsequent burning of the biogas, generally, with energy recovery (Speece 1996). For both technologies, about half the organic carbon remains in the compost and is slowly released to the soil (Epstein 1997). Part of the carbon is sequestered in the soil for a long time period. Compost is used in farmland to raise soil fertility and crop yield. In a series of farm-scale experiments, conducted in several areas in Israel, it was shown that expected yield increase is 10%–20% for an application of about 10 tons of compost per hectare (Avnimelech 1995). These figures are equivalent to an increased carbon fixation on the order of 2 tons $CO_2$/ton dry compost.

Finally, recycling of industrial raw materials (especially paper) and/or waste minimization, obviously lead to direct and indirect reduction of GHG emissions. These options should be dealt with specifically according to each component of the waste and its relative contribution to GHG mitigation.

Table A. GHG emissions mitigation means by waste management: quantities calculated for Israel, 1996

| Alternative | GHG emissions, considerations and assumptions (+ = increase ,− = decrease) | $CO_2$ eq. reduction (kt yr) [a] |
|---|---|---|
| Landfilling | | |
| Without LFG treatment | MSW sector contributes 13% of total GHG emissions in Israel, 1996 using $CH_4$ factor of 21 (100 yr horizon)<br>− Credit for long term carbon storage in landfills<br>+ Transport emissions to landfill | baseline no mitigation of $CH_4$ |
| With LFG flare (assuming 50% efficiency) | − $CH_4$ is converted to $CO_2$<br>− Credit for long-term carbon storage in landfills<br>+ Transportation emissions to landfill | 2,782 (7,418) |
| With LFG energy recovery (assuming 50% efficiency) | − $CH_4$ conversion to $CO_2$<br>− Avoided emissions from conventional energy sources<br>− Credit for long term carbon storage in landfills<br>+ Transportation emissions to landfill | 2,782 (7,418)<br>94 |
| Incineration | | |
| Without energy recovery | − $CH_4$ conversion to $CO_2$, total emissions comprise only 4% of total GHG emissions in Israel, 1997<br>+ $N_2O$ emissions<br>+ Transportation emissions to incineration plant | 5,564 (14,837) |
| With energy recovery | − $CH_4$ conversion to $CO_2$<br>− Avoided emissions from conventional energy sources<br>+ $N_20$ emissions<br>+ Transportation emissions to incineration plant | 5,564 (14,837)<br>548 |
| Aerobic composting (assuming 90% efficiency) | − $CH_4$ conversion to $CO_2$<br>− Increase in soil carbon storage<br>− Increase in crop yield and carbon uptake (1 ton dry matter = 2 ton $CO_2$)<br>+ Transportation emissions to composting plant<br>+ Compost machinery emissions | 5,000 (13,333) |
| Anaerobic digestion (assuming 100% efficiency) | − $CH_4$ emitted burnt to $CO_2$<br>− Avoided emission from conventional energy sources<br>− Increase in crop yield and carbon uptake (1 ton dry matter = 2 ton $CO_2$)<br>+ Transportation emissions to AD plant | 5,564 (14,837)<br>200.4 |
| Recycling | − *In some products*: Decrease in energy consumption due to lower energy requirements (compared to manufacture from virgin inputs)<br>− Paper recycling prevent logging and increases forest carbon sequestration<br>+ Transportation emissions- to recycling plant | *Need specific information for each component* |
| Source reduction | − Decrease in energy consumption due to lower production<br>− Decrease in process emissions<br>− Less consumption of wood & paper products increases forest carbon storage<br>− Avoided transportation emissions | *Need specific information for each component* |

[a]Calculations for 4 million tons of MSW for a time horizon of 100 years. Values in parentheses represent equivalent $CO_2$ for a 20-year horizon.