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Linkages of Waste Management Options to Environmental and Human Health Risks

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Abstract - Owing to increasing population, urbanization and waste generation rates per capita, the capacity for managing wastes is exceeded by the technical, policy and material resource investment challenges in many regions of the world. This circumstance exists in spite of the fact that in 1992, many nations had agreed to develop national environmental action plans (NEAPS) under the auspices of the United Nations Rio de Janeiro Conference. Resource constraints imply that quantitative risk methodologies need to be developed and used to screen contaminated sites and management options for wastes. This is particularly necessary in low-midlevel income countries. The principal management options are treatment to reduce volumes, contaminant concentrations and contaminant mobility to levels that pose acceptable risk levels; recycling of waste materials into products and in facilities as construction materials; and containment of wastes and contaminant sources by implementing engineered systems. Scenarios in which contaminants exist freely in various media have justifiably been the primary focus of current risk assessment methods because they pose the most immediate risks. However, exposure risks of various magnitudes exist in time and space for virtually all waste management methods. In this lecture, approaches to linking prospective performance levels of waste management methods to environmental and human exposure risks are discussed. Within the context of global sustainable development, opportunities for risk reduction through control of significant parameters are identified and analyzed.

I. Introduction

Waste management and contaminant containment are significant challenges in both technologically advanced and developing countries. Under the auspices of the 1992 United Nations Rio de Janeiro Conference, more than 100 nations have sought the implementation of their National Environmental Action Plans (NEAPs) to control contaminant generation and spreading. By necessity, such plans must include regulations, policies, technical guidance systems, research/education and enforcement. In the technologically advanced countries, the continuing challenges with respect to waste management derive from the excessively large number of chemicals that are introduced into commerce each year and high levels of material use per capita although environmental management infrastructure and systems are often adequate at least for hazard reduction. In the developing countries, the support systems listed above are inadequate for control of environmental and human health hazards from exposure to contaminants from wastes. Such wastes may be produced in three main forms: solids, liquids and gases. In some cases, their forms may be intermediate as in sludges. In this assessment, the discussion is limited to solid wastes because of the great logistical challenges that they pose to many communities and management agencies throughout the world.

Although different countries have developed regulatory definitions for solid wastes to support administrative and related legal actions, for the purposes of this assessment, solid wastes are defined as solid objects and materials that are produced without recycling, from industrial and civil facilities and operations. Examples of such wastes are biosolids, mining wastes, municipal refuse, dredged sediments, combustion ash, agricultural wastes and dewatered industrial sludges. Sometimes, due to inadequate management practices, these wastes may mix with clean geomaterials, thereby contaminating them as well. Possible contaminants in these materials are inorganics (heavy metals, etc), organics (pesticides, cleaning fluids and chemical agents) and bacterial viruses. Owing to high rates of urbanization, especially in the developing countries, solid waste generation in urban centers is currently high. For example, in Japan, the current annual generation density of waste is about 650 metric tons per square kilometer [1].

In 2000, about 210.4 million metric tons of municipal waste was generated but only 58.4

million tons was recycled in the United States [2]. Solid waste management is a critical sustainable development need. The management options employed are characterized by various levels of human health and ecological risks. With the declaration of the first decade of this millennium as the "Decade of Education for Sustainable Development" by the United Nations General Assembly in December 2002, the development of concepts, approaches and mechanisms for identifying risk parameters that can be managed in waste management systems of various countries is essential. This is achievable through analysis of the determinants of the magnitudes of such parameters in quantitative risk assessment schemes.

II. Solid Waste Management Scenarios

Solid Waste handling, transportation and storage processes and systems provide opportunities for emissions of contaminants as gases, leachates and fugitive particles.

- **Scenario 1 - Exposed Waste Piles:** This is very common in low income sections of large cities, especially in developing countries. Temporary piles may also be found in developed countries during operations such as mining, construction of facilities, cleanup operations and demolition of structures. The exposure of waste piles as illustrated in Figure 1 to weather elements such as wind, rainfall and snowfall provides opportunity for the emission of dusts, contaminated sediment generation by erosion and deposition, and leachate production.
- **Scenario 2 – Covered Waste Dump Without Bottom Liner:** In many countries, this scenario is very prevalent. Even in the technologically advanced countries, prior to the inception of bottom-lining systems for waste storage sites in the late 1960s, this management system was very common. Those sites are still managed today under a variety of regional and national waste-site cleanup programs. The absence of a bottom liner as illustrated in Figure 2, implies that contaminants that are dissolved by infiltrating water can be leached out into the groundwater system such that they can pollute water bodies and water wells as contaminated recharge water. This is particularly hazardous in the humid tropics where heavy rainfall patterns supply high quantities of leachant.
- **Scenario 3 – Covered and Lined Waste Disposal Facility:** As illustrated in Figure 3, coverage and lining of waste disposal facilities reduces the risk and potential levels of contaminant emissions. However, in the long run, both the cover and lining systems will degrade although some level of protection of the ambient from the contained contaminants will still be provided. This system of waste containment is not widespread in the low income countries, where generated waste densities (waste quantity per unit area of land) are generally high despite low waste generation rates per capita.
- **Scenario 4 – Waste Handling and Recycling Facilities:** These facilities include excavation systems, transfer stations and sorting facilities. Weather elements may gain contact with the waste but the primary exposure issue is occupational. Dermal contact with waste, inhalation and ingestion are principal exposure pathways.

III. Risk Assessment Framework

The selection and implementation of solid waste management options that generate the scenarios outlined above require assessments of both human health risks and ecological risks related to the potential emission of contaminants. Using the generic exposure assessment equation designated as (1) below, options that allow opportunities for minimization of exposure can be selected.

$$IN = C\left[\frac{(CR)(EF)(ED)}{(BW)}\right]\frac{1}{AT} \qquad (1)$$

IN (the intake) is the quantity of the chemical at exchange interface of the body (M/M·T); C is the average chemical concentration contacted over the exposure duration (M/L^3); CR is the contact rate (L^3/T); EF is the exposure frequency (T/T); ED is the exposure duration (T). Details on the protocols for estimating each of the intake parameters are provided by standard risk assessment texts. It should be noted that equation (1) and its surrogates are usually operated for specific exposure pathways and land use types.

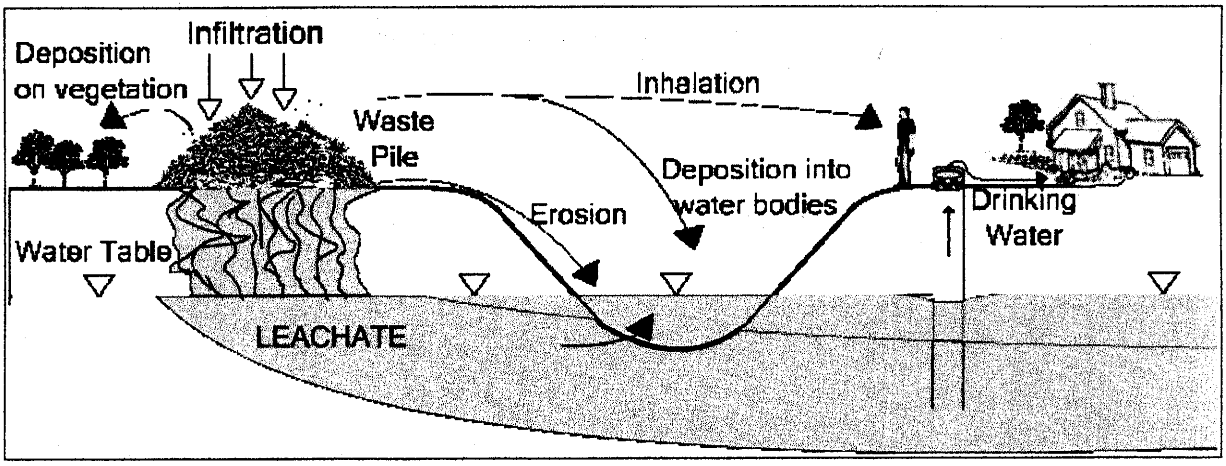

Fig. 1. Waste piles exposed to rainfall and wind

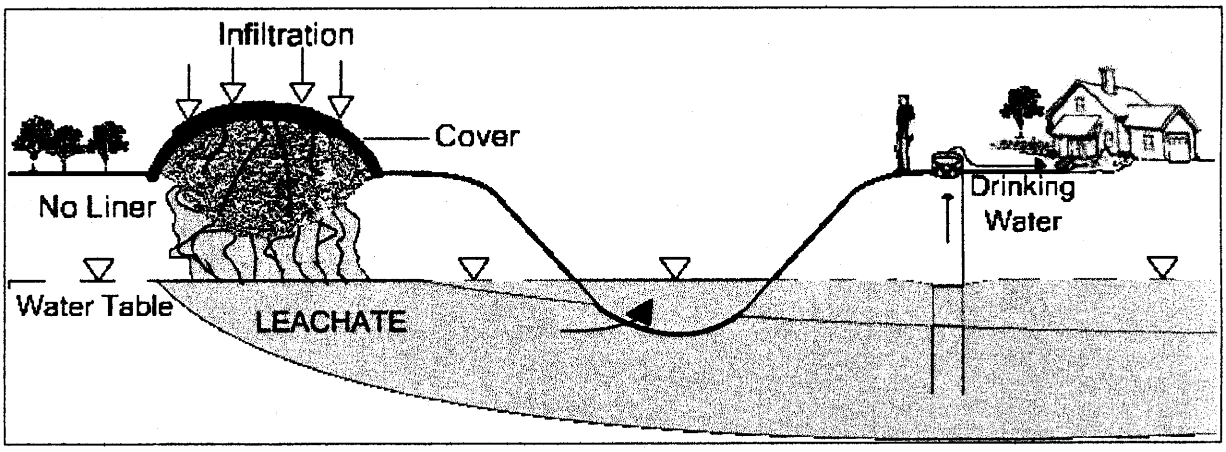

Fig.2. Covered waste dump without bottom liner

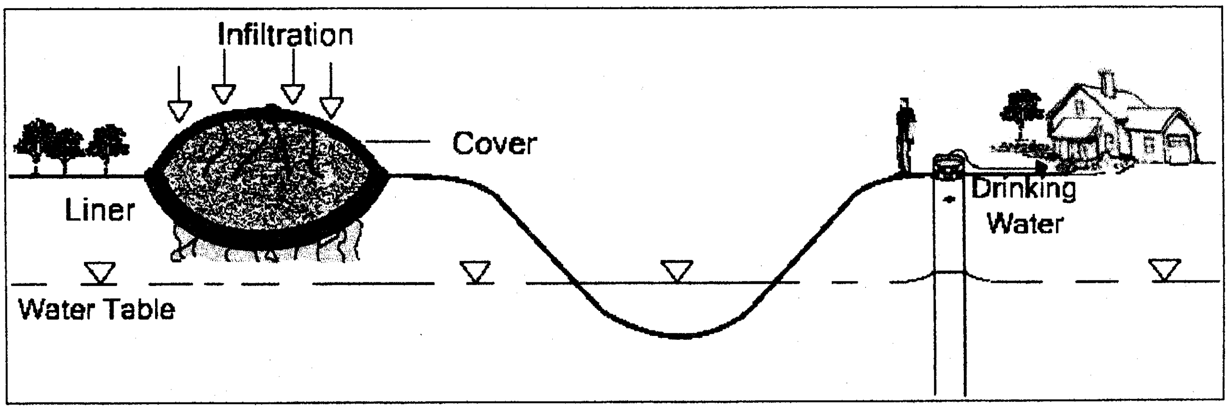

Fig. 3. Covered and lined waste disposal facility

For the various scenarios, the principal human exposure pathways are identified and summarized in Table 1. However, assessments of risks associated with the four waste management scenarios should go beyond human health assessments to include ecological risk assessments. The overall framework for such an integrated risk assessment is presented in Figure 4. Collection of data

TABLE 1
Exposure pathways of humans to contaminants generated under various solid waste management scenarios

SCENARIO	EMISSION MODE	HUMAN EXPOSURE PATHWAY
1. Exposed waste piles	• Dusting • Leaching	• Inhalation • Dermal Contact • Ingestion • Drinking Water
2. Covered waste dump without bottom liner	• Leaching	• Drinking Water
3. Covered and lined waste disposal facility	• Leaching	• Drinking water
4. Waste handling and recycling facilities	• Dusting • Volatization	• Inhalation • Dermal Contact • Ingestion

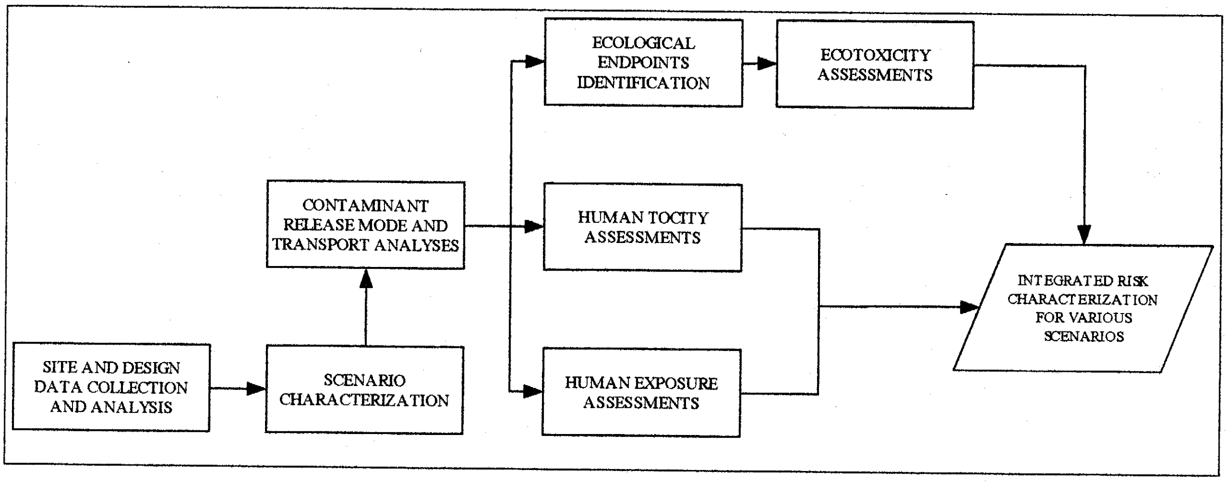

Fig. 4. Integrated risk assessment framework for solid waste management scenarios

on an existing facility or on one that has been designed should precede scenario characterization. The *n* contaminant release mode analyses can provide data on the probable ranges of concentrations of the target contaminants. Transport analyses enable the estimation of the contaminant concentrations in time and space such that values can be estimated for selected exposure points. For the human exposure assessments, the significant pathways can be identified and analyzed while for the case of ecological impacts, the desirable endpoints on contaminant transfer sequence covering biota and fauna are specified for use in the risk assessment. The exposure concentrations and contact times for which toxic effects are experienced need to be determined from literature or through testing, for comparison with estimated exposure concentrations. The contaminant-toxicity assessments and exposure assessments feed into risk characterization for each solid waste management option.

IV. Framing Design, Siting and Management Options within Risk Assessment

The initial solid waste facility design, site factors and management actions directly affect the magnitudes of *EF*, *ED* and *C*. Optional measures that are determinants of the three parameters are summarized in Table 2. An exhaustive analysis of the quantitative linkages between the exposure parameters and all the measures listed in Table 2 is not attempted here. However, for the purposes of illustration, the effect of the introduction of a leachate barrier system underneath a waste mass as in scenario 3, on the parameter *C* is analyzed herein. Considering Figure 5, the original concentration of the target contaminant in the landfilled material is designated as C_1. Due to the attenuative action of the liner, the concentration would be reduced to C_2 if the service duration of the facility is long enough and the original concentration C_1 is high enough for the contaminant to travel through the barrier. As the contaminant travels downward through the vadose zone and with groundwater in the direction of the water wells, its concentration can decay by sorption and dilution such that the concentration C_4 could be much smaller than C_2. Indeed, Inyang and Ogunro [3] have developed equation (2) to account for this reduction

$$C_4 = \frac{C_2}{F_d}\left[\sum_{i=1}^{n} A_i\right]^{-1} \tag{2}$$

In equation (2), F_d is the dilution factor which is in this formulation, a dimensionless fraction; A_i is the contaminant attenuation factor which is also a dimensionless fraction; and n is the number of soil compartments of distinct characteristics through which the contaminant travels. Essentially, for the ingestion (drinking water pathway), the parameter C in equation (1) is C_4 for untreated water or C_5 if the water is treated to reduce the concentration of the contaminant.

TABLE 2
Control of risks through design, siting and management options

EXPOSURE PARAMETER	APPROACH	MEASURE
EF: exposure frequency	Minimization	• Siting controls • Scavenging bans • Reduction in work frequency • Process automation
ED: exposure duration	Minimization	• Siting controls • Scavenging bans • Reduction in work frequency • Process automation
C: Contaminant exposure concentration	Minimization	• Reduction in stored waste quantity • Occupational health and safety controls • Effective waste coverage • Effective leachate barrier system • Exclusive distances for water wells

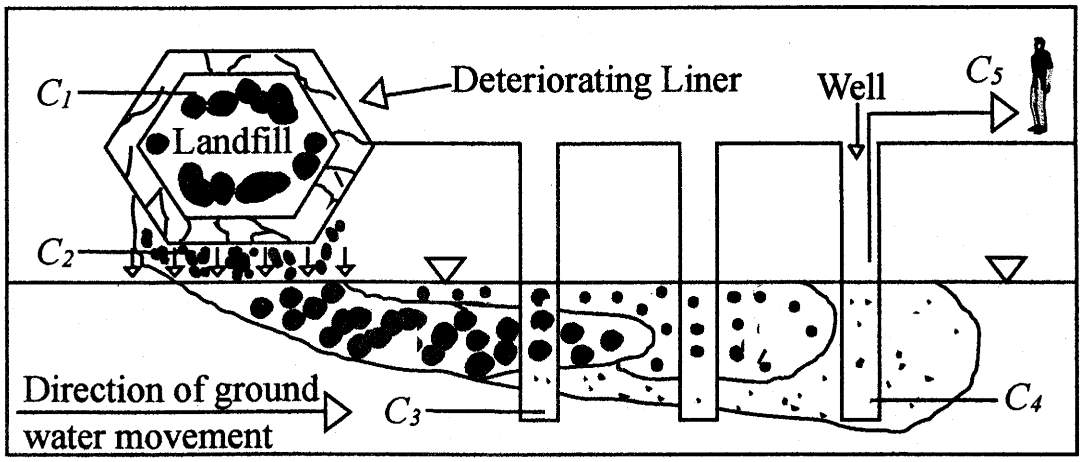

Fig.5. Schematic illustration of the different concentrations of a contaminant to be noted in exposure assessments for ingestion of drinking water

The introduction of the leachate barrier (liner) into the landfill is expected to reduce the contaminant concentration from C_1 to C_2 which is linked through equation (2) to other concentrations at locations that are closer to the point of exposure. Using the Ogata-Banks [4] solution of the one-dimensional dispersion-advection equation for a case in which the barrier has aged, C_2 can be estimated as follows:

$$C_2 = 0.5C_1 \cdot erfc\left[\frac{(R_d - V_t)}{2(DtR)^{0.5}}\right]^{-1} \tag{3}$$

In equation (3), the contaminant concentrations C_1 and C_2 given in units of M/L^3, correspond to the descriptions provided earlier and the illustration in Figure 5; d is the thickness of the barrier (L); t is time since the beginning of contaminant transport (T); D is the dispersion-diffusion coefficient (L^2/T), and R is the retardation coefficient.

The complimentary error function (erfc) is obtainable from mathematical tables and associated figures, as illustrated by Inyang and Tumay [5], in Figure 6. Equation (5) is relevant to a case in which the barrier material is porous but otherwise intact. Environmental stresses during the service life of a barrier may cause large fissures and fractures to develop such that fluid flow through fractures dominate over permeation. Bai et al. [6], Grisak and Pickens [7], and Gense et al. [8] have provided relevant numerical details. For the fracture flow case, contaminated liquid transport is relatively rapid and is best represented in terms of the flow rate across the barrier.

The retardation coefficient R can be determined as follows for the case of inorganic contaminants.

$$R = 1 + \left(\frac{\rho_b}{n}k_d\right) \tag{4}$$

In equation (4), ρ_b is the bulk density of the barrier material (M/L^3); n is the effective porosity (fraction); and k_d is the distribution coefficient of the material for the contaminant (L^3/M).

V. Global Distribution of Materials and Climate Limitations to Options

Geographic factors influence risk factors and constrain the implementation of some management options in some regions of the world. Using the example of Scenario 1 discussed above, some low-lying regions in Southeast Asia and Africa, and pounded expanses of land in northern Europe present high risk factors because the closeness of the water table to the ground surface generally reduces the difference between C_2 and C_4 in the same geomedia. Furthermore, high rainfall intensities that are typical of the humid tropics are conducive to high transit rates of the leachate through the barrier although groundwater dilution may induce positive impacts. Furthermore, some of the materials on which there is considerable experience (as regards their use as barrier materials), are not readily available in some regions of the world. An example is bentonite, a Na-clay with minimal impurities that is frequently used as an admixture to reduce the permeability, diffusion coefficient and cracking potential of liners. Large deposits are common mostly in North America. Laterite, the reddish brown clayey soil is more common in the tropics, but may not produce k_d values that are as acceptable as temperate zone soils.

VI. Research and Management Needs on Waste Management

The cost-effective operation of solid waste management systems in all countries requires physical infrastructure development, tailoring of management of management systems to socio-economic conditions of each country applied research and incorporation of local technology and materials, and training of technical personnel, program managers/policy makers as well as the general public. On these factors, there is significant disparity between the adequacy of support systems in the technologically advanced countries and that of the less developed (low-mid income) countries. In the United States [2], of the municipal solid wastes generated in 2000, about 55.4% was managed in landfills, 23% was recycled, 7.1% was used in composting and 14.5% was converted to energy. Barlaz

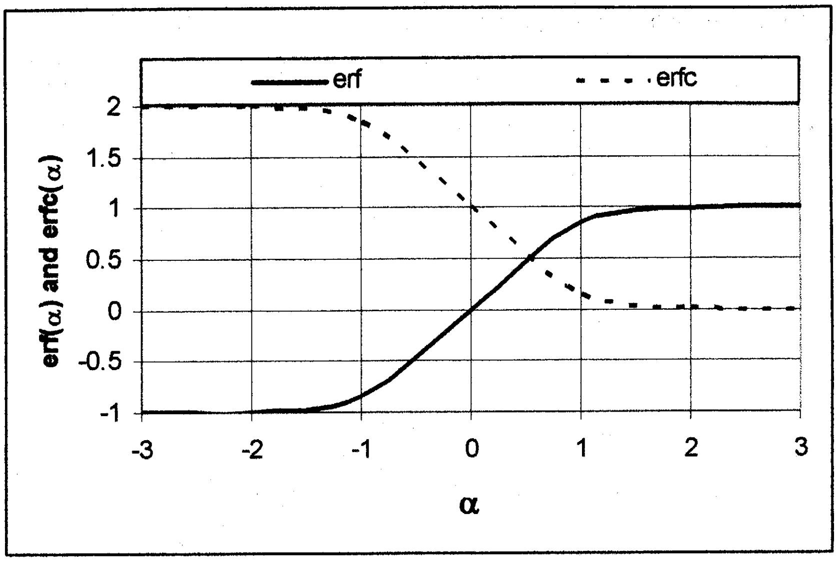

Fig.6. The relationship between error function (erf) and complimentary error function (erfc) [5]

TABLE 3
Needed systems for solid waste management improvements in developing countries

NEEDS CATEGORY	ASPECTS AND SUPPORT MODALITIES
A. Policy Support	• Organization of policy institutions with domestic and international support • Analysis of waste management options with consideration of experience in similar situations in other countries • Alignment of policies with estimates of future socio-economic conditions which have both internal and external determinants • Integration of cultural factors into municipal and regional policies on waste management • Creation of markets for wastes that can be recycled by formulation of incentives
B. Technical Support/Training	• Development of technical guidance manuals that incorporate region-specific designs of systems, with the collaboration of regional and external institutions • Organizations of regional training workshops that involve policy makers, citizens of waste sites, research institutions and system designers under the auspices of regional and international agencies • Selection of regional solid waste management centers with specification of well-defined roles in problematic major metropolis with significant coordination by international agencies such as UNESCO
C. Research	• Collaborative identification of research needs at each regional center, involving local officials, researchers, UNESCO technical support representatives, etc. • Institution of mini-research grants with the support of international agencies on identified problems on which applied research is needed • Creation of Sustainable Waste Management Fellowship for representatives from affected cities at high-capacity institutions in both advanced and low-mid income countries to tackle specific projects. • Intensive research on the development of region-specific configurations, local material specifications, recycling opportunities and environmental impact control
D. Interchanges	• Creation of forums for interchange of ideas on cost-effectiveness of approaches and technologies under various scenarios in different regions

et al [9] have discussed the environmental and economic factors that are significant with respect to solid waste management approaches in the United States. Inyang [10] and Sorvari [11] have formulated comprehensive methodologies for large-scale recycling of materials in constructed facilities. However, experience in the low-mid income countries reveals implementation difficulties. In India, a 1989 [12] survey of 159 cities indicated waste collection efficiencies in the range of 66-77%. There is no evidence that there have been significant improvements since this survey was conducted.

Scavenging of waste dumps which increases the intake of contaminants by *C*, *EF* and *ED* of equation (1) is still common in many developing countries. For example, a survey [13], indicated that there were as many as 30 permanent scavengers, 80% of which were aged between 20 and 39 years. Furthermore, about 60% of the scavengers had been engaged in that risky profession for 6-12 years.

In Table 3, the systems that are needed for solid waste management improvement in developing countries are summarized. Effective implementation of programs on each of the issues requires collaboration among educational/research institutes, public agencies, the private sector and international agencies.

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