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SUSTAINABLE MUNICIPAL SOLID WASTE MANAGEMENT IN EMERGING ECONOMIES: AN INNOVATIVE ROUTE

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ABSTRACT

Presented is an innovative and local driven solution to sustainable management of municipal solid waste in emerging economies. It is anchored on source separation and draws on the zone’s two strengths: abundance of cheap labour and abundance of organic waste fraction. It discusses the problems responsible for the zone's dismal performance, and puts forward a way out. The presentation next examines the zone’s solid waste features, including composition and characterization. This is followed by the material recovery phase. Finally examined is the energy recovery phase employing waste-to-energy technologies involving incineration, pyrolysis and biodegradation, to augment energy supply.

Keywords: Energy, Environment, Management, Municipal, Organic, Resource, Sustainable, Waste.

1.0 INTRODUCTION AND THE MUNICIPAL SOLID WASTE PROBLEM

Rapid urbanization, no doubt, has resulted in generation of increased (higher tonnage per capita) municipal solid waste in emerging economies, creating for the zone, a problem of immense proportion in municipal solid waste management (MSWM). Age-long adopted methods of waste management which relied essentially on disposal using open dumping/landfill or incineration have become inadequate. The old methods have become environmentally and economically unacceptable, and will have to give way to sustainable methods of solid waste management. This has resource recovery at its core. Today, management of wastes has evolved beyond mere disposal, to embrace perhaps more importantly, resource recovery [1]

An array of valuable resources locked up in municipal solid waste (MSW) can be harvested by employing appropriate resource recovery methods. The time has come to move away from old disposal methods of landfill or open incineration to resource recovery. Ideally this will result in the recovery of energy and valuable materials suitable for recycling including perhaps a small proportion of inert materials that can be safely land filled and or used as a building material composite. By so doing, modern waste management will augment the overall effort at resource conservation while engendering sustainability.

Open dumping, landfill and incineration have largely remained the traditional waste disposal methods in emerging economies. These methods have fallen short of providing the solution to the solid waste problem. Open dumping is considered the least expensive, albeit it poses serious environmental problems. At the heart of the problem is pollution. There is usually an objectionable stench at the dump site, which is associated with organic waste decomposition, together with release of toxic gases which are harmful to humans. The dump site is also usually infested with roaches, rodents, and all manner of scavengers, all foraging. This makes work crew and people living in the vicinity to be vulnerable to a number of animal-to-human transmittable diseases. Ground water sources can also be contaminated and can lead to epidemics like cholera. Open incineration of MSW is no less hazardous. In addition to the wanton release of CO_2 with its green house and climate change effect, open incineration can cause a number of aforementioned health problems, particularly those associated with release of choking toxic gases, largely resulting from incomplete combustion. To navigate out of this mess, there is need to adopt sustainable MSWM which addresses environmental concerns, in addition to promoting economic benefits.

Without doubt, MSW presents a significant environmental challenge to the developing world. For example, African countries have been unable to properly manage their enormous wastes; hence there is need for adoption of innovative strategies that will aid them to tackle this problem [2]. There is therefore the dire need to embrace re-use of waste through a variety of resource recovery options. This will contribute in generating employment and income, while at the same time promoting clean and healthy cities.

The maintenance of clean environment in our cities requires effective MSWM that embodies waste evacuation, resource recovery and disposal [3]. Although Waste-To-Energy (WTE) technologies had long been adopted and practiced in the developed world, emerging economies that have been largely left out, are now gradually coming on board [4].

In South Africa, like other emerging economies, there has been an increase in urbanization, population, industrialization and modernization which has led to generation of more waste and consequently more pollution [5]. There is a growing interest in resource recovery from MSW among some developing countries, particularly in Africa, for instance in Namibia, Nigeria and South Africa where cogeneration is receiving serious attention [6, 7]. In Cameroon, efforts have been made to recover useful bio-methane from landfills [8]. The first promising MSW Incineration plant is currently undergoing construction in Addis Ababa, Ethiopia [9]. While the main aim of WTE technology is waste management, it can also be viewed as a sustainable source of energy products to compliment dwindling fossil sources [10, 11, 9].

Solution variants exploited by the developed economies might not effectively address the peculiarities of emerging economies, hence, the need for scrutinizing local conditions and limitations in proposing options for management of wastes in developing economies. The prevalent high organic fraction in the zone's MSW, together with its abundant cheap labour force form two important strengths yet unexploited. Perhaps the Organic Waste Buyback Scheme (OWBS) enunciated in [12], is worthy of consideration, adoption and implementation in the developing world.

2.0 SUBJECT MSW STREAM: FEATURES, COMPOSITION AND CHARACTERIZATION

The daily global estimate of MSW is currently put at 3.5 million tons. The geographical distribution is presented in Figure 1. Data for Organization for Economic Cooperation and Development (OECD) countries are more often aggregated by the World Bank whereas those for all other countries are grouped in line with the respective regions. From available data, while OECD countries put out about 2.2kg of MSW per capita per day, the rest of the developing countries report about 0.45-1.1kg per capita per day [13]. From Figure 1, it can be seen that due to a considerably high population density in non-OECD countries (which are generally developing countries), they generate about 55% of the total.

The features of MSW is predicated on a number of factors that include the level of economic development, living standards and life styles, and it has generally been noted that developing countries, generate MSW with a higher organic/biodegradable content than is the case in developed countries [13]. This organic component is essential in the generation of Refuse Derived Energy (RDE), implying that the emerging economies have the potential for higher WTE output per capita in comparison to developed economies.

Composition of MSW by region is presented in Table 1, which reveals a higher percentage of organics and paper for developing countries, while the remainder of the composition portrays a unified trend. The higher organic content has implications for WTE applications. This organic waste is moisture rich and therefore more suitable for WTE composting/biogas application, as it is too wet for WTE incineration application [14].

Table 2 compares the physical composition of MSW for seven Nigerian cities, obtained in a separate study. It shows differences attributable to each city's population and industrialization. Table 3 presents waste generation for some Nigerian cities.

The physical composition of MSW for Harare city, Zimbabwe, is presented in Figure 2, and mirrors that of developing countries, where the organic content constitutes a larger proportion in comparison to that of developed economies. Thus, Harare registers a combustible fraction of 70-80%by Mass. The proportions for other cities in Sub-Saharan Africa include Accra (Ghana) 89%; Abeokuta and Onitsha (Nigeria) 86.3% and 83.1%, respectively [15, 7]. The proportion of plastics is 13.4%, which exceeds by 8%, the average value for low income economies [16]. It is important to note that MSW has appreciable moisture content, and the rainy season increases this significantly. Table 4 shows regional percentage composition by moisture, of the different components of the MSW, for Harare, Zimbabwe.

2.1 Energy Content of MSW

If MSW is to be utilized for energy generation, it is imperative that the heating value of MSW be known. The heating value of any fuel represents the amount of heat released from completely burning 1 kg of the fuel. This ranges from a Lower Heating Value (LHV) to a Higher Heating Value (HHV) depending on the fuel’s composition. For MSW, the LHV on a wet basis is preferable because WTE thermal processes will require extra energy to expel excess moisture from the wet fuel before the onset of sustained exothermic combustion. Plastics with a heating value of about 40 MJ /kg provide good combustibility to MSW [17]. However, plastics have been known to possess high potential for recycling thus making them practically unavailable as substrate for WTE applications [18].

The mean energy contents of MSW (for Harare city) both by direct measurement and empirical estimation have been reported to be 10.09 and 9.32MJ/kg as shown in Table 5. Similar studies in select sub-Saharan urban cities, report measured values as 12.0, 7.0, 13.1 and 11.9 MJ/kg for Addis Ababa, South Africa, Nigeria’s Southern and Northern cities, respectively [19, 7].

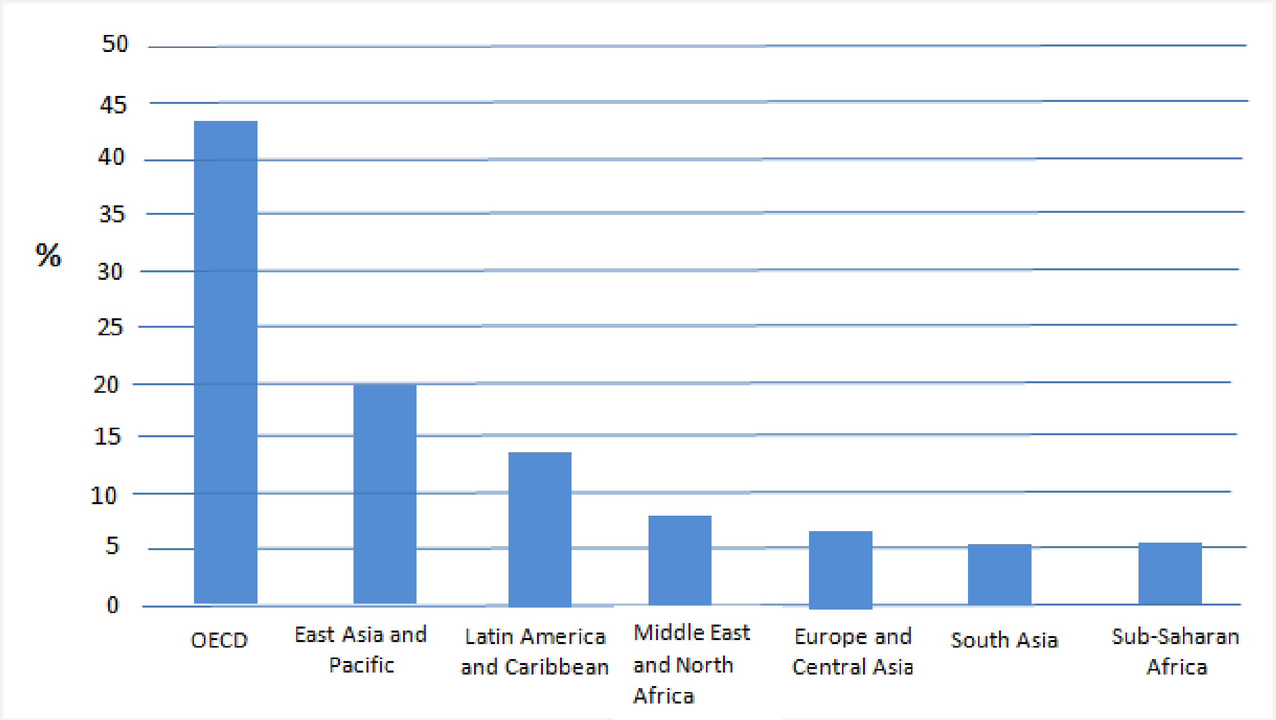


Figure 1: Distribution of global waste generation. OECD: Organization for Economic Co-operation and Development. Source [13]

Table 1. **Regional variation of Municipal Solid Waste (MSW) composition percentage. Source [12]**

	Organic	**Paper**	**Plastic**	**Glass**	**Metal**	**Other**
East Asia & Pacific	62	10	13	3	2	10
Middles East & North Africa	61	14	9	3	3	10
Africa	57	9	13	4	4	13
Latin America & Caribbean	54	16	12	4	2	12
South Asia	50	4	7	1	1	37
Eastern Europe & Central Asia	47	14	8	7	5	19
OECD	27	32	11	7	6	17

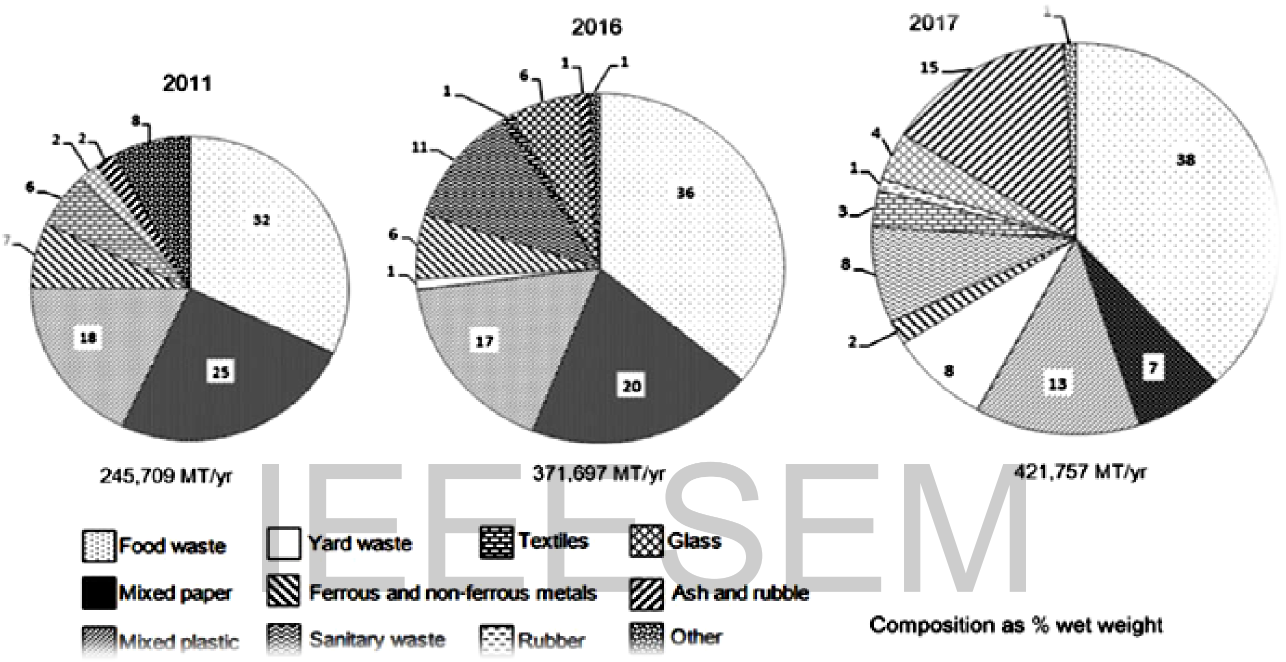


Figure 2. Physical composition of MSW in Harare city in 2016 and 2017 as compared to the national urban mean for 2011 Data. Source [20]

Table 2: Composition of waste stream for seven Nigerian cities source [21]

	Nsukka	Lagos	Makurdi	Kano	Onitsha	Ibadan	Maduguri
Putrescible	56	56	52.2	43.0	30.7	76	25.8
Plastics	8.4	4	8.2	4.0	9.2	4.0	18.1
Paper	13.8	14.0	12.3	17.0	23.1	6.6	7.5
Textile	3.1	-	2.5	7.0	6.2	1.4	3.9
Metal	6.8	4.0	7.1	5.0	6.2	2.5	9.1
Glass	2.5	3.0	3.6	2.0	9.2	0.6	4.3
Others	9.4	19.0	14.0	22.0	15.4	8.9	31.3

Table 3: Waste generation for some Nigerian cities. Source [21]

City	Population	Agencies	Tonnage per month	Density (kg/m^3)	Kg/capita/day
Lagos	8,029,200	Lagos Waste Management Authority	255,556	294	0.63
Kano	3,248,700	Kano State Environmental Protection Agency	156,676	290	0.56
Ibadan	307,840	Oyo State Environmental Protection Commission	135,391	330	0.51
Kaduna	1,458,900	Kaduna State Environmental Protection Agency	114,433	320	0.58
Port Harcourt	1,053,900	Rivers State Environmental Protection Agency	117,825	300	0.60
Makurdi	249,000	Urban Development Board	24,242	340	0.48
Onitsha	509,500	Anambra State Environmental Protection Agency	84,137	310	0.53
Nsukka	100,700	Enugu State Environmental Protection Agency	12,000	370	0.44
Abuja	159,900	Abuja Environmental Protection Agency	14,785	280	0.66

Table 4. Harare MSW moisture content (MC). Source [20]

	Wt% MC as-discarded									
	Food waste	Paper	Yard waste	Other fines	Plastics	Textiles	Rubber	Wood waste**	Rubble and ash	O/IC
Harare	70.4	19.87	41.5	32.04	3.6	22.8	0.25	9.98	3.72	0.03
Chitungwiza	71.01	18.7	32.03	21.3	2.1	19.8	0.62	8.67	2.89	0.06
Epworth	68.01	14.45	21.05	21.08	2.08	18.7	0.31	9.09	2.01	0.04

O/IC: other incombustibles. Wood quantities were insufficient to form a separate category but for their importance in WTE, their MC was measured

Table 5. MSW Energy Content. Source [20]

		Energy content (MJ kg-^{1})		
		Combustible fraction (LHV$_{db}$)	Combustible fraction (LHV$_{wb}$)	Full MSW stream (LHV$_{wb}$)
Direct measurement				
	Harare	22.26	14.62	12.87
	Chitungwiza	18.09	10.7	8.34
	Epworth	21.03	12.96	9.07
	Mean	20.46	12.76	10.09
Estimation				
	Harare	18.42	12.73	11.2
	Chitungwiza	16.53	10.58	8.25
	Epworth	18.57	12.18	8.52
	Mean	17.84	11.83	9.32
Agreement* (%)		87	93	92

*between mean values

3.0 UPSTREAM MSWM WITH MATERIAL RECOVERY

Effective MSWM in developing economies must take into consideration prevailing local situations. On this premise, MSWM in emerging economies will need to exploit the zone's two greatest strengths: abundance of cheap labor and abundance of organic waste stream in the generated MSW. In the broad context of waste management in general, it is convenient to categorize MSWM activities into two phases: the upstream phase and the downstream phase. The spectrum of MSWM activities, starting with waste collection from source, to transporting/handling, through sorting, to separation for material recovery, and finally to WTE recovery, can be classified into two broad activities, namely, upstream phase and downstream phase. The upstream phase encompasses waste collection, handling, sorting, separation, and finally obtaining the left-over energy rich organic waste stream. The downstream phase embodies the utilization of the prepared organic waste stream as feedstock to run a variety of WTE applications to produce marketable energy products.

Abundant cheap labor will be leveraged for the upstream phase while abundant organic waste stream will be leveraged for the downstream phase, with the former driving the latter. While the upstream phase will engage the services of mostly unskilled labor, the downstream phase will be manned by a technically competent workforce. In sub-Sahara Africa, typical of emerging economies, the informal labor sector which is currently fairly organized and very much active and vibrant in the upstream phase needs to take center stage, and partner with the municipal authorities. The upstream phase will be highly labor intensive with little or no automation. Upstream operators can be empowered to own and operate simple lifting/tipping vehicles. Working with compacting trucks is not necessary. It appears these trucks underperform in the developing world possibly as a result of prevailing poor infrastructure. Experience has shown these specialized trucks are expensive to operate as they breakdown very frequently. Upstream operations will be devoid of unnecessary mechanized gears which are expensive to install and maintain.

Separation at source is the bedrock of upstream MSWM. Buyback incentives can be used to encourage source separation at households with provision of separate labeled containers for metals, glass, paper, plastics and organic/food waste. In this regard the work by Hettiarachchi et al [12] is brilliant and quite commendable, as it discusses in great detail the organic waste buyback concept. Waste collectors can augment sorting and separation at source making use of hand-held permanent magnets and using hand-drawn carts, wheel barrows and tricycles to move aggregated collections to nearby collection centers. Collection from sources can be scheduled twice weekly. This arrangement should mop up accumulating refuse and prevent rot/putrefaction of organic waste at sources. Trucks can now move the bulky largely organic streams from the collection centers to receiving stations for certification and use in a variety of WTE applications, while market is found for recycled materials. The upstream phase deals essentially with waste evacuation, material recovery and marketing of same. Again the informal sector of waste pickers is at hand to help with marketing these recycled materials, to ever willing artisans. In Onitsha Nigeria, it is reported that about 40% of Artisans and small scale industrial outfits source approximately 48% of their raw materials from waste pickers [21]. From the foregoing, the upstream phase will create hundreds of jobs, which will help alleviate economic hardship in the community while leaving the cities clean.

This huge informal sector contribution in Nigeria MSWM is solely responsible for evacuating about 30% of wastes in urban cities [21]. These waste pickers are driven by poverty and a determination to make a living; their activities provide employment to a large number of people. Their activities should be encouraged but need to be regulated as stakeholders in MSWM. In some public places, industrial clusters and markets, these waste collectors are paid to routinely remove accumulated waste, thus providing services in many areas where the agencies cannot. Inaccessibility to refuse disposal trucks is one reason responsible for non-collection in impoverished neighborhoods and illegal settlements, with narrow walk ways and alleys. Resort to the use of motorbikes and/or tricycles in moving MSW from such difficult terrains to nearby transfer sites has provided the solution in some Asian cities [22, 23]. This can be replicated in other emerging economies. The waste pickers are usually able to sieve through waste dumps and salvage material for eventual re-sale. It is clear that in MSWM this informal sector is seriously and methodically involved in material recovery and recycling. Truly this informal sector is a cost-effective contributor to enhanced MSWM, which needs to be fully integrated in the upstream phase. Source separation is advocated as a strong component of upstream phase, as this is key to material recovery and recycling. Integrating this with an incentive like aforementioned organic buyback scheme will definitely be a game changer in the MSWM. No doubt, the waste pickers/scavengers of this informal sector are well-experienced in the business of material recovery from MSW.

Here is the scenario/action plan. These waste pickers will be positioned as zonal collection agents each manning a separate zone for an agreed registration fee that goes to the municipal authority. Each agent hires and caters to his workforce, which he equips with portable weigh scales, metal prongs, hand-held magnets, shovels, tough reusable sacks, ropes, protective wears, wheel barrows, hand-drawn carts, bikes/tricycles etc. The collection agents in addition to augmenting sorting and separation in their zones along the MSW supply line for their own direct benefits, will buy up recycled materials from household sources at an agreed rate(price/kg for each material) to be regulated by the municipal authority. Each agent will then re-sell the acquired recycled materials to end users i.e. artisan/industries. Finally each agent undertakes the re-sale of the prepared largely organic waste stream, at a marginal price (based on moisture content) to the municipal authority for use in designated WTE applications.

Thus the entire upstream phase featuring material recovery will be run by the profit oriented private sector. The municipal authority will erect and operate a few number of MSW collection/processing centers and one or two organic waste receiving stations depending on WTE options. Waste collection centers will be equipped with moveable roof covering to enhance aeration/sun-drying, while the receiving station(s) will be equipped with truck drive-through weigh scales.

4.0 DOWNSTREAM MSWM WITH ENERGY RECOVERY:

Downstream MSWM involves the utilization of the predominantly organic waste fraction to execute various WTE options. This means turning the organic waste into energy resources. A number of products are possible including thermal energy, compost and a variety of storable solid, liquid, and gaseous fuel. High moisture content organic waste stream is better suited for production of compost and biogas using WTE biodegradation technology. Production of both resources is cheap and achievable with simpler technologies [14, 24]. The organic waste stream destined for other WTE applications like incineration and pyrolysis will need to be sundried to reduce its moisture content to acceptable level. It will appear that WTE biodegradation route enjoys comparative advantage in emerging economies, as much of the zone can boast of abundance of high moisture organic waste. However the necessary condition for such WTE projects to be viable and sustainable is securing a steady market for the products. This is the needful for municipalities shopping for WTE technologies. Demand and supply must exist side by side. Thus, the downstream phase featuring energy recovery would be under the control of the municipal authority, possibly executed with government-private sector partnership arrangement.

From the energy resource point of view, organic waste stream provides the feedstock for various competing WTE technologies. It is therefore left to each municipality to fashion out the WTE option that best suits its special circumstances. Conversion of waste to wealth via energy resource recovery is a viable solution to the solid waste menace. The organic fraction of MSW has a vast store of energy resource which can be harvested using three broad conversion routes namely, incineration, pyrolysis and biodegradation.

4.1 INCINERATION

Incineration is the burning of refuse in air, which results in the production of energy. Incineration is arguably the oldest WTE recovery method practiced by man for decades. It is credited with achieving 90 and 70% volume and mass reduction, respectively; hence, the incineration technology is at present the most acceptable waste to energy technology [25]. The developed world has been successfully producing heat/electricity from the firing of municipal refuse. Incineration is widely practiced without energy recovery in mind, but essentially for volume reduction of refuse headed to landfills. However, the incineration process is associated with the generation of some harmful gases, including sulphur oxides (SO_X), carbon oxides (CO_x), and nitrogen oxides

(NO_x), as well as polyaromatic hydrocarbons (PAH) and heavy metals which degrade environmental safety ecosystem, and thus shielding from the environment becomes imperative [25].

Modern energy recovery incineration plants meet clean air standards. The quantity of heat energy released from burning of MSW is dependent on the constituents of the wastes. Modern incinerator equipment comprises: Stocker, Furnace/heat exchanger and Emission control devices. The stocker feeds the waste to the furnace and ensures intimate mixing of the refuse for improved combustion. The furnace is essentially the combustion chamber. The heat exchanger transfers heat from the product of combustion to the working fluid which puts the recovered energy to use. An efficient way of heat recovery is a furnace that is water walled. In this arrangement, the furnace wall is fitted with steel tubes through which water or steam flows and absorbs heat from the walls of the furnace. Furnace temperatures must be kept high to ensure elimination of all odors. The emission control device (ECD) traps harmful substances from the flue gas and prevents their release into the atmosphere. A variety of emission control devices are in use. Four popular types include mechanical collectors, wet scrubbers, fabric filters, and electrostatic precipitators.

4.1.1 Incinerator Energy Output

The thermal output of the incinerator can be readily delivered to a consumer, either as electricity, hot water or steam. The hot water/steam can be conveniently piped and sold to nearby consumers for applications like process/space heating, comfort cooling and electric power generation. Steam is a very valuable resource from refuse. Another approach to energy recovery from solid waste is by direct utilization of the incinerator combustion products for powering turbine generators, and such turbines can be brought on and off the grid. Modern incinerators employ water-walled furnace and the combustion gases transfer heat in the boiler section resulting in a substantial drop in the existing gas temperature. Thereafter the gases pass through an emission control device such as the electrostatic precipitator for removal of particulates.

4.2 PYROLYSIS

Pyrolysis can be described as the thermal decomposition of a material with limited oxygen. Thus, it offers a very viable option in obtaining storable fuels. Pyrolysis is thought to comprise complex chemical reactions. It is generally believed that the reactive component of the solid waste is composed primarily of cellulose whose decomposition commences at about 180^oC, producing a mixture of solids, liquids, and gas, the proportion and composition depending on reactor conditions and environment [26]. Three common types of pyrolysis methods can be identified, namely conventional pyrolysis (temperature range 550-900K), fast pyrolysis (temp range 850-1250K), and flash pyrolysis temp range 1050-1300K) [25]. Associated environmental challenges include production of pollutants like HCl, H_2S, NH_3, SO_X, NO_X, exhaust gases, and odor impact. The pyrolysis reactor is fitted with ECD to combat these challenges.

4.2.1 Reactor Types

A number of reactor designs are employed for pyrolysis. There are three common basic types namely, shaft, rotary and fluidized bed.

Shaft Reactor: Shaft reactors comprise vertical and horizontal configurations and are the cheapest. Vertical ones have the solid wastes fed from the top from where they settle at the bottom. Pyrolysis produced gases rise up the shaft and are discharged from the top. In the horizontal shaft type, the solid waste is usually conveyor admitted into the reactor from inlet and progresses to the outlet, thus solid waste is continuously pyrolysed from the conveyor in motion. Though problems associated with feed and discharge are minimized, the reliability of the conveyor at elevated temperature is a major challenge. Shaft reactor vessel is made of metal that can withstand high temperatures or is lined with refractory material.

Rotary kiln: The rotary kiln type is essentially rotating vessel with slight inclination to the horizontal and usually a length-to-diameter ratio ranging from 4 to 10 [26]. Refuse introduced through the top progresses down the bottom due to rotation and tilt as pyrolysed products exit the lower end. The reactor internal is usually lined with refractory material. The rotary kiln provides better churning action in comparison with the shaft type reactor. Its major drawback is sealing problem associated with the rotating vessel vis-à-vis non-moving inlet and discharge ports.

Fluidized Bed Reactor: in the fluidized bed reactor type, a bed of solid particles held by gas streams flowing upward undergoes pyrolysis as the solid waste is heated to provide the heat source for the reactions. It surpasses other reactor types in performance through enhanced heat exchange and temperature regulation. Major setbacks include the manifestation of accelerated chamber corrosion, gas velocity control and solid particle transfer/separation problems [26].

4.2.2 Process Variables

Reactor temperature is the dominant factor that determines the end product of the pyrolysis process. Thus, varying the reactor temperature profiles result in the variation of product composition and yield. At elevated temperatures of about 1600°C the gaseous phase comprises hydrocarbons with low molecular weight and gaseous combustion products such as H_2, CO, CO_2, etc., with the slag essentially a mass of solid residue; at lower temperatures the gaseous phase is richer in hydrocarbons with higher molecular weight, with the possibility of a liquid phase, while the solid phase becomes heterogeneous [26].

4.2.3 Heating Methods

In general pyrolysis reactions are endothermic and therefore require heat addition. Two heating methods, namely, direct and indirect methods are employed. In the direct heating, heat input is from part burning of refuse and/or use of supplementary fuel in the reactor, in the presence of oxygen as an oxidant. This yields gases rich in CO and H_2O with product gas being diluted which results in reduced heating value. Using air as oxygen source will lead to NO_X formation with environmental consequences in addition to the dilution resulting from enormous amount of N_2.

In indirect heating method, the heating zone is external to the pyrolysis chamber. The heat can be transferred across an interface wall or through a heat laden medium, (say sand, molten bed) to the pyrolysis chamber. Wall heat transfer is generally not adopted in solid waste application due to large thermal resistance presented by refractory linings and the likes. Hence, the adoption of a separate interface is desirable from a heat transfer perspective. The setback is the problem associated with the transport and separation of solids.

Indirect heating methods are generally not as efficient as the direct heating but are desirable to reduce the problems of large accumulation of CO_2 and H_2O (that lowers heating value) and high amount of NO_X and N_2 (that degrades the environment) [26].

4.2.4 Feedstock Condition: A variety of pyrolysis reactor designs are available to process a large number of feed conditions of solid waste. Some reactors will accept raw municipal solid waste as direct feedstock while some may accept only feedstock that has undergone some pre-conversion processes such as size reduction and/or non-organic components recovery. On the whole, dry feedstock that is finely shredded without solid inorganics (i.e. the solid inorganics have been removed) is most desirable in terms of reaction dynamics [26].

4.2.5 The Product Line: The pyrolysis process is capable of producing storable fuel in solid, liquid, and gas phases. The chemical composition and amount contained in each phase is determined by: the pre-conversion carried out on the feedstock, reactor temperature and residence time and heating method used. Capacities exist from 20 to 200 tons/day.

4.3 BIODEGRADATION

This is the digestion (reduction or breakdown) of refuse using organic methods. The organic methods have two broad routes, namely, biological and biochemical. The former uses biological organisms to effect digestion in either oxygen rich (aerobic) or oxygen starved (anaerobic) environments; the later causes digestion using biochemical methods such as application of chemicals and/or extractions from species of protozoa or fungi [26].

4.3.1 Biological Methods

In aerobic digestion the organic contents of refuse are broken down by microorganism and oxidized to produce humus also known as compost. Compost can be used as a fertilizer which is a marketable resource. Passive composting involves a gradual decay process which requires retention time that runs into weeks. If anaerobic digester is employed refuse is convertible to methane (CH_4) gas, a hydrocarbon fuel. There are usually two steps in the conversion process. The first is the breakdown of organic materials in refuse into organic acids and CO_2. The second step involves bacteria (known as methane formers) acting on the organic acids to produce CH_4 and CO_2.

4.3.1.1 Composting

The basic characteristics of composting from MSW will be examined. The operation of a composting plant involves five sequential steps, namely: preparation, digestion, curing, finishing (or upgrading) and storing [26].

Preparation (or preprocessing) comprises sourcing MSW, sorting, separation, grinding, and adding moisture and/or sewage sludge if available. Next phase is decomposition or digestion. This can take place in either vented chamber or unvented chamber. For a majority of modern composting plant aerobic digestion is more desirable to the anaerobic digestion. This can be viewed in the context of process time, temperature, and odor associated with digestion. Host microorganism that cause aerobic digestion require oxygen rich environment. The speed of the digestion is oxygen dependent. The process becomes slow or anaerobic in the absence of adequate oxygen. Thus we can talk of forced digestion system and passive (or windrow) digestion system. In forced digestion system oxygen is introduced by forced draft while windrow system obtains oxygen by the turning of the heap. The forced system brings down the windrow composting time of about six weeks to about six days [26]. Since aerobic systems attain temperature range of 60^o-70^oC or higher. The associated heat buildup suppresses the growth of pathogenic organisms that can generate weed, fly, ova, odor, etc.

However in anaerobic systems temperature range attained is only about 38^o-55^oC, which allows pathogens to thrive producing foul odors. Any odor or pest problems that manifest in windrow systems arise from pockets starved of oxygen and where anaerobic digestion has set in.

4.3.1.2. Anaerobic Digester/Methane Production

If anaerobic digester is employed organic rich MSW is convertible to methane gas (CH_4), a hydrocarbon fuel. There are usually two stages in the conversion process. The first is the bacteria activated breakdown of organic materials in refuse into organic acids and CO_2. The second step involves bacteria (known as methane formers) acting on the organic acids to produce CH_4 and CO_2. Methane is a gaseous hydrocarbon fuel produced in a two stage process by the anaerobic decomposition of organic materials. Large scale production of methane can be embarked upon if there is an assured source of waste from animal farm and food processing plants. This will include poultry farm, piggery, and feed lots for cattle, sheep, and goats. The methane gas so produced could supply the energy needs of the processing facility.

4.3.2 Biochemical Methods

Here chemicals/enzymatic actions of specific organisms are employed in the processing and conversion of organic materials to an energy product. Microorganisms such as bacteria, protozoa or fungi process the organic material for their metabolic needs. In biochemical conversion, anaerobic breakdown and fermentation are widely used [25]. Biochemical processing involves complex technology and is generally expensive. Apart from cost, other challenges associated with biochemical processing include non-homogenous composition of organic waste stream for consistency of product, toxicity in organic waste arising from the presence of: metallic salt, organic cyanides compounds, industrial solvents (which can poison a biological system).

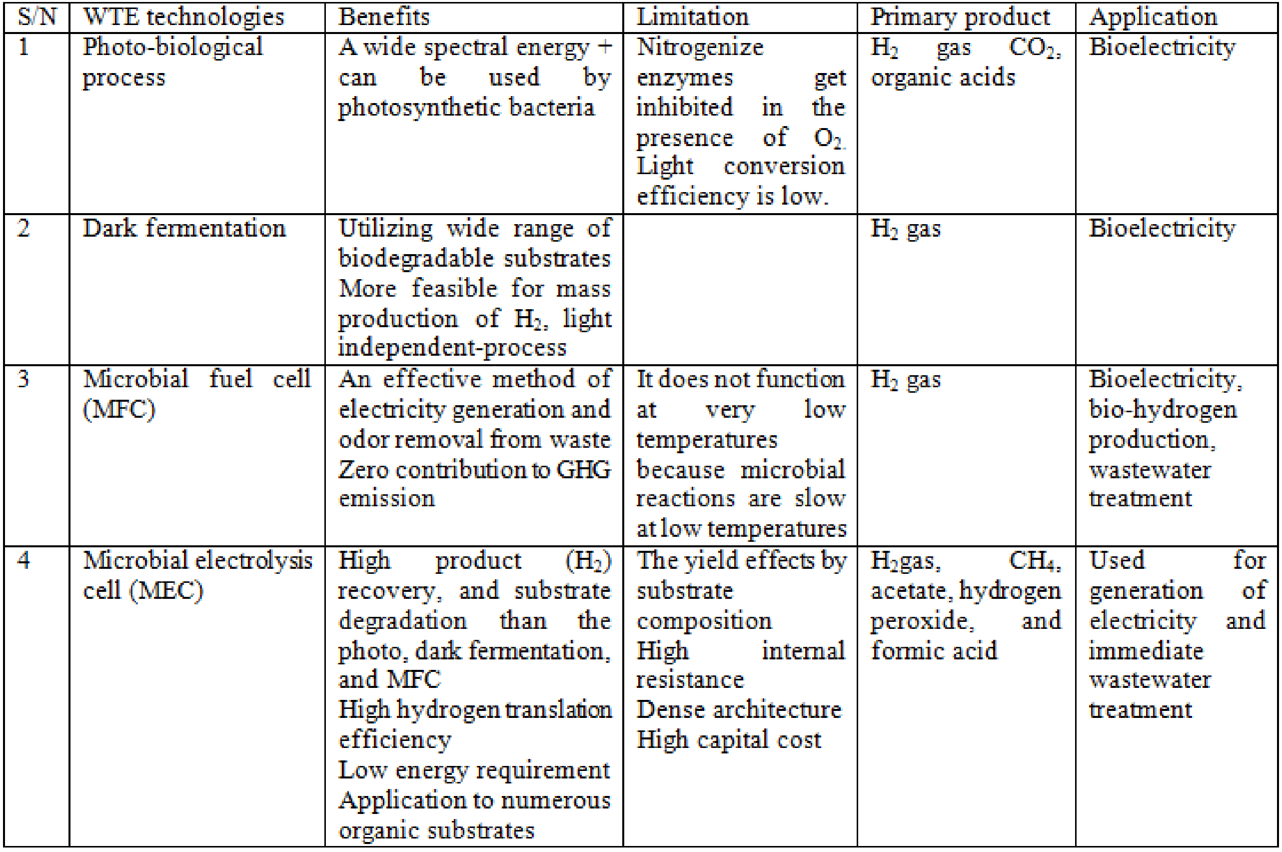
In order to recover the processing cost, the end product must necessarily be of sufficient value. Most biochemical systems are geared to producing food sources [26] but limiting their use as feed to livestock because of toxicity concerns. Biochemical processing is still unraveling with the potential of wide range of applications. Biochemical processing has focused mainly in converting organic solid wastes into yeast or fungal protein simply because of the established process and production industries which depend on yeast for their production, such as breweries.

Production Of Ethanol: it is important to note that ethanol, a hydrocarbon liquid fuel/cleaning agent can be produced by the anaerobic breakdown of organic waste cellulose by yeast while aerobic culture of organic yeast produces a source of protein that can be used as protein supplement in livestock feed [26]. Above production methods are far more expensive and cannot compete with current industrial production methods not employing organic waste as substrates. Current industrial production uses as feedstock, cheap ethylene from petrochemical industries. The use of nutrient yeast produced by biochemical action or process, as a protein supplement for animal feed will have to favourably compete with protein supplements made from fish meal and soya bean meal. Considering the current prices for these two commodities, biochemically processed yeast protein still remains more expensive, even with the abundant cheap cellulose from organic waste.

4.4 EMERGING WTE TECHNOLOGIES

Emerging WTE technologies utilizing organic waste as feedstock are at various stages of development. A number of them are showing promise in various applications that may revolutionize the entire spectrum of WTE technologies. They include Biological Hydrogen Production using Photo-Biological processing (light aided) and Dark Fermentation (light deficient), Microbial Fuel Cells (MFC), Microbial Electrolysis Cell (MEC), to mention but a few. Table 6 presents summary assessment of four emerging WTE technologies.

Table 6: Summary assessment of four emerging technologies. Source [25]



S/N	WTE technologies	Benefits	Limitation	Primary product	Application
1	Photo-biological process	A wide spectral energy + can be used by photosynthetic bacteria	Nitrogenize enzymes get inhibited in the presence of O_2. Light conversion efficiency is low.	H_2 gas CO_2, organic acids	Bioelectricity
2	Dark fermentation	Utilizing wide range of biodegradable substrates More feasible for mass production of H_2, light independent-process		H_2 gas	Bioelectricity
3	Microbial fuel cell (MFC)	An effective method of electricity generation and odor removal from waste Zero contribution to GHG emission	It does not function at very low temperatures because microbial reactions are slow at low temperatures	H_2 gas	Bioelectricity, bio-hydrogen production, wastewater treatment
4	Microbial electrolysis cell (MEC)	High product (H_2) recovery, and substrate degradation than the photo, dark fermentation, and MFC High hydrogen translation efficiency Low energy requirement Application to numerous organic substrates	The yield effects by substrate composition High internal resistance Dense architecture High capital cost	H_2gas, CH_4, acetate, hydrogen peroxide, and formic acid	Used for generation of electricity and immediate wastewater treatment

Researchers have posited that hydrogen (H_2) is the fuel of the future as renewable bio-hydrogen may replace hydrogen from non-renewable fossil sources. Bio-hydrogen production using organic waste is one promising emerging technology. Micro-organisms have flexible metabolic potential to convert organic MSW to bio-hydrogen energy. Hydrogen fuel parades several interesting attributes; it is environmentally friendly fuel with zero Green House Gas (GHG) emission, has high energy yield of 142KJ/Kg (2.75 times of fossil fuel). It is highly utilized by the chemical industry and can be produced by either physical-chemical or biological process [25]. The former is energy intensive and emits GHG, while the later is less energy intensive, environmentally sustainable and has lower cost substrate. Bio-hydrogen production is currently channeled through anaerobic fermentation via two core routes: Photo-Biologic (presence of light) and Dark Fermentation (absence of light) [25].

5.0 CONCLUSION

Sadly, in much of sub-Sahara Africa as it is in emerging economies, raw MSW is still largely surface dumped, burnt in the open or land-filled. Clearly, most emerging economies do not have adequate human capacity, nor the budget to set up requisite institutions to combat this menace.

Hopefully, with growing awareness, improved funding and right investments in resource recovery technology, waste can be turned into needed resources for the socio-economic growth of the zone. In developed economies, recycled waste is generating useful resources for their thriving economies. It is hoped that this will be replicated in emerging economies if the proposed innovative approach to MSWM is embraced.

Overall, it is the expectation that this work will spur the growth of sustainable MSWM anchored on source separation and complimented by WTE technologies. This way the many undesirable waste dumps found in many cities across emerging economies, will quickly disappear and give way to clean cities.

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