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Urban food waste generation: challenges and opportunities

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Abstract: Greater economic activity and a wider economic gap between rural and urban areas have accelerated the growth of cities worldwide, along with their waste management issues. As a result, urban food waste (UFW) generation is expected to increase by 35% from 2007 to 2025. This paper examines the possible solutions to implement the environmentally safe recycling of UFW. If landfilling seems to be easy and economical for developed countries, it is not affordable for many large cities of Asia, Africa and South America. The on-site recycling of UFW is a more sustainable solution, but can only be justified economically if properly organized, community supported and recognized for its environmental benefits. On-site UFW composting is a solution which has already been implemented with success and which, if introduced worldwide, could provide agricultural soils with a good source of organic matter, capable of improving water management and fertilizing 3 million ha/yr. As compared to composting, anaerobic digestion could provide energy as biogas for a few high energy demanding industries within cities while also producing some organic soil amendment, after dewatering. Accordingly and for Asia and Africa, the on-site composting and anaerobic digestion of UFW could reduce the mass of MSW by 43 and

55%, respectively, thus help there cities manage almost all of their MSW. For North America and Europe, such practice could reduce earth warming trends.

Keywords: urban; municipal solid waste; food waste; landfill; methane; compost; fertilizer; community

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Dr. José Martinez currently leads as research director, the Environmental Management and Biological Treatment of Wastes Research Unit at Cemagref, a public research body in France. He is also the former coordinator for the FAO research network Ramiran (Recycling of Agricultural Municipal and Industrial Residues in Agriculture Network), and adjunct Professor with the Department of Bioresource Engineering of McGill University. In 2004, he was invited by McGill University to deliver a semester course on “livestock farming and climate change”. He has published over 50 scientific and technical papers on livestock slurries and manures. He has strong links with other member states through involvement in various competitively achieved EU projects including MATRESA, ALFAM, NUMALEC. Currently, his research interests are centered on N transformation processes in soils and manures, the reduction of greenhouse gases from organic waste management and utilization, and improving the efficiency of composting systems.

1 Introduction

Besides population growth, two main factors will impact the earth's environment in the upcoming decades: economic growth especially for countries with a large population, like India and China; and greater economic disparity between rural and urban areas, driving the rural population into cities. While the first factor leads to a greater demand for resources, such as fossil fuels, metals, water and food, the second factor leads to a more costly waste management burden on large cities. Cities world wide are already experiencing waste handling problems and smog issues (Kumar et al., 2004).

From 20 to 80% of the mass of municipal solid waste (MSW) is made up of UFW. The UFW percentage was found to be inversely correlated to the economic status of the community, while the mass of UFW produced per capita was directly correlated (Adhikari et al., 2006). In many countries around the globe, the landfill practice is not even feasible, resulting in land and water dumping (Louis, 2004; Korfmacher, 1997). Because of its biodegradability, UFW attracts disease vectors such as parasites, pathogens, insects and vermin (Louis, 2004; Yedla and Parikh, 2001) and its proper disposal can improve the environment and reduce health risks. In Asia, for example, a large number of cities can generally afford the management of 10 to 30% of their MSW (Sharholy et al., 2007). Because the UFW fraction of such cities generally constitutes 50 to 70% of MSW, the on-site treatment of UFW could resolve most of the garbage issue, and in parallel, reduce the mass of MSW to be transported outside city limits, as well as the smog and greenhouse gas emissions.

Where landfilling is practiced, the UFW fraction has a major impact on water, soil and air resources. Besides reducing the amount of land available for food production, landfilled UFW brings moisture producing contaminated leachate which can pollute groundwater and soils with heavy metals and toxic organic compounds (Louis, 2004; El-Fadel et al., 2003). Landfilled UFW accelerates global warming by producing greenhouse gases (GHG) composed of 60% methane (CH_4) and 40% carbon dioxide (CO_2) (Adhikari et al., 2006; Kumar et al., 2004; Bhide, 1994; Wang et al., 1997). Worldwide, the anthropogenic emission of greenhouse gases from landfill sites is estimated at 8% and results mainly from landfilled UFW. When installing systems to recover these greenhouse gases in young landfill sites, methane capture is costly and represent half of that produced from the anaerobic digestion of UFW (Ortega-Charleston et al., 2007).

Recycling UFW is a challenge even for developed countries. In the late 1990's and for Europe, only about 0.7% of the total organic fraction of MSW was treated anaerobically (Mata-Alvarez et al., 2000) and between 6 and 27% was composted (De Baere, 2000) while the rest was sent to landfills along with the MSW main stream. In the early 2000's and for Canada, only the Maritime Provinces, with less than 10% of the country's population, were actively recycling over 50% their UFW (Wagner and Arnold, 2006). The success of this recycling program relied on higher tipping fees for garbage, reaching $100 US/ton, strict legislation and community training and involvement. Far from reaching this level in 2001, other Canadian provinces such as Quebec, with 20% of the country's population, were recycling only 7% of their UFW (Da Costa et al., 2004).

Although source separation and the on-site treatment of UFW looks attractive from a health and environmental point of view, it is far from being implemented because the general public is not convinced of its economic feasibility (Isa et al., 2005; Kumar et al., 2004). The purpose of this paper is therefore to assess the challenges and economic benefits of the on-site recycling of UFW within an urban context, and to evaluate the opportunities resulting from the conversion of UFW into useful resources. The following sections will investigate the cost of UFW handling and landfilling versus the benefits of recycling the organic matter either as a fertilizer, through composting, or an energy source through anaerobic digestion.

2 Continental MSW and UFW generation

The estimated continental growth in MSW and UFW is presented in Figures 1a and 1b (Adhikari et al., 2006), assuming no changes in the present economic trend. With the largest share of world population, Asia produces the largest amount of MSW which is expected to increase from 617 Gkg/yr in 2007 to 967 Gkg/yr in 2025; during this time, UFW production will grow from 278 Gkg/yr to 416 Gkg/yr. Asia is followed by the Americas with 130 Gkg/yr of UFW in 2007, which is expected to increase to 174 Gkg/yr in 2025. Europe and Africa are producing 98 and 53 Gkg/yr of UFW in 2007, and this production is expected to reach 113 Gkg and 87 Gkg/yr in 2025.

INSERT FIGURES 1A AND B

The estimations presented in Figures 1a and 1b consider the impact of the wider economic gap between rural and urban populations. In Asia, this gap is widening and attracting rural communities to move towards cities with the expectation of a better life. Adhikari et al. (2006) demonstrated a clear relationship between the economic development of a country and the displacement of its population from rural areas to urban centres. By maintaining their present economic growth, most Asian countries such as China and India, could see their urban population growing from the present 50% to a future 70%, such as found in Europe and North America (Table 1). The recycling of UFW is not an issue for rural populations because of the space and land at their disposal.

INSERT TABLE 1

In comparison to Adhikari et al. (2006), Sharholy et al. (2007) estimated that 90% of the MSW produced in India's urban centres is improperly disposed of, leading to serious environmental and health risks for the population. Sharholy et al. (2007) also reported that the general urban population was producing some 0.4 kg/capita/day of MSW in 1999 and that its UFW content ranged from 45 to 60%, for a net UFW production of 0.2 kg/capita/day. Adhikari et al. (2006) estimated that in 2007, due to economic growth, the urban population of India could be producing 0.34 kg/capita/day of UFW (Table 1).

In the following sections, estimates of resource requirements will be presented for countries around the world to properly dispose of all their UFW through landfilling. Then, the savings in resources will be estimated if on-site composting and anaerobic digestion were used instead of landfilling.

3 Disposal of UFW through landfilling

Landfilling is presently the most widely accepted practice for the disposal of MSW (De Baere, 2000). Although this solution is attractive to large cities, it lacks in scope and overall resource sustainability besides creating a poor environment for those living close to the landfill site. Environmental issues introduced by landfill sites are: risk of groundwater contamination from the leachate, greenhouse gas emissions, truck circulation bringing noise, dust and smog, and garbage decomposition creating odours.

Furthermore, landfills require more often than not, the sacrifice of good agricultural soils which otherwise could be used to feed the world.

3.1 Land used for UFW landfilling

In terms of agricultural land, landfills occupy large areas which can no longer be used for food production, because of contamination risks. Typically and with a density of 260 to 500 kg/m^3, each Gkg of urban UFW requires 33 ha of land when piled to a height of 15 m using a waste to soil cover ratio of 5:1 (Peavy et al., 1985; Bhide, 1994). When extrapolating this number and assuming that all future UFW generation will be landfilled, MSW management is observed to have an impact on world agricultural land and food production capacity.

In Asia and for 2007, the annual land use is estimated at 9174 ha for UFW landfilling and this area is expected to increase to 13728 ha in 2025. Similarly, the Americas will require 5742 ha/yr in 2025, which is a 40% increase compared to that required in 2007. Europe and Africa (Figure 2) follow in terms of land use for landfilling, with an estimated increase of 18 and 70% in 2025 as compared to 2007, respectively.

INSERT FIGURE 2

Over the upcoming 18 years (2007-2025), the landfilling of all UFW could require some 400 × 10^3 ha of land with a deep soil profile. In Asia alone, the land area required for such purpose is estimated at 210 × 10^3 ha, representing 53 % of total global land requirement for landfilling. If UFW was recycled, an equivalent amount of land could be maintained in agricultural production to produce food for the Asian population.

A surface area of 210 × 10^3 ha can grow enough wheat, at 2.0 metric ton/ha, to provide a population of 1.0 million with 100% of its carbohydrate requirements.

Many large cities around the globe are suffering from lack of landfilling space for the disposal of their MSW. The city of Singapore plans to build an off-shore island of 350 ha to dispose of its MSW for the upcoming 30 years; the creation of this land base alone will cost almost $10 US/ton of MSW, while the land base for a landfill site in Ohio State cost $0.10 US/ton (Ohio State University, 2001). Where the land and handling costs cannot be afforded, open spaces, street corners and river banks serve as uncontrolled dumping sites for as much as 90% of all MSW (Sharholy et al., 2007).

In developed countries, landfill sites use good agricultural land which is becoming a national priority, and bring other forms of regional pollution besides. Landfill sites are often forced onto rural communities to allow urban centres to dispose of their MSW, and as such, introduce additional contamination in the form of truck traffic, dust and odours. Recently, North American authorities introduced laws for the cleaning and restoration of old landfill sites (Minnesota Pollution Control Agency, 2004). Urban sprawl is becoming a threat to agricultural land, as many government authorities are initiating laws to preserve farm land; agricultural land protection legislation has been implemented in Canada, the United States, Australia and Europe (USDA, 2005). In the United States from 1992 to 2001, urban regions have tripled in area, at a growth rate of 100 × 10^3 ha/yr. During this same period, landfilling operations have reduced US land surfaces designated for agriculture at an additional rate of 1.5 × 10^3 ha/yr. Finally, agricultural land will be even more pressing in the years to come, as the transformation of corn into ethanol is expected to compete with fossil fuel production. From 2005 to 2025, in the Americas alone, landfill sites will remove 110 × 10^3 ha of land, which could produce enough ethanol to replace a net (energy above that required to produce the ethanol) amount of 147 × 10^3 m^3 of diesel/yr (USDA, 1995). Although this diesel represents only a small percentage of the world demand of 4 million m^3 of diesel/day for 2007 (US EIA, 2007), it represents 1.3% of Canada's 2007 consumption. In terms of meeting the Kyoto agreement, this is a major share of Canada's 6% reduction commitment.

3.2 Cost of handling and landfilling urban UFW

The land base required for landfill sites often represents the tip of the iceberg (Isa et al., 2005). In North America, the purchasing of land represents only 0.5% to 1.0% of the total cost of handling and disposing of MSW. Besides the land base, environmentally safe landfills require the expertise of professionals, the construction of access roads, the installation of impermeable membranes and the collection and treatment of leachate. In 2001, the implementation, operation (transportation of MSW to the site and burial) and closure of a safe landfill site for 5.4 Gkg of solid waste were estimated at $20 US/ton, in Ohio State, USA (Ohio State University, 2001). Since the collection cost is in the range of $16.00 US/ton (Smart Storage, 1998), the total MSW management cost amounts to $36 US/ton. The operations of collecting, transporting and landfilling consume fossil fuels at a rate of 10L/ton (Ohio State University, 2001; University of Tennessee, 1993). Although the handling of all UFW, world wide, would only use 0.4% of the world's diesel consumption, it is still equivalent to 50% of Canada's requirements. Nevertheless, the energy cost generally represents 10% to the total cost of handling and disposing of

MSW, while the labour cost represents 70% and the capitalization and maintenance costs add up to 20%.

Mumbai spends some $29 US/ton for the collection, transportation and landfilling of what ever MSW can be handled (Department of Chemical Engg, 1997). Similarly and in 2000, the Malaysian MSW handling cost of $16 US/ton, along with its waste generation of 0.8 kg/capita/d (Tean, 2001), implies that $105 million US/year would be required to the waste generated by a population of 23 million (Isa et al., 2005). The low labour cost, despite higher land cost, makes landfilling a cheaper operation in Asia than in North America.

If the present landfill practice is maintained and the entire wet mass of UFW is landfilled, the cities around the world are facing huge economic challenges (Figure 3). At present, Asia needs $10 billion US/yr for the handling of its urban UFW and is expected to spend $15 billion US/yr more in 2025. The Americas are next, presently spending $4.5 billion US/yr and expected to increase this spending by $6.2 billion US/yr, in 2025. Whereas in Europe, $3.4 billion US/yr is estimated for 2007, the cost is expected to increased by 18% in 2025; Africa needs $1.8 billion US$/yr in 2007 and its cost is estimated to increase by 71%, in 2025.

INSERT FIGURE 3

Landfilling brings no economic benefit, besides providing employment. The recovery of methane is costly and only 50% efficient (Ortega-Charleston et al. 2007) as compared to directly digesting UFW using an anaerobic digester. Some 200 L of methane/ton of landfilled UFW (dry basis) (Wang et al., 1997) need collecting and flaring at a cost of $4.00 US/ton of wet UFW (Ngnikam et al., 2002). The transformation of this methane into electricity is even more expensive, because of its low conversion efficiency of 35%.

3.3 Total cost of landfilling urban UFW

In total, the collection, transportation, landfilling of UFW and the greenhouse gas ramification is a non sustainable operation which costs in the range of $ 20 to $40 US/ton UFW, depending on labour and land costs. For developing countries, this cost is often not affordable despite the health issues at stake. For developed countries, this cost is too affordable, and the resources required are relatively limited, explaining the lack of UFW recycling. The on-site recycling of UFW will be implemented for both developing and developed countries, when additional benefits are considered, from an aspect of environment and resource conservation.

4 On-site treatment and utilization of urban UFW

Considering the environmental issues associated with the landfilling of the world's UFW, alternative sustainable solutions must be developed. The implementation of these solutions requires the involvement of communities, through awareness programs and incentives, and the logical valorization of the organic waste.

4.1 Source separation

Source separation is a pre-requisite for the on-site treatment of UFW to reduce MSW handling, transportation and landfilling costs, especially for large cities. In 2025, such practices could reduced by 43% the total MSW disposal cost in Asia, 29% in Americas, 29% in Europe and 53% in Africa (Figure 4).

INSERT FIGURE 4

In the past, many countries around the world have developed large scale composting centers for organic waste which was mechanically separated from MSW. Many of these composting centres have not been kept in operation (Sharholy et al. 2007) for three reasons: the poor quality of the compost resulting from its contamination with glass, heavy metals and other pollutants into contact with the acidic leachate during handling; the workers often get hurt while handling and sorting the various components of the MSW; and the value of the compost produced being lower than the cost of composting (Furedy et al., 2007).

4.2 Composting source separated UFW - a success story

The authors of the present paper were involved with the implementation of a successful on-site composting centre operating in the heart of the city of Montreal, Canada (Barrington et al., 2005). In operation since 2003, the composting centre is located in a municipal park, along a popular pedestrian path. The 125 participating families are source selecting and dropping of their UFW on their way to work in the morning, three times weekly, when an attendant operated the centre. The composting centre is visible to all walking by, and those curious enough can stop to ask questions.

The successful operation of this 6.0 m^3 centre was based on three main elements: the implementation of community awareness, training and educational programs before opening the centre; the easily accessible and visible site selected for the urban composting centre; and the fact that most of the local residents were highly educated, with at least a university degree.

In 2007 and with a capacity of 1.0 tons of high quality compost/week, this Montreal centre operates at a cost of $220 US/ton of finished material or $140 US/ton of wet UFW processes. Labour, power, bulking agent and capitalization represent 40, 1, 9 and 50% of the costs. As bulking agent, the centre uses pellets of cereal flour residues, because of their high moisture absorbing capacity. The operating cost of this centre could be reduced to $70 US/ton of UFW ($110 US/ton of compost produced) if the capacity was increased to 5 tons/week of compost. Although similar in cost to that of larger operations, composting obviously does not seem economical when compared to landfilling and its methane recovery at $40 US/ton UFW (US EPA, 2003; US EPA, 1999).

4.2.1 Proposed on-site UFW composting for Mumbai, India

Flooding is a threat to public health in Indian cities because of the uncontrolled street dumping of MSW. Composting could therefore be a highly suitable solution, along with the fact that once recycled as soil amendment, water conservation and soil fertilization practices can be enhanced (Kumar et al., 2004).

Mumbai is one of the biggest cities in India with a population 27000 per km^2 (Demographia, 2007). Its MSW management is one of the major challenges because of a waste production rate exceeding 0.50 kg/person/day (Department of Chemical Engg, 1997) with over 50% UFW (Adhikari et al., 2006).

Table 2 presents a scenario where the Montreal park composting centre could be implemented in Mumbai. To deal with the intense population, it is proposed to use 6 in-vessel composters per km^2, each with a capacity of $27m^3$. The operating cost for such centre could be lower than that of Montreal, because of cheaper labour costs and the larger capacity of the system. The compost production cost is estimated at $85 US/ton, implying a cost of eliminating UFW of $53.00 US/ton on a wet basis. Nevertheless, these composting centres would first of all require the participation of the population to source separate UFW and bring it to the composting centres. Because not all the population is environmentally aware and committed to environmental issues, monetary incentives may be required.

INSERT TABLE 2

As for Montreal, this composting cost of $85.00 US/ton for Mumbai is still above that of $39.00 US for landfilling. Hence, promoting the on-site recycling of UFW requires the demonstration of additional benefits, for both developed and developing countries.

4.2.2 Advantages of on-site UFW composting

Once composted, UFW are stabilized, of lower moisture content and have lost 50% of their original mass (US EPA, 2003). At present, Asia has a compost production potential of 83 Gkg and its production is expected to increase by 51% in 2025 (Table 3). In the Americas, compost production from UFW can potentially amount to 52 Gkg in 2025, which is 37% higher than that of 2007. In Europe and Africa, the compost production potential is estimated at 34 and 26 Gkg, which represents an increase of 18 and 73% compared to 2007.

INSERT TABLE 3

To compare the cost of composting UFW with that of landfilling, all benefits must be considered (Table 4). First of all, this compost has a mineral fertilizer value because each dry ton of compost produced from UFW can potentially offer 24 kg N, 2.4 kg P and 32kg K (Adhikari et al., 2006). In Asia, the value of N, P and K is \$0.25, \$0.65 and \$0.65 US/kg, while in North America the value is \$1.15, \$1.15 and \$0.60 US/kg (Barrington, 2007). The cost recovery from the fertilizer value of compost produced from the entire Asian urban UFW is estimated at \$1418 million US/yr in 2007 and is expected to increase by 50% in 2025, while in the Americas it will reach \$1550 million US/yr in 2025. In Europe and Africa, the 2025 value is estimated at \$995 and \$435 million US/yr. If all UFW was properly separated and composted in Asia, some 3 million ha could be fertilized with 40 kg of P/ha (the equivalence of 28kg of P/ha in mineral fertilizer), which in turn, could feed 12 million persons. Illegally disposed of along river banks or leached to groundwater as landfill leachate, this phosphorous has a tremendous eutrophication impact.

INSERT TABLE 4

The application of UFW compost, at a rate of 40 kg of P/ha/yr, adds 33 tons/ha/yr of organic matter or 1.4%/yr, over a depth of 200mm. Such rate of organic matter application to land can help reduce erosion and improve fertilizer and water absorption, thus advantage the quality of water resources. The value of organic matter in reducing risks of erosion and mineral fertilizer leaching needs further investigation, but in this paper will be evaluated as equal to its mineral content. Similarly, 1.0kg of dry compost can absorb up to 3.0kg of water and 2.0kg of this water is readily available to plants (Soussi et al., 2006). The land application of compost, at a rate of 33 tons/ha/yr, can therefore improve water retention by 7 mm following rainfall events, and thus reduce irrigation requirements. This is particularly interesting because water is becoming an increasingly precious commodity. Table 4 estimates the water holding value of UFW compost using a cost for wholesale water of \$0.50 US/m^3, which corresponds to water obtained from reservoirs. When the water is obtained by desalination, the cost ranges between \$0.75 to \$1.00 US/m^3 (Hamer, 2007).

Finally, the on-site composting of UFW eliminates a major portion of the MSW handling, landfilling and greenhouse gas recovery costs. On-site composting in urban areas allows local residents to bring their UFW to the composting centre as opposed to hiring expensive equipment for the collection. Furthermore, composting reduces the mass of FW by 50%, even after adding a bulking agent, and this compost can be used on farm land on the outskirts of the city whereas landfills are further away to avoid nuisance. Accordingly, collection and transportation of UFW can be reduced by over 50% and landfill greenhouse gas emissions are dropped to negligible levels, eliminating the need for their recovery.

When considering all benefits introduced with the on-site composting of UFW, composting becomes a profitable operation. Considering all the added benefits as soil amendment, farm land users will most likely be willing to use the compost in Asia as well as in North America. The high quality of the compost will be an added value.

4.3 On-site anaerobic treatment of UFW and energy generation

Besides composting, anaerobic digestion is the other available technology to treat UFW on-site. Anaerobic digestion produces biogas which can replace natural gas, does not require the purchase of bulking agents and can deodorize UFW rather than release odours. Nevertheless, composting produces a dry, stabilized and volume reduced product, as opposed to anaerobic digestion which generates a large volume of wet and non-disinfected sludge (Bagge et al., 2002) requiring dewatering to produce a high quality soil amendment.

At present, the anaerobic treatment of the Asian UFW can produce 17 Gkg of CH_4 and this production is estimated to increase to 25 Gkg, in 2025 (Table 5a). If burned to get the highest conversion efficiency of 56 MJ/kg CH_4 (EDM, 2007), the 2025 energy recovery potential from UFW in Asia is equivalent to 1400×10^{12} KJ/yr which also represent 44 million kW of energy generation on a continuous basis (Table 5b). Similarly, the urban UFW from the Americas, Europe and Africa can produce 616×10^{12} KJ, 392×10^{12} KJ and 280×10^{12} KJ of energy respectively, in 2025. If all urban UFW could be anaerobically treated on-site, the total global energy recovery for 2025 is estimated at 2688×10^{12} KJ; Asia alone could produce 52% of total energy recovery. Nevertheless, this only represents 1.4% of the energy offered by the 15 million m^3/d of crude oil presently utilized by the world.

INSERT TABLES 5a and b

When compared to the total world energy demand including that obtained from crude oil, the conversion of UFW into biogas represents less than 0.5% (Table 6). Even for India, UFW could only generate 0.66% of all of its energy needs. For the anaerobic digestion of UFW to produce at least 1% of the world energy, in terms of biogas, wastewater sludge and green wastes (ex. grass clippings) will have to be added.

INSERT TABLE 6

Justifying biogas production from UFW therefore requires its use by a plant with a high demand for clean fuels, such as a food processing plant, a foundry or a community heating plant. The anaerobic digestion of the UFW and sludge produced by a population of 1.0 million represents 10 GW of power (100% efficiency), which becomes interesting when used by a single large plant. Sludge added to the UFW can provide sufficient liquid to liquefy the UFW for its anaerobic digestion, but introduces additional health risks for the workers.

4.3.1 Community UFW anaerobic treatment centres for Mumbai, India

Energy is one of the major issues for the city of Mumbai, India. Each anaerobic digester implemented per km^2 of urban area could generate 130 kW of power on a continuous basis, assuming 100% efficiency (Table 7). This energy could easily be used by a factory or industry, but could not be distributed to all the contributing families. As opposed to 6 composting centres/km^2, one anaerobic digester/km^2 is preferred to optimize the size of the operation. Thus, local communities would need more incentives to bring their UFW for treatment. The sludge produced would need pasteurization and dewatering before being suitable for soil fertilization (Hartmann et al., 2004). Sludge produced by the anaerobic digesters could be used as soil amendment by nearby gardens rather than farm land outside the city limits, to eliminate the need for dewatering.

INSERT TABLE 7

The benefits of anaerobically digesting UFW can be analyzed, as done for composting (Table 8). The anaerobic digestion of UFW generates less organic matter but just as much mineral fertilizer as composting. In exchange, biogas produces energy and eliminates most cost associated with landfilling, except for the collection and 75% of the transportation. As for composting, anaerobic digestion becomes interesting when considering the added benefits on the environment and world resources.

INSERT TABLE 8

5 Conclusions

The rapid urbanization and growing economic activity around the world accelerates the generation of municipal solid waste (MSW) and urban food waste (UFW) within city limits, especially in developing economy. While presently most large city in Asia, Africa and South America does not have the funds to even collect all of its MSW, those in North America and Europe do not see the incentives to recycle UFW.

The on-site recycling of UFW through composting or anaerobic digestion can be demonstrated as attractive when considering all benefits, including those having an effect on the environment and the world water, soil and air resources. Source separation is a pre-requisite to successfully compost and to anaerobically digest UFW, with the least risk of contamination for agricultural soils and the food supply chain. The organic matter recycled by such treatment technologies could produce a soil amendment capable of fertilizing 3 million ha/yr while increasing the soil organic matter by 1.4%/yr and the water retention by 7mm. If composting requires a plentiful source of bulking agents and a biofilter for odour control, anaerobic digestion requires additional hygienic protection for the operators and sludge users.

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List of tables:

Table 1 Total and urban population for various countries and their food waste generation

Continent	Country	Population		Food waste generation	
		Total 10^6	Urban %	UFW kg/c/d	UFW Gkg/d
Africa	Algeria	30.24	59.3	0.34	6.1
	Ethiopia	65.59	17.7	0.33	3.8
	Kenya	30.55	33.1	0.37	3.7
	Morocco	29.11	55.3	0.35	5.6
	Niger	10.74	20.6	0.50	1.1
Asia	China	1275.2	52.0	0.34	243.0
	India	1071.0	42.0	0.34	153.0
	Kuwait	2.25	97.6	0.60	1.32
	S. Korea	46.84	86.2	0.60	24.2
Europe	France	59.30	75.6	0.60	26.9
	Germany	82.28	87.5	0.60	43.2
	Poland	38.67	65.6	0.35	8.9
	U.K.	58.69	89.5	0.60	31.5
	Spain	40.75	77.6	0.60	19.0
	Sweden	8.86	83.3	0.60	4.4
North America	Canada	30.77	77.1	0.60	14.2
	USA	282.19	77.2	0.70	152.5
	Mexico	98.93	74.4	0.40	29.4
South America	Argentina	39.20	76.0	0.40	11.9
	Brazil	179.00	67.0	0.37	44.4
	Peru	27.60	61.0	0.36	6.1
	Chili	16.08	71.0	0.40	4.5

Note: UFW generation is on a wet mass basis for 2007.

Table 2 Community composting centers for Mumbai, India

Description	Numbers and specification
*Population/km^2	27000
Food waste production/person/day	0.25kg
Number of composting center/km^2	6
Number of in-vessel composters/center	2
Specification of each composter	6m long and 2.4m diameter
Composting cost (fixed and operational)	85 US$/ton wet compost

*Demographia (2007)

Table 3 Estimated annual continental compost production from urban food waste (UFW) in Gkg

Year	Asia	Americas	Europe	Africa
2005	83	38	29	15
2010	94	41	30	18
2015	103	45	34	21
2020	114	48	33	23
2025	125	52	34	26

Note: compost generation is presented on a wet basis; these masses are computed from UFW production data presented in Table 1 assuming a 50% mass reduction after inclusion of a bulking agent followed by composting.

Table 4 Value of composted UFW for Asia and North America

Valorization	Value of composted UFW $ US / ton	
	Asia	North America
Fertilizer value[1]	$14.20	$24.75
Organic matter advantages[2]	$14.20	$24.75
Production from land saved[3]	$ 5.70	$ 2.85
Agricultural water[4]	$14.40	$14.40
Saved landfilling cost[5]	$35.70	$44.60
Greenhouse gas recovery[6]	$ 6.40	$ 6.40
Total savings	$90.20	$117.75
Composting cost	$85.00	$110.00

Note:

[1] $0.25, $0.65 and $0.65/kg for N, P and K in Asia and $1.15, $1.15 and $0.60/kg in North America (Barrington, 2007) for compost at 50% moisture containing 12, 1.2 and 16 kg of N, P and K per wet ton;

[2] less soil erosion and improve fertilizer adsorption efficiency for higher quality water resources; estimated at 100% of fertilizer value;

[3] land saved from landfilling after 20 years of recycling UFW for 2 and 1 crops/yr in Asia and North America, valued at $1000/ha;

[4] improved water holding capacity estimated at 1.2 m^3 /ton/yr for 4 years, after 6 rainfall events/year, at $0.5 US/$m^3$ (Hamer, 2007);

[5] saving 50% of collection and transportation costs ($16.00 and $1.40 US/ton UFW) plus 100% of landfill cost ($18.60 US/ton UFW) in North America, where 1.0 ton of compost represents 1.6 tons of UFW; in Asia, this cost is 20% lower;

[6] composting produces 50% less methane than landfilling; 1.6 tons of UFW generates an additional 56 m^3 of methane when landfilled (West et al., 1998) at a cost of $4.00 US/ton UFW.

Table 5a Continental methane (CH_4) production from the anaerobic digestion of UFW in Gkg/yr

Year	Asia	Americas	Europe	Africa
2005	17	8	6	3
2010	19	8	6	4
2015	21	9	7	4
2020	23	10	7	5
2025	25	11	7	5

Source: Adhikari et al. (2006)

Note : UFW – urban food waste.

Table 5b Continental energy recovery potential from the anaerobic digestion of UFW in 10^{12} KJ/yr

Year	Asia	Americas	Europe	Africa
2005	952	448	336	168
2010	1064	448	336	224
2015	1176	504	392	224
2020	1288	560	392	280
2025	1400	616	392	280

Note : UFW – urban food waste.

Table 6 Total energy need versus that recovered from UFW anaerobic digestion

Continent	Country	Energy consumption		Energy from UFW	
		OE kg/c	Energy kW/c/d	UFW kg/c/d	Energy of total
Africa	Continent	1628	2.74		
	Algeria	1038	1.74	0.34	0.35%
	Ethiopia	278	0.47	0.33	1.28%
	Kenya	481	0.81	0.37	0.84%
	Morocco	357	0.60	0.35	1.07%
	Niger	777	1.31	0.50	0.70%
Asia	Continent	991	1.67		
	China	1138	1.91	0.34	0.32%
	India	512	0.86	0.34	0.75%
	Kuwait	9076	15.25	0.60	0.07%
	S. Korea	4347	7.3	0.60	0.15%
Europe	Continent	3700	6.2		
	France	4518	7.6	0.60	0.14%
	Germany	4203	7.1	0.60	0.13%
	Poland	2370	4.00	0.35	0.16%
	U.K.	3918	6.59	0.60	0.16%
	Spain	3228	5.43	0.60	0.20%
	Sweden	5765	9.67	0.60	0.11%
North America	Continent	7844	13.20		
	Canada	8300	14.00	0.60	0.08%
	USA	7795	13.10	0.70	0.10%
	Mexico	1533	2.57	0.40	0.28%
South America	Continent	1083	1.82		
	Argentina	1575	2.65	0.40	0.27%
	Brazil	1066	1.79	0.37	0.37%
	Peru	432	0.73	0.36	0.88%
	Chili	1652	2.78	0.40	0.26%
World		1674	2.81		

Earth Trends (2007); Adhikari et al. (2006).

Note : OE – oil equivalent; UFW – food waste; energy from food waste after anaerobic digestion and at 100% efficiency. All UFW production values are on a wet basis.

Table 7 Example of urban anaerobic UFW digester for Mumbai, India

Description	Numbers and specification
*Population/km^2	27000
Food waste production/person/day	0.25kg
Number of anaerobic treatment center/km^2	1
Water to be added/0.25 kg of UFW	0.15kg
Capacity of digester/km^2	162 m^3
Dimension of digester	10 m diameter and 4 m deep @ 2/3 capacity
Methane production /day	290 m^3
Energy generation, kW	130 kW (100% efficiency)

*Demographia (2007)

Table 8 Value of anaerobically digested UFW for Asia and North America

Valorization	Value from UFW $ US / ton digested Asia	 North America
Fertilizer value[1]	$ 8.90	$15.50
Organic matter advantages[2]	$ 3.10	$ 5.40
Production from land saved[3]	$ 3.60	$ 1.80
Agricultural water[4]	$ 3.20	$ 3.20
Energy production[5]	$28.80	$28.80
Saved landfilling operations[6]	$16.00	$20.00
Greenhouse gas recovery[7]	$ 4.00	$ 4.00
Total savings	$67.60	$78.70
Anaerobic digestion cost	$43.20	$43.20

Note:

[1] same fertilizer value as compost because both process loose nutrients through leachate (compost) and from dewatering (anaerobic sludge);

[2] 70% loss of organic matter versus 15% loss with composting; estimated at 35% of fertilizer value;

[3] land saved from landfilling after 20 years of recycling UFW for 2 and 1 crops/yr In Asia and North America, valued at $1000/ha;

[4] at 35% of the capacity of compost, because of organic matter losses during digestion;

[5] 1.0 ton of wet UFW produces 360 kW-h of energy at 80% efficiency when burned, worth $0.10 US/kW-h;

[6] saving of 0% collection, 75% transport and 100% landfilling;

[7] same recovery as for composting.

[8] the cost of producing this energy without gas scrubbing is evaluated at $0.15 US/kW-h as experienced in Europe.

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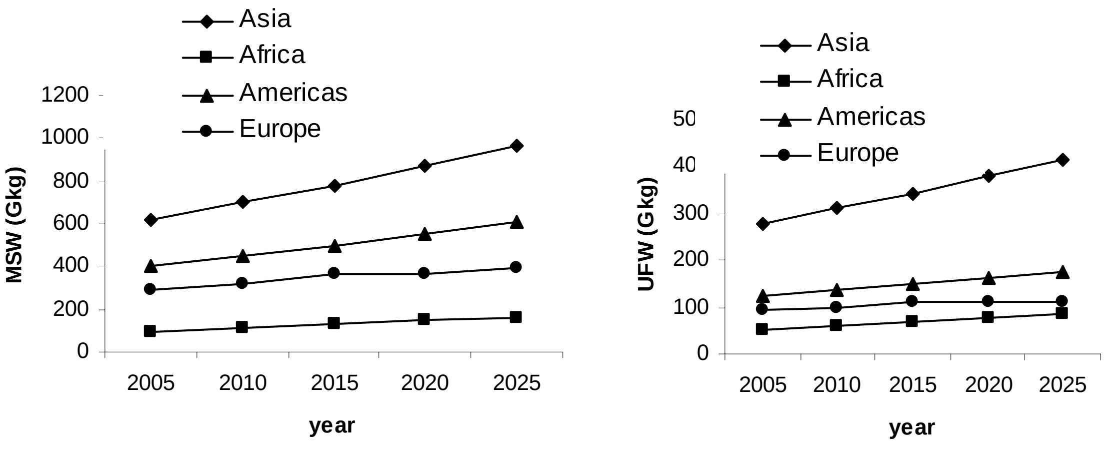
Figure 4 Estimated municipal solid waste (WSW) management cost reduction if urban food waste (UFW) is separated at source and treated onsite



(a) (b)

Figure 1 Continental urban solid waste production on an annual basis: (a) municipal solid waste (MSW); and (b) urban food waste (UFW)
(Source: Adhikari et al., 2006)

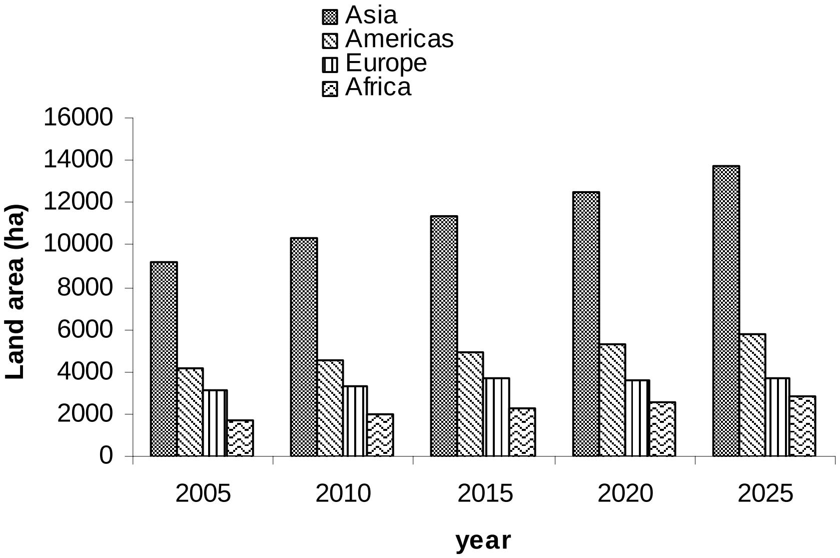


Figure 2 Estimated land requirement for landfilling of urban food waste (UFW)

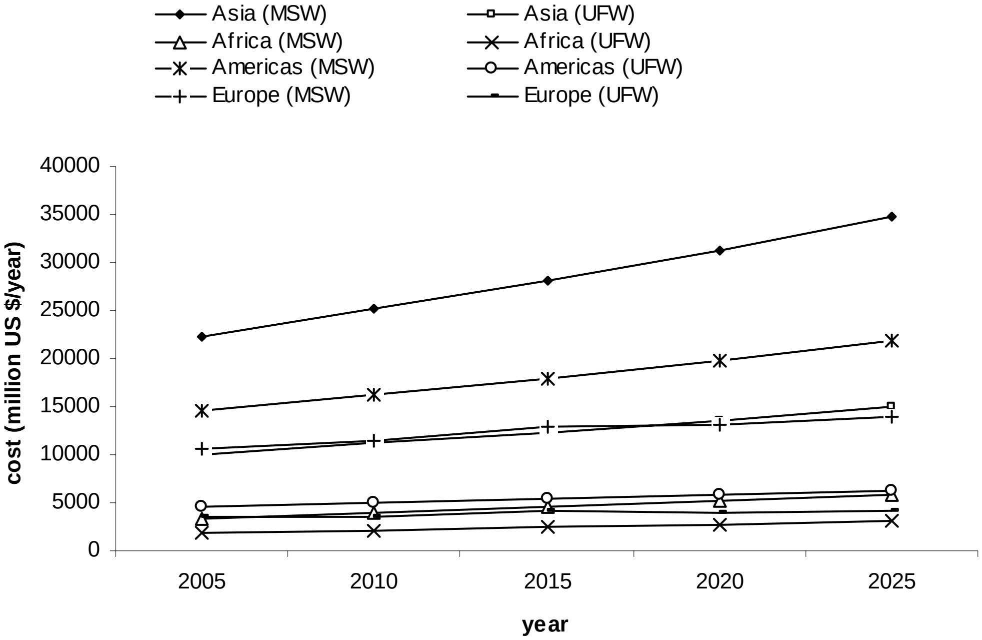


Figure 3 Estimated continental cost requirement for handling of municipal solid waste (MSW) and urban food waste (UFW)

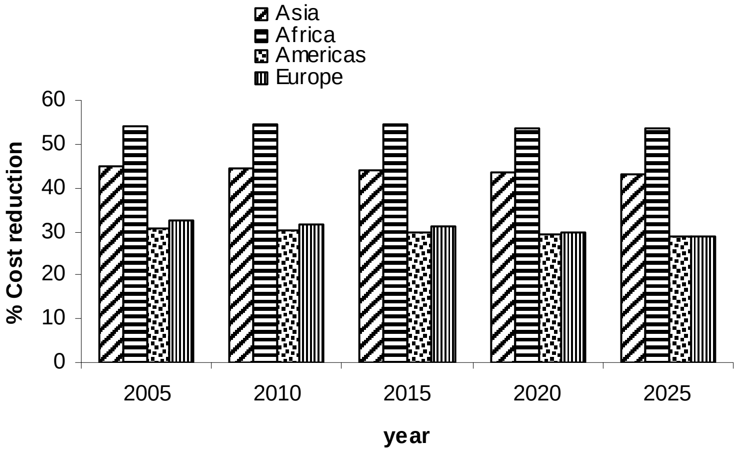


Figure 4 Estimated municipal solid waste (MSW) management cost reduction if urban food waste (UFW) is separated at source and treated onsite