PYROLYSIS: AN ALTERNATIVE TECHNOLOGY FOR MUNICIPAL SOLID WASTE MANAGEMENT

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Abstract

This paper reviews the process of pyrolysis with an aim of assessing its potential as an alternative technology for managing municipal solid waste in Kenya. Pyrolysis is the thermo-chemical decomposition of organic matter, at high temperatures, in the absence of oxygen. Organic matter simultaneously undergoes a change in chemical and physical phase, forming a gas, liquid and carbon-rich solid residue, which can be used as fuels. Pyrolysis is one of the processes involved in charring of wood, burning of solid fuels and volcanic eruptions which bring lava into contact with vegetation. Pyrolysis has been applied widely in the chemical industry for production of charcoal, methanol, PVC, activated carbon and gasoline. The process has also been applied to convert solid waste into safely disposable substances. In Kenya, pyrolysis has been widely applied in local production of charcoal. This continues to pose serious environmental challenges due to widespread deforestation and emission of greenhouse gases into the atmosphere. Meanwhile, Kenya continues to face serious municipal solid waste management challenges associated with urbanization and population pressure. Pyrolysis energy recovery from MSW has been successfully practiced in countries such as the UK, Turkey and Japan, where used tetra pak is now being used as a source of fuel, reducing its presence in Municipal Solid Waste by over 80%. Pyrolysis can also be used to convert plastic waste and waste rubber, which pose a great environmental problem in Kenya, into useful energy. Pyrolysis is relatively insensitive to input material and prevents formation of dioxins and combustion materials associated with burnt waste. This guarantees my strong recommendation to Kenyan environmental management agencies to adopt pyrolysis to help manage plastics and tetra pak in Municipal solid waste and as an alternative source of energy.

Key words: pyrolysis, thermochemical decomposition, municipal solid waste, energy recovery

1.0 Introduction

Pyrolysis is one of the most rapidly developing technologies for resource recovery from solid waste matter. The process involves thermo-chemical decomposition of carbonaceous organic matter, in the absence (or very limited supply) of oxygen. The organic matter undergoes a simultaneous change in chemical composition and physical state resulting in the formation of a gas, a liquid and carbon-rich residue (Caruso, Sorenson & Mossa, 2008).The gaseous product is synthetic gas (commonly known as syngas), a mixture of carbon dioxide (CO_2), carbon monoxide (CO), methane (CH_4) and hydrogen (H_2) gases, whereas the liquid and solid products comprise pyrolysis oil (a bio-fuel) and char/ash respectively (Friends of Earth, 2002). The products of pyrolysis can all be used as fuels. Syngas and pyrolysis oil can be used for direct generation of heat and electric power in specialized heat/power plants. In addition, syngas has been used as a basic chemical in refineries and petrochemical industries. Pyrolysis energy recovery from MSW has been successfully practiced in the UK, Turkey and Japan, where used tetra pak packages are now being used as a source of fuel, reducing its presence in municipal solid waste by over 80%. Traditionally, pyrolysis is the primary process involved in production of charcoal (Caruso, Sorenson and Mossa, 2008).

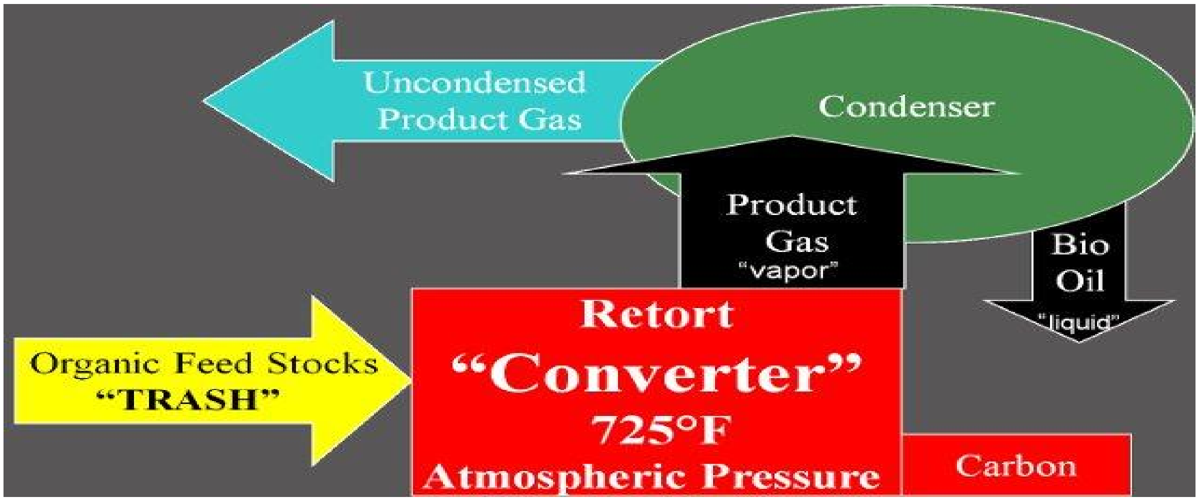
With respect to municipal solid waste (MSW) management, the primary goal of pyrolysis is to convert MSW into components that are biologically and chemically stable and would require minimal storage space. Resource/energy recovery from solid waste forms the secondary goal of pyrolysis as a component of integrated MSW management. Serio *et al.,* (2001) consider pyrolysis as an alternative to the conventional methods of solid waste management (SWM) mainly, incineration, landfilling, aerobic/anaerobic digestion, open-air burning and composting. Some of these methods are unsustainable due to their relatively high cost, inefficiency and emission of greenhouse gases which pose a long-term threat to the environment (Scott *et al., 1988*). This paper reviews the process of pyrolysis with an aim of assessing its potential as an alternative technology for MSW management in Kenya. It critically analyzes various areas in which pyrolysis has been successfully applied particularly: Resource recovery from solid waste in space; pyrolysis of used aseptic packages (Tetra-pak); thermal decomposition of polymeric materials (mainly rubber and plastic); and the potential use of biochar as a soil amendment. From a wide range of literature review, important conclusions and recommendations are made with respect to the technical and economic feasibility of the technology.

1.1 The Basic Process of Pyrolysis

Basically, Pyrolysis is a thermal-chemical decomposition process that converts carbon-rich matter into bio-oil, syngas and char, usually in the absence of oxygen. The products are highly refined and can be used directly as highly efficient fuels or indirectly as raw materials for other chemical/material industrial processes. Materials such as coal, food scraps, human waste, animal waste, rubber, cardboard, paper and biomass can be suitably processed by pyrolysis (Korkmaz, Yanik, Brebu and Vasile, 2009). Overall, the main components of biomass are carbohydrates (cellulose and hemicellulose) and lignin. On heating, the carbohydrate components disintegrate into volatile products of lower molecular weight (bio-oil and syngas) while the lignin gets charred into a carbon-rich residue. This process involves a series/cycle of complex chemical reactions and physical changes initiated by heating at elevated temperatures (Sadaka, 2010). Primarily, three types of pyrolysis reactions have been isolated on the basis of temperature and residence/processing time of the feedstock/biomass, namely, slow, flash and fast pyrolysis (Fortuna et al, 1997).

In slow pyrolysis (also known as conventional pyrolysis), the feedstock is heated at low rates (0.1-2^0C/Second), low temperatures (about 500^0C) and low residence time (seconds to a few days). The feedstock is slowly devolatilized to produce char and tar as the main products, which can then be allowed to undergo recombination/re-polymerization (Fortuna, Cornacchia, Mincarini & Sharm, 1997). On the other hand, flash pyrolysis involves heating at rates above 2^0C/Second and moderate temperatures (400-600^0C). Under these conditions, the residence time is often less than two seconds with the main products being tar and bio-oil. Unlike slow and flash pyrolysis, fast pyrolysis (also known as thermolysis) occurs at very high heating rates (200-10^5 ^{0}C/Second) and temperatures greater than 550^0C. As such the residence time is very short and the products formed (gases rich in ethylene) are of high quality and can be used for subsequent production of gasoline/alcohols. The amount of char and tar produced significantly reduces during fast pyrolysis (Sadaka, 2010). It is important to note that most practical applications of pyrolysis are based on fast pyrolysis since the nature of its resulting products is much close to the currently used fossil fuels (Fortuna et al, 1997).

In order to engineer viable application processes of pyrolysis, it is important to understand its basic mechanism. During pyrolysis, the biomass undergoes simultaneous changes in chemical as well as physical state. Physically, the feedstock changes in color, size, weight and mechanical strength. At about 350^0C, the feedstock disintegrates by up to 80% in weight and the remnant feedstock forms char. If heating is prolonged to about 600^0C, the amount of char formed would further reduce to barely 9% by weight of the original feedstock (Sadaka, 2010). Chronologically, pyrolysis begins by dehydration of the feedstock. This occurs at temperatures below 300^0C (slow pyrolysis) and is responsible for weight reduction and formation of CO, CO_2, water and char. The dehydration process is followed by fragmentation of the biomass at temperatures above 300^0C (flash and fast pyrolysis). Here, the biomass depolymerizes into some anhydrous glucose compounds as well as light combustible volatile materials (Fortuna et al, 1997). Sadaka (2010) classifies the products of pyrolysis into three groups: “volatile products of molecular weight below 105 (CO, CO2, H2O, acetol, furfural and unsaturated aldehydes); tars of higher molecular weight; and chars” (p.4).



(*Source*: www.Pyrolysis/Municipal Solid Waste Pyrolysis.htm)

Figure 1: Summary of the basic process of pyrolysis

Pyrolysis reactions are driven by a combination of three main factors namely, temperature, pressure and residence time. At a temperature of 200-600^{0}C, high pressures and prolonged residence time, primary products (volatile materials and light char) tend to recombine to form secondary tars which are more stable. On the other hand, when the feedstock is exposed to low temperatures for longer residence times, the secondary tar forms char, H_2O, CO_2 and CO whereas at very high temperatures, the secondary tar cracks to form hydrocarbons, CO, CO2, H2 as well as carbon black (Scott *et al., 1988*). Char is a result of devolatization of the feedstock during pyrolysis, at low heat treatments. Higher temperatures favor the aromatization of char and subsequent oxidation of the resulting aromatic clusters, thereby reducing char production (Sadaka, 2010). On cooling, some volatiles are condensed to yield bio-oil (pyrolysis oil), a liquid with similar elemental composition to biomass but higher in density (1200kg/m^3 than normal fuel oil or the original biomass). According to Sadaka (2010), this implies that the energy content of the resulting pyrolysis oil is 42% and 61% higher than conventional fuel oil on a weight and volumetric bases respectively. Chemically, bio-oil is a mixture of several oxygenated compounds of diverse functional groups (carboxyl, carbonyl and phenolic) as shown in Table 1.

Table 1: Chemical composition of pyrolysis oil

Constituent Compound	**Percentage Composition**
Water	20-25%
Water insoluble pyrolytic lignin	25-30%
Organic acids	5-12%
Non-polar hydrocarbons	5-10%
Anhydrosugars	10-25%
Other oxygenated compounds	10-25%

(*Source*: Sadaka, (2010)

In addition to temperature, pressure and residence time, biomass pyrolysis is influenced by the heating rate, substrate/feedstock composition, the ambient atmosphere as well as presence of a catalyst (Scott *et al., 1988*). In practice, three general types of pyrolysis reactors exist namely, rotary kilns, fluidized bed reactors and rotary hearth furnaces, as shown in Figure 2.

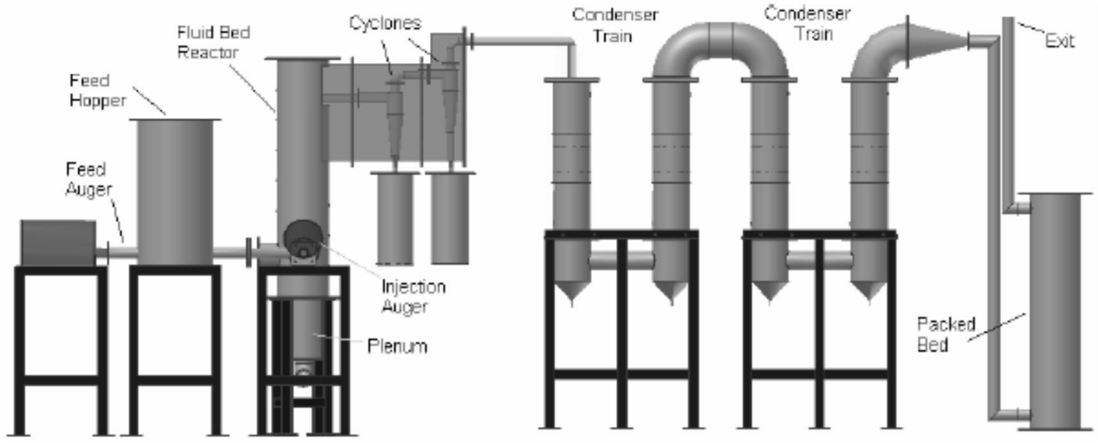
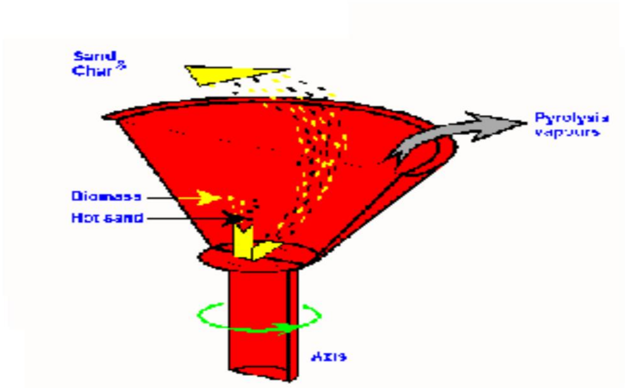


Figure 2a: Fluidized bed pyrolysis reactor



Source: Sadaka (2010)

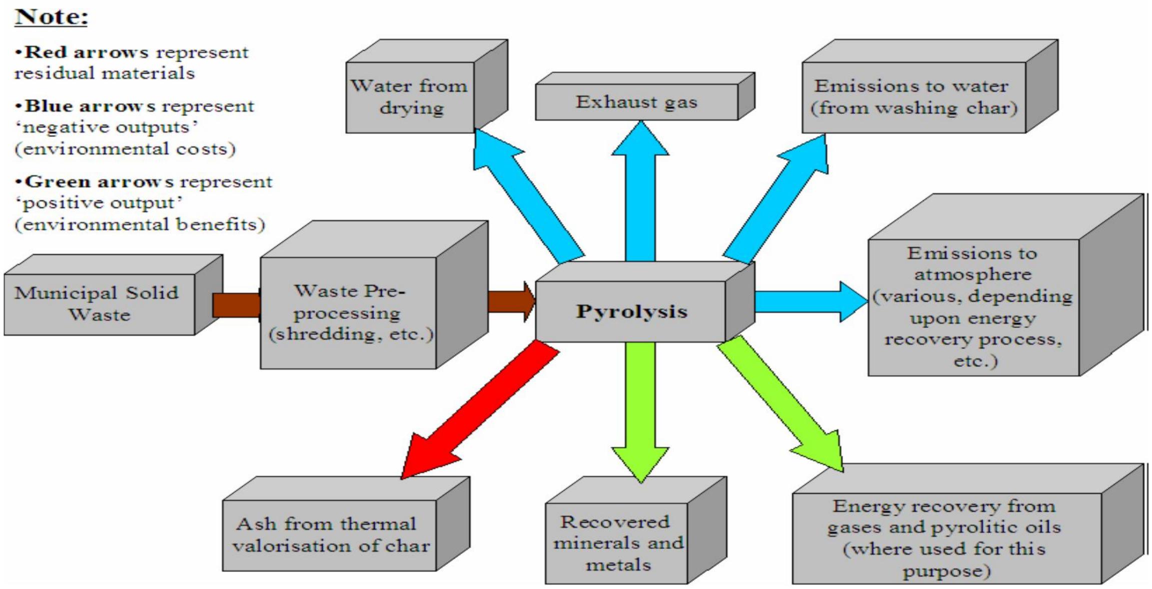
Figure 2b: Rotating Cone Pyrolysis Reactor

Pyrolysis of Municipal Solid Waste

Solid waste generation is an inevitable result of human activities and its management has a direct impact on public health as well as public welfare. Over the years, the world has experienced tremendous increase in quantities of solid waste generated and the complexity of its composition. This is compounded by the growing use of plastics and electronic consumer products, posing a great challenge to the agencies charged with managing MSW (UN Habitat, 2011). The United Nations Development Program attributes the increasing quantity and complexity of MSW to growth in economic development, urbanization and improvement in living standards across the globe. Unfortunately, despite the rapidly growing quantities of MSW, there is an alarming decline in the capacity and effectiveness of MSW management options available (Regassa, Sundaraa & Seboka, 2011). Regassa, Sundaraa and Seboka further note that less than 50% of MSW, generated in African urban centers, is collected out of which, about 95% is improperly disposed in open damping sites around the cities.

In Kenya, the situation is no different. It is estimated that Kenyan, and other developing countries' local authorities, spend at least 30% of their annual budget to manage only 50-70% of MSW generated within their areas of jurisdiction. Currently, open damping remains the most common method of disposing solid waste in Kenya. This poses serious health and environmental risks to the surrounding populations, a situation that compelled the Local Government Minister, in 2003, to order for relocation of the famous Dandora Dumping Site to Ruai (Rotich, Zhao & Dong, 2006). The traditional methods for managing MSW include: landfilling, incineration, open dumping and open air burning. However, some of these methods have proved unsustainable due to increased costs, limited land area for expansion and potential environmental risks. This shifted focus to the search for more sustainable MSW management strategies with growing interest in composting, digestion and thermal treatment (pyrolysis and gasification) of MSW, with specific interest in resource/energy recovery and an integrated approach to solid waste management (Friends of the Earth, 2002).

Pyrolysis is a suitable alternative to the conventional MSW management options (particularly incineration) for partial decomposition and volume reduction of MSW. This is made possible by the fact that much of MSW is constituted by long-chain hydrocarbon-rich matter such as plastic, cellulose and rubber. Such organic materials are a great reserve of organic building blocks which can be harnessed as organic carbon (Friends of the Earth, 2002). Through pyrolysis, much of the chemical energy contained in waste biomass can be harnessed and reused, a secondary benefit to environmental management. Pyrolysis of MSW begins with a pre-processing stage of collected MSW. This involves sorting, shredding and any possible treatment of the feedstock to prepare them for pyrolysis. Pre-treated biomass is then subjected to the pyrolysis reactor in which the long-chain organic matter is disintegrated by thermal treatment to form a gas (syngas), bio-oil and char/tar (Korkmaz et al, 2009). These products can be used as fuels in other processes as well as to sustain the pyrolysis reactors, as discussed above. Figure 3 shows a summary of the processes involved in MSW pyrolysis.



(*Source*: Caruso et al., 2008)

Figure 3: Summary of MSW pyrolysis

Practical Applications of Pyrolysis for MSW Management

Caruso, Sorenson and Mossa (2008) highlight a number of pyrolysis plants that have been developed around the world to treat MSW. In the UK, a company known as *WasteGen UK* specializes in development of Materials and Energy Recovery Plants which integrate pyrolysis with composting and recycling. The plants have an annual capacity of 200,000 tonnes out of which 118,000 tonnes is set aside for energy/materials recovery while the rest (82,000 tonnes) is recycled or composted. In addition, about 18.3 MW of electric power is generated. Such other plants have been developed by the UK-based company in Burgau, Germany and Bristol, UK with great anticipation to "reduce climate change, meet the requirements for sustainable waste management and provide a solution for the processing of difficult and industrial waste" (Caruso et al., 2008). Other interesting developments in the application of pyrolysis for MSW management are discussed below.

Pyrolysis for Recovery of Solid Waste in Space

Serio et al.,(2001) developed a prototype pyrolysis plant for recovery of mixed solid waste in space crafts. This is a relatively simple plant with a double-stage reactor capable of processing 1kg of solid waste per cycle. In the reactor's pyrolysis (first chamber) chamber, waste matter is subjected to heating to about 600^0C, resulting in formation of volatiles (gaseous and liquid products) which are then purged by nitrogen gas into the second chamber. In the second chamber, catalytic cracking of tars occur (1000-1100^0C) to form carbon, most of which is gasified by the primary products from the first stage, and more gases. The final stage involves regulation of the reactor temperatures and reversing the purge gas between nitrogen and CO_2 to regulate the amount of char produced. An artificial neural network would be developed to control the system. This is a promising system and can help handle solid waste in space craft applications without harming the external environment while making use of the products for other processes. However, Serio, Kroo, Bassilakis and Wojtowicz do not give an insight into its economic feasibility. Moreover, the system would require high rate of controls due to the very high temperatures involved, which they intended to do by designing an artificial neural control network. It would further be interesting to know whether such a system could be applied with other types of automobiles.

Pyrolysis of Waste Tetra Pak Packages

Korkmaz et al.,(2009) conducted a study to assess the possibility of recovering valuable products from tetra pak packaging material by pyrolysis. Tetra pak is an aseptic packaging material used all over the world for beverages, milk, nectar, soy and juices. The ability of tetra pak packages to increase the shelf-life of perishable products, by at least six months, has warranted its widespread use worldwide. By 2007, at least 137 billion tetra pak packages were estimated to be in circulation, annually, around the world (Mario, 2010). In Kenya, tetra pack is a common packaging material for processed milk (long-life milk), juices (Del Monte, Quencher, Minute Maid, Ribena, etc.) and yoghurt, among others. As a result, waste tetra pak packages commonly constitute a significant proportion of MSW not only in Kenya, but also around the world. It is therefore important to find a sustainable way by which tetra pak packages, among other waste materials can be conveniently disposed as well as recover any valuable contents from such waste (Korkmaz et al, 2009).

The tetra pak packaging material comprises of three raw materials namely, 75% duplex paper, 20% light polyethylene and 5% aluminum. Like other aseptic packages, waste tetra pak can be recycled hydro-pulping, a simple process by which the thin plastic and aluminum layers are separated from the cellulosic fibers. The fibers may be used in paper industries to manufacture fine writing paper, tissue paper as well as paper towels whereas the polyethynene and aluminum constituents can be recovered by incineration (to generate energy), reprocessing and pyrolysis (Kanturk *et al.,*2013). In their study, Yanik, Brebu and Vasile (2009) conducted pyrolysis experiments with tetra pak in an inert environment. The batch reactor was set at different temperatures (400-600^0C) and different pyrolysis modes. The pyrolysis products were then collected and quantified. These include: gas, wax, carbon residue and pure aluminum. The study revealed that the char obtained from the process had a high calorific value and low ash content hence could be suitably used as a fuel. The gaseous product was found to be dominated by oxides of carbon. Further, a thermo-gravimetric analysis of the pyrolysis process pointed out two processes; primary cardboard degradation below 400^0C and polyethylene disintegration above 400^0C.

From the results, it is evident that waste tetra pak packages can be suitably recycled into valuable products through pyrolysis. This is a positive study and the details of its findings present a step-by-step approach by which tetra pak, and related waste materials, can be conveniently removed from the MSW stream and converted into useful products. It is important, however, to go ahead and establish the calorific values of the three pyrolysis products obtained in this study, in order to assess their feasibility for practical applications.

Pyrolysis of Polymeric Materials (Rubber & Plastics)

Over the years, the world has witnessed a tremendous increase in the use of polymeric materials, particularly plastics and rubber. In the year 2009 alone, about 2.3 billion tons of plastics were produced in the world, 54% of which ends up in waste disposal sites. Similarly, rubber demand for the world stood at 26.5 million metric tons in 2011 with an estimated annual increase rate of 4%. Most of the rubber too ends up in solid waste disposal sites mainly in form of used tires (Freedonia, 2010). In Kenya, the use of plastics and tires is also on the rise with plastic bags being the main packaging system used by shoppers in the country. In addition, the number of motor vehicles in the country is on a rapid upward trend, due to acquisition of cars by many Kenyans as well as the increasing use of motor bikes (popularly known as *bodaboda* taxis) in the country. This certainly translates in an increase in the use of tires which in turn means that their proportion in the resulting MSW is on the rise. Overall, waste polymeric materials present a serious disposal challenge that has drawn overwhelming interest. Furthermore, due to their non (or slow) bio-degradability, complex composition, high calorific value and environmental risks associated with their open-air burning, their management is being focused in terms of sustainable recycling, reuse and recovery rather than incineration and landfilling (Westerhout *et al.,* 1998).

Pyrolysis presents an alternative option for obtaining valuable raw materials from waste plastics and rubber. Recent developments have also seen the advancement of microwave heating, in addition to conventional heating, to steer pyrolysis of waste polymeric materials (Freedonia, 2010). Tires vary in composition with respect to their brands, use and dimensions. Chemically, car tires are composed of about 14% polisoprene; 27% synthetic polymers; 28% carbon black, 14-15% steel, 1.5% sulfur and 16-17% textile additives. Truck tires vary slightly in composition as follows: 27% polisoprene; 14% synthetic polymers; 28% carbon black; 14-15% steel; 2.5% sulfur and 16-17% textile additive. On pyrolysis, the three basic products are formed. The gaseous product is a mixture of H_2, H_2S, CO_2, CO, CH_4, C_2H_4, C_2H_6, C_3H_6, and C3H8 in addition to small amounts of other organic compounds. The bio-oil produced in this case has very high calorific value and comprises benzene, xylenes, toluene and limonene, among others. The bio-oil is a source of energy, often used as a feedstock in refineries or a reserve for limonene and aromatics. The solid product comprises carbon and non-volatile materials. The carbon-rich solid is used in the manufacture of tires, production of activated carbon and as a smokeless fuel (Juma *et al.,* 2006).

Like tires, the pyrolysis of plastics has also gained significant interest in the recent past. A wide range of polymers, including polyethylene, polypropylene, polystyrene, polyethylene terephthalate and polyvinylchloride have been tested for pyrolysis under microwave as well as conventional heating, with positive results. For microwave pyrolysis, an additional microwave absorbent material (such as carbon powder or chopped tire) has to be employed due to the poor ability of plastics to absorb microwave energy (Saeed, Tohka, Haapala, & Zevenhoven, 2004).

However, conventional pyrolysis of pure plastics has been widely studied with the main products being gases and liquids, although some few experiments have reported small amounts of a solid product (Westerhout *et al.,* 1998). Overall, plastics, and plastic containing waste, can be successfully subjected to pyrolysis (microwave or conventional) to form valuable fuels, oils as well as important hydrocarbons of high calorific value. Studies present microwave pyrolysis as an optimal means of transforming plastic wastes (simple/complex) into these valuable products (Saeed, Tohka, Haapala, & Zevenhoven, 2004).

MSW Pyrolysis Biochar as a Soil Amendment

Biochar is the charcoal-like by-product of biomass pyrolysis. The product has been studied for its potential to store carbon for very long periods for mitigating greenhouse gases. Most studies conducted in the Amazon basin have shown significant soil alterations (in chemical and physical properties) resulting in long-term soil carbon sequestration and enhanced crop yields ((Lehmann, Gaunt & Rondon, 2006).). Recently, Krug and Hollinger (2003) showed dramatic effects of fire on American soils, mainly grass and forest vegetation maintenance. This is because fire converts plant biomass into stable carbon, usually in form of charcoal. Despite the loss of some soil nitrogen by fire, repeated burning of plant biomass replenishes soil nitrogen. A study commissioned by the American Centre for Sustaining Agriculture and Natural Resources (2009) also sought to assess the potential of biochar, obtained by pyrolysis of waste organic matter as a soil amendment. An evaluation of biochar from a wide range of feedstock was conducted to establish their effect on five soils in Washington, America. Their results are summarized in Table 2.

Table 2: Carbon and nitrogen composition of biochar from different feedstock

Type of Feedstock	Carbon Content	Nitrogen Content
Herbaceous Feedstock	60%	Very high
Digester Fiber	67%	Very high
Woody feedstock	>75%	176-588 (C:N Ratio)
Activated Charcoal	87%	0.47%

The American Centre for Sustaining Agriculture and Natural Resources found out that biochar from all the above mentioned feedstock increased soil pH, with minimal effect on plant growth. Nitrate levels of the soil tended to decline with increased biochar application (possible due to adsorption of ammonium by biochar). In addition, all the soils tested exhibited an increase in carbon content, the greatest increase being realized in soils with the lowest organic matter content (Quincy sand). The bio-char induced soil carbon was shown to be significantly stable and can last for a long as hundreds of years in the soil; without accelerating indigenous organic matter loss from the soil (Lehmann, Gaunt & Rondon, 2006).

Merits and Demerits of MSW Pyrolysis

Pyrolysis of MSW has a number of advantages over other methods of resource recovery from solid waste. First, the process is very flexible – it can be used to treat a wide range of solid wastes since the process can adapt easily to variations in composition of the feedstock. Secondly, pyrolysis is a relatively simple technology which can be used even for small-scale practical applications such as in spacecraft (Bieda, 2008). Thirdly, the process can be conducted at such low pressures that minimize feedstock preprocessing requirements. In addition, pyrolysis yields a wide range of valuable products and the system design can be made in such a way as to minimize production of unusable byproducts. It is also important to note that pyrolysis of MSW significantly reduces their storage volume, with valuable constituents (carbon and nitrogen) can be suitably stored as char. These elements can subsequently be recovered by means of incineration or gasification. As such, pyrolysis of MSW can not only be used as a primary waste treatment option, but also as pretreatment method for other waste management processes (Serio, Chen, & Wojowicz, 2007). With respect to environmental pollution, pyrolysis does not produce many air emissions due use of limited oxygen. Furthermore, it easier to control air pollution due to cleaning of syngas, after production to eliminate potential contaminants Caruso, Sorenson & Mossa, 2008).

However, despite the overwhelming potential of pyrolysis as a management option for MSW, certain factors, that may limit its applications have to be considered. First, there is a potential for generating possibly toxic residues for instance, unreformed carbon, some inorganic compounds and inert mineral ash. Secondly, certain possibly toxic air emissions may be liberated. Such emissions include dioxins, acid gases, oxides of nitrogen, sulfur dioxide and certain particulates, among others Caruso, Sorenson & Mossa, 2008). The complexity of the product stream of pyrolysis has also been enlisted as a potential constraint for its applications. However, this is subject to the pyrolysis process itself, which can be suitably controlled to vary the product stream. The potential threat of air pollution can be addressed by use of water gas shift reactors or by incinerating or subjecting the product gases thigh temperature fuel cells (Serio, Chen, & Wojowicz, 2007).

Economic Feasibility of MSW Pyrolysis

Today, the world has about 150 companies that market MSW pyrolysis and gasification systems, with at least 100 facilities in operation around the world. These systems have the capacity to handle more than four million tonnes of MSW annually. In Europe, USA, India, Japan and China, MSW pyrolysis has been applied on commercial scale. The commercial feasibility of MSW pyrolysis has also been proven by many scientific studies (Juniper, 2012). In USA, self-sufficient and self-regenerative pyrolysis plants have been developed to handle up to 100 tonnes per day. In Delhi, India, there exists a city garbage pyrolysis plant with a daily capacity of 2000 tonnes of MSW. On pyrolysis, this garbage yields char (600 tonnes); glass (30 tonnes), metal (30 tonnes) and bio-oil (80000 liters). These products are used as fuels and for electricity generation with an economic annual turnover of at least 27% (Roy, 1988). As such, it is clear that MSW pyrolysis, in addition to providing a potential answer to the MSW management menace, also presents a potential answer to the energy and economic crisis facing the modern world. A quick online shopping reveals a number of modern low-cost pyrolysis plants that can be suitably applied, even in small scale, to treat plastics, tires and the MSW in general. A few are summarized in table 3 below. It is important to note that he long-term environmental benefits, and economic yields, are likely to far much outweigh the initial costs of plant installation.

Table 3: Modern MSW pyrolysis plants available in the world market

Plant Specification	**Designation/Application**	**Cost (US $)**
High efficiency 15 tons pyrolysis oil refinery	Waste tire/plastic/rubber	34,800 – 55,800
2013 old tires pyrolysis equipment	Old tires/rubber	43,800 – 78,000
Environmental friendly waste tires pyrolysis equipment	Waste tires/rubber	32,000 – 1,000,000
7th generation pyrolysis recycling plant	Waste rubber/plastic/tire	98,00 – 128,000
Newest high configuration waste oil recycling plant	Pyrolysis oil refining without pollution	32,000 – 1,000,000
Best pyrolysis machines for waste tires into crude oil	Waste tires/rubber	32,000 – 1,000,000
5-6 tons waste tire pyrolysis plant	Waste tire/rubber	34,800 – 83,800
New equipment for pyrolysis oil refinery from waste matter	Waste tire/rubber/plastic	36,800 – 68,000

(www.alibaba.com/productgs/522644811/solid_waste_pyrolysis_equipment_in_machinery.html)

Summary, Conclusion and Recommendations

This paper reviews the process of pyrolysis with an aim of assessing its potential as an alternative technology for MSW management in Kenya. Pyrolysis is the thermo-chemical decomposition of organic matter, at high temperatures, in absence of oxygen. The organic matter undergoes simultaneous changes in chemical composition and physical state resulting in the formation of a gas, a liquid and carbon-rich residue. The gaseous product is synthetic gas (syngas), a mixture of CO_2, CO, CH_4 and H_2 gases, whereas the liquid and solid products comprise pyrolysis oil (a bio-fuel) and char/ash respectively. The products of pyrolysis can all be used as fuels. There are various areas in which pyrolysis has been successfully applied particularly: Resource recovery from solid waste in space; pyrolysis of used aseptic packages (Tetra-pak); thermal decomposition of polymeric materials (mainly rubber and plastic); and the potential use of biochar as a soil amendment. From this study, it is evident that pyrolysis provides a suitable alternative means of recovering valuable resources from MSW.

However, in view of the great MSW management challenge facing Kenya, and many other developing countries, resource recovery is only a secondary goal of MSW pyrolysis. The primary goal is the use of pyrolysis for managing MSW by reducing their storage volumes and converting them to more stable/disposable/usable products. From an economic perspective, pyrolysis of MSW is still a viable option despite the seemingly high initial costs involved in installation of the equipment. Furthermore, the technology has long-term environmental benefits that, no doubt, will outweigh the initial costs, especially in view of the prevailing world economic, energy and environmental crises. I strongly recommend the adoption of MSW Pyrolysis to the Kenyan agencies charged with the responsibility of managing MSW in the country, especially in cities and urban centers, where MSW is a menace. As the county governments take off their operations under the new devolved system of government, they should make it a priority to attain a sustainable environment that in turn promotes sustainable development, by investing in MSW management technologies such as pyrolysis. Further local research should also be commissioned in the area in order to develop pyrolysis plants relevant to the Kenyan context.

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