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Mass Balance of Plastic Waste Conversion to Fuel Oil- A case in Uganda

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Abstract

The current rate of plastic usage and the manner in which they are being disposed of is unsustainable. This is because more resources such as crude oil are utilized for their production and on the other hand, more waste plastics are generated. Since these waste plastics are made from crude oil, there is a high chance that they can be turned back into diesel that can be used to power irrigation pumps, drive engines for transport and industrial purposes among other potential uses. This paper sought to evaluate the pyrolysis of waste plastics to fuel oil potential of Uganda. The estimated waste plastics generated in Uganda was quantified as 545 851 kg/day. In this study, mass balance estimation indicated that the initial feed of 545 851 kg of waste plastics yields 451 419 kg liquid fuel using an appropriate technology for pyrolysis. The production potential of the gaseous and char fractions was calculated to be 50 764 and 43 668 kg in a day, respectively. This estimated amount has the potential to power approximately 234 small portable threshers of 5-7 horsepower. A total of 365 000 tonnes of fresh paddy can be threshed using these threshers. The gaseous fraction also has the potential to be used as a source of fuel for cooking. This is particularly important for postharvest handling and food security in Uganda as well as development of waste to energy technologies such as pyrolysis.

Keywords: Mass balance analysis, waste plastics, pyrolysis, sustainability, waste to energy technologies

1. Introduction

1.1 The Waste Plastic Situation

There have been many major changes on the surface of the planet in the last 50 years. But one of the most instantly observable wastes on the environment is the ubiquity and abundance of waste plastics (Barnes, Galgani, Thompson, & Barlaz, 2009; Eriksen et al., 2014; Sharma, Moser, Vermillion, Doll, & Rajagopalan, 2014). Global usage of plastics is increasing (Thompson, Moore, vom Saal, & Swan, 2009). Plastics are used in many applications (Bashir, 2013) because of their versatility, light weight and also easy to manufacture (Andrady & Neal, 2009). Plastics are used extensively in automobiles (Gerrard & Kandlikar, 2007; Mazzanti & Zoboli, 2006; Smink, 2007), building and constructions (Cleetus, Thomas, & Varghese, 2013), packaging (Al-Salem, Lettieri, & Baeyens, 2009), bags (Bashir, 2013) and phones (Kasper et al., 2011; Yamane, de Moraes, Espinosa, & Tenório, 2011) and computers (Balakrishnan, Anand, & Chiya, 2007; Guo, Guo, & Xu, 2009; Hall & Williams, 2007). As a consequence, the production of plastics has increased substantially over the last 60 years (Thompson et al., 2009). In 2004, the world's total production of plastics was estimated at 225 million tonnes. By 2014, global production of plastics increased to 311 million tonnes, representing a rapid increase of 38% (PlasticsEurope, 2015). Other drivers responsible for the steady growth of plastics are its user-friendly design, and low costs (Bashir, 2013; Panda, Singh, & Mishra, 2010; B. Singh & Sharma, 2007) and also higher pursuit of life (United Nations Environment Programme [UNEP], 2014). About one third of the current production of plastics is used for packaging and other short-lived applications (Thompson et al., 2009). This current rate of plastic growth makes it unsustainable (Hopewell, Dvorak, & Kosior, 2009; Jambeck et al., 2015). More resources are needed to meet the increased demand of plastic, and conversely, more plastic waste is being generated (UNEP, 2009).

Plastic waste management is a serious environmental and public health issue in most cities all over the world. Efforts to manage plastic wastes are always overwhelmed by the ever increasing urbanization (Troschinetz & Mihelcic, 2009) and consumption of plastic materials (Nabukeera Madinah & Boerhannoeddin, 2014) coupled with low levels of infrastructure to handle wastes. A definite contrast exists between usage of waste plastics in Europe and developing countries. In Europe, plastic waste is increasingly recognized as a resource (European Commission [EC], 2010). In 2014, 69.2% was recovered through recycling and energy recovery processes while 30.8% still went to landfill (PlasticsEurope, 2015). However, in Kampala, only 2% of about 62 050 tonnes of plastic wastes generated annually are recycled (Tukahirwa, Mol, & Oosterveer, 2010). The drainage system in Uganda is in the same way choked with plastic materials such as ice cream wrappers, polyethylene-film bags and other plastic materials.

1.2 Recent Scholarship on the Management of Waste Plastics

Currently, there are three most common ways to utilize plastic wastes: landfilling, incineration with or without energy recovery and recycling (Ali, Garforth, Harris, Rawlence, & Uemichi, 2002). The largest amount of plastic wastes is disposed of by landfilling (65-70%) and incineration (20-25%). Recycling is only about 10%. Moreover, the problem of plastic wastes cannot be resolved by landfilling and incineration, because suitable and safe depots are expensive, and incineration stimulates the growing emission of harmful, greenhouse gases (Chung et al. 2003; Sarker and Rashid 2013). Chemical recycling can either be a thermal or catalytic process by which waste plastics are converted into petrochemical products (Almeida & Marque, 2015). Since plastics are made from crude oil, there are high chances that these plastics can be turned back into diesel or petrol to power vehicles through a process called pyrolysis. Fuel oil, gas, wax and sometimes char are the products of pyrolysis (Chandrasekaran, Kunwar, Moser, Rajagopalan, & Sharma, 2015; Demirbas, 2004; Walter Kaminsky & Zorriqueta, 2007; Panda et al., 2010). The fraction of each product depends on the composition of plastics, type of reactor, temperature and heating rates (Bajus, 2011; Kluska, Klein, Kazimierski, & Kardas, 2014). The yield of liquid oil from the pyrolysis of waste plastics found in literature is reported to be more than 80% (weight) (R. K. Singh & Ruj, 2016; Wong, Ngadi, Abdullah, & Inuwa, 2015). The oil products can either be used as a feedstock for plastic production or as a fuel to run engines. This is one of the best ways to utilize waste polymers (Sarker & Rashid, 2013; W. Kaminsky, Predel, & Sadiki, 2004). The prospects of turning plastic waste into a resource is attractive for a developing country like Uganda where local authorities struggle to cope with the ever increasing volumes of such materials in public areas. It is against this background that this study aims at evaluating waste plastics to fuel oil potential of Uganda.

2. Composition of Municipal Solid Waste in Developing World

Municipal Solid Waste (MSW) is made up of wastes from durable goods (e.g., tires, furniture), non-durable goods (e.g., newspapers, plastic plates/cups), containers and packaging (e.g., milk cartons, plastic wrap), and other wastes (e.g., yard waste, food) (Center for Sustainable Systems [CSS], 2015). It is necessary to present data on waste generation and its composition in order to understand the current situation of municipal solid waste management (Chen, Geng, & Fujita, 2010). Sources of MSW are residential, commercial, institutional and municipal services. Residential and commercial solid wastes are made up of both organic and inorganic wastes. Organic waste materials include food wastes, papers, leathers, yard wastes, ashes, and wood. The inorganic wastes comprise of glasses, tin cans, crockery, dirts and metals. Other wastes from commercial and residential sources are waste oil, electronics, batteries, tires and paints. Institutional sources of solid wastes include prisons, hospitals, universities and schools, and centers. Other community wastes result from street sweepings, dead animals, abandoned automobiles, tree cuttings and roadside litter (Guangyu, 2010). The composition of MSW is city specific (Guangyu, 2010). The major factors that contribute to the amount of MSW are population growth, standard of living and diet habits (Kinobe, Niwagaba, Gebresenbet, Komakech, & Vinnerås, 2015; Komakech, 2014; Troschinetz & Mihelcic, 2009). A number of authors (Komakech et al., 2014; Miezah, Obiri-Danso, Kadar, Fei-Baffoe, & Mensah, 2015; Nabukeera Madinah & Boerhannoeddin, 2014) have provided several overviews on the composition of MSW in sub-Saharan Africa. The per capita generation of waste plastic is estimated as 0.056 kg/day. Table 1 shows the estimated daily waste plastics in major districts in Uganda.

Table 1. Estimated amount of plastics generated in major districts in Uganda

Districts	Population	Waste plastic (kg/day)
Wakiso	2 007 700	112 431
Kampala	1 516 210	84 908
Kibaale and Iganga	1 295 102	72 526
Arua and Kasese	1 487 218	83 284
Mubende and Mukono	1 288 636	72 164
Tororo and Rakai	1 044 386	58 486
Hoima and Kabale	1 108 063	62 052
Total	**9 747 315**	**545 851**

3. Solid Waste Management in Developing Countries

Municipal solid waste management (MSWM) has been one of the most serious environmental problems in countries without proper waste management system (Achankeng, 2003; Chen et al., 2010). In Uganda, both the formal and informal sectors are involved in solid waste management. Waste management begins with the collection of the waste. However, in developing countries, due to high population growth coupled with lack of available resources (money and infrastructures) to provide a better SWM leads to insufficient waste collection, open dumping and indiscriminate disposal of waste along the streets (Sembiring & Nitivattananon, 2010). In Kampala, the capital of Uganda, the collection, transportation and disposal of MSW is now a shared responsibility of the Kampala City Council Authority (KCCA) and private sector players. As a matter of fact, KCCA plans to withdraw from solid waste collection such that it is a private sector led service to city dwellers.

3.1 Waste Collection

Road-side and household and community collections are the adopted methods of waste collection in residential areas in Kampala. In road-side waste collection, residents sort recyclable items into particular collection containers offered by the waste collection authorities. In the household collection system, a bell is rang to remind residents to send their waste to the street level for disposal (Zhang, Tan, & Gersberg, 2010). The household system of waste collection have been taken out and replaced with a new system. Residents are now advised to place their wastes in dustbins and bags outside their houses for collection. Also, households send their wastes to community collection points such as skips and bunkers and the waste is later transported by a truck to a landfill site called *Kiteezi*, which is privately owned by Otada Construction Company (Komakech et al., 2014) and other waste disposal sites. The other waste disposal sites are owned and operated by the urban councils and are poorly managed. This can be attributed to the fact that most resources are assigned to only waste collection and not to disposal management. The highest collection level is normally done by private companies. The urban poor receive very low if not no waste collection facilities due to inaccessible roads, unplanned facilities and disregard by the urban authority (Okot-Okumu & Nyenje, 2011). The collection of MSW is very important when it comes to its management. With no labeled street numbers or numbered houses, waste collection is very hard and any traceability is not possible.

3.2 Waste Separation and Recycling

MSW is principally composed of organic, recycling and non-recyclable wastes (Sembiring & Nitivattananon, 2010; Zhang et al., 2010). Waste sorting, separation and classification are currently not done at disposal point. Sometimes residents volunteer to participate in the sorting out. Residents then sell the recyclables from the wastes to itinerant buyers (door to door buyers) or exchange items such as containers, footballs, and cutlasses, who in turn sell them to factories as raw or processed materials. The mixture that ends up at the various landfill sites are collected and sorted out by waste collectors patrolling the sites (Komakech, 2014). The separation and sorting out allows recovery and therefore reduces the amount of waste that is sent to landfill sites (Fauziah & Agamuthu, 2012). Generally speaking, weak rules and regulations enforcement, poverty and lack of education hamper waste separation and recycling in Kampala.

3.3 Landfilling

The management of MSW in most developing countries is by landfilling. This is because it is very cheap and can accommodate large amount of any kind of waste (Zhang et al., 2010). Figure 1 shows scavengers at *Kiteezi* landfill site. The waste dumping site at *Kiteezi* has been upgraded to sanitary landfill. Although, it has inbuilt leachate treatment plant, there is a leakage and this pollutes surface and groundwater (Nabukeera Madinah & Boerhannoeddin, 2014). 55% of the wastes generated are successfully dumped to the landfill site at *Kiteezi.* The remaining 45% remains mismanaged (Nabukeera Madinah & Boerhannoeddin, 2014).

3.4 Overview of Energy Recovery from Waste in Developing Countries

The generation of energy from waste is a valuable option in choosing MSW management technique. However, due to the high capital cost of waste-to-energy (WtE) technologies, they are normally adopted in most advanced countries. China, for instance, installed approximately 100 WtE plants as at 2009 (Dong, 2011). This has helped improved public health in the rural areas of China. The Uganda Government set a target to produce 30 MW from solid waste by the end of the year 2017 (El-Agroudy, Warith, & El-Zayat, 2015). The government of Uganda also set a target to install about 100 000 family-sized digesters by the year 2017 (Veit, Excell, & Zomer, 2011). So far, about half of the 500 installed biogas digesters are in operation (Owusu & Banadda, 2017; UBOS, 2010). The rate of adoption of biogas technology in Uganda is slow due to lack of technical capacity for installation and maintenance and high initial costs of installation (Okello, Pindozzi, Faugno, & Boccia, 2013).

Incineration with energy recovery as a waste management technique can be used to recover energy and many attempts have been made to promote it in sub-Sahara African cities such as Lagos. However, organic waste makes a bigger fraction of the MSW and it has low calorific value and high moisture content (Narayana, 2009). These and other factors such as release of harmful greenhouse gases make incineration unsustainable for developing cities in sub-Sahara Africa (Giusti, 2009). Incineration without energy recovery is a common practice in developing countries. This is done purposely to reduce the amount of organic wastes in MSW before disposal (Dhokhikah & Trihadiningrum, 2012). Waste minimization principles such as the 3Rs (reduce, reuse and recycle), composting and anaerobic digestion that offer social, environmental and economic benefits to the urban community should be encouraged in developing countries. There is also the need to adopt pyrolysis for the treatment of plastic wastes. This process is sustainable in the sense that the process is environmentally friendly, easy to run and requires materials that already exist. These factors make the process more suitable for rural and underdeveloped countries (Joshi & Seay, 2016).

Figure 1. Scavengers at *Kiteezi* Landfill Site (Komakech et al., 2014)

4. Mass Balance Calculation and Products Yield During Pyrolysis of Waste Plastics

For an industrial scale up of pyrolysis process, it is important to know the quantity of plastic waste that is needed to produce a certain amount of fuel oil at optimum conditions (i.e. the quantity of waste plastic needed to produce, say, 1 kg of fuel oil). Mass balance is always based on the law of conservation of mass. The flow sheet for a mass balance on plastic wastes in a batch reactor is illustrated in figure 2.

If it is assumed that there are no leaks and the measurements made are correct, a mass balance for the system can be written in general as in equation (1):

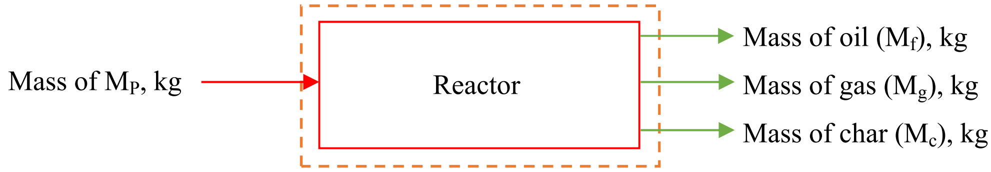

Figure 2. Illustration of mass balance on waste plastics

$$mass\ in = mass\ out$$

$$M_p = M_f + M_g + M_c \tag{1}$$

Where: Mp-mass of waste plastics, M_f-mass of fuel oil obtained, M_g-mass of uncondensed gas, M_c-mass of char remained in the reactor. It is important to note that all the terms are of the same unit (kg).

According to R. K. Singh & Ruj (2016), pyrolytic temperature and heating time are the factors that determine the quantity of char remaining in the reactor. Higher heating temperatures and times are associated with the reduction of solid residues in the reactor. The optimum residence time and temperature is reported in literature to be four hours and 400-600 ^{o}C respectively (Joshi & Seay, 2016).

4.1 Mass Balance on Plastic Wastes Generated in Uganda

Previous researchers (Deneve, Joshi, Samdani, Higgins, & Seay, 2017) carried out a pyrolysis experiment using a batch reactor, which was designed and fabricated by the University of Kentucky Appropriate Technology and Sustainability (UKATS) team. This reactor was designed to be specifically used in underdeveloped countries such as Uganda (Joshi & Seay, 2016). Results from their experiment indicated that, on average, about 82.70 % of fuel oil can be obtained from the pyrolysis of a mixture of waste plastics at a temperature of 475 ^{o}C. The remaining products are uncondensed gas and char. The amount, each of the gaseous and char fractions was not quantified. However, other authors (Grause, Matsumoto, Kameda, & Yoshioka, 2011) estimated the yield of char from the pyrolysis of a mixture of waste plastics to be 8% (weight). Also, Sharma et al. (2014) estimated the density of plastic-based diesel (PBD) to be 802 kg/m^3 at a temperature range of 420-440°C. Based on this data, the mass of fuel oil that can be obtained from various districts in Uganda is summarized and presented in table 2. Polyvinyl chloride (PVC) and polyethylene terephthalate (PET) polymers are included in the estimation. It is therefore necessary to consider a dechlorination step (stepwise pyrolysis) to avoid problems such as the production of hydrochloric acid which corrodes the pyrolysis reactor. Equation 2 can be used to determine the mass of fuel. Equation 3 can also be used to estimate the volume of liquid fuel.

$$Yield(wt\%) = (M_f/M_p)\,100 \tag{2}$$

$$Density(kg/m^3) = mass\ (kg)/volume(m^3) \tag{3}$$

Table 2. Estimated mass balance on waste plastics in kg

Districts	Waste Plastic	Fuel oil	Gas	Char
Wakiso	112 431.00	92 980.44	10 456.08	8 994.48
Kampala	84 908.00	70 218.92	78 96.44	6 792.64
Kibaale and Iganga	72 526.00	59 979.00	6 744.92	5 802.08
Arua and Kasese	83 284.00	68 875.87	7 745.41	6 662.72
Mubende and Mukono	72 164.00	59 679.63	6 711.25	5 773.12
Tororo and Rakai	58 486.00	48 367.92	5 439.20	4 678.88
Hoima and Kabale	62 052.00	51 317.00	5 770.84	4 964.16
Total	545 851.00	451 418.78	50 764.14	43 668.08

5. Potential Application of the Estimated Amount of Fuel Oil from Waste Plastics

Fuel oil from waste plastics has a high heating value (Cleetus et al., 2013; Kumar & Singh, 2013). The high heating value (HHV) of fuel derived from plastic waste is higher than that of conventional petroleum. Sharma et al. (2014) reported that the HHV of plastic-based diesel is 46.16 MJ/kg while that of conventional fuel oil is 45.15 MJ/kg. This HHV, together with its high density (802 kg/m^3), makes PBD useful in many applications. Additional advantage of the use of PBD is its minimal or sulfur free content which benefits the environment tremendously (Joshi & Seay, 2016).

Many farmers in Uganda face a lot of challenges in processing their produce after harvest. For example, threshing of rice is predominantly done by beating the harvested crops on tarpaulin or bare ground. This results in heavy contaminations of small stones, straws and weed seeds. For the market value of these crops to go high, these extraneous materials have to be removed. Similarly, milling of maize to produce flour for local food such as *posho, ugali, nshima* and *sadza* is not a common practice in some districts. Women and children predominantly use heavy pestles that require a lot of effort to pound maize into fine particles for local food. This is also laborious and time consuming. They resort to these methods because there is no electricity grid available. Lack of electricity grid also has negative effects on farmers' income, health and food security (van Gevelt, Holzeis, Jones, & Safdar, 2016).

Farmers therefore have to adopt the use of mechanical equipment for threshing. Mechanical threshers reduce drudgery, save time, reduce losses and contamination of foreign materials. These equipment however need to be powered. Small portable threshers that are commonly used in Uganda are powered by 5-7 horse power petrol engines that may use 1 L of fuel per hour for handling 550-650 kg of threshed fresh paddy. If a thresher works 8 hours/day for 300 days/year, a total of 1 560 tonnes of paddy will be threshed in a year. A total of 234 rice threshers can be powered by 562 866 liters of fuel oil from waste plastics. Therefore, 234 rice threshers will handle approximately 365 000 tonnes of fresh paddy annually.

On the other hand, the power requirement of hammer mills for grinding maize ranges between two and 50 kW. A 15 kW hammer mill uses 3 liters of diesel per hour for handling approximately 400 kg of maize flour (Clarke & Rottger, 2006). If the mill can work 8 hours/day for 300 days/year, it will grind a total of 960 tonnes of maize flour per year using 7 200 liters of fuel oil. Therefore, 562 866 liters of fuel oil that can be obtained from waste plastics will be able to power a total of 78 hammer mills of 15 kW capacity. These 78 hammer mills will be able to grind approximately 74 880 tonnes of maize annually.

6. Conclusions and Recommendations

Pyrolysis potentially offers prospects for sustainable way of solving plastic waste problem in Uganda. The quantity of plastic wastes generated in Wakiso; Kampala; Kibaale and Iganga; Arua and Kasese; Mubende and Mukono; Tororo and Rakai; and Hoima and Kabale districts was estimated approximately as 112, 85, 72, 83, 72, 58 and 62 tonnes/day respectively. The total amount of fuel oil that can be generated from 545 851 kg of plastic waste was quantified as 451 419 kg; which is equivalent to 582 866 L under pyrolysis using an appropriate technology from major districts in Uganda. This potential can be used as a power source to run seventy eight 15 kW hammer mills to grind 74 880 tonnes of maize flour per year. Likewise, it can be used to power 234 small portable threshers of 5-7 horse power to thresh 365 000 tonnes of fresh paddy. Also, comparing the composition of MSW in SSA, the fraction of the organic wastes constitutes a higher percentage i.e. 59% on average. However, in the most developed world, such as U.S. the percentage of organic wastes in MSW is as low as 14.6%, which is far below the value reported for SSA. 65-70% of MSW generated in developing countries ends up at landfill sites with only 10% recycled. This is always attributed to inadequate infrastructure and high capital costs. Even though, the Government of Uganda set a target to produce 30 MW from MSW by the end of the year 2017, this seems unrealistic. This is because there are no infrastructure or whatsoever to accomplish such a target. For efficient solid waste management in SSA cities, waste minimization principles such as reduce, reuse and also energy recovery techniques such as pyrolysis, anaerobic digestion and composting that are sustainable should be encouraged.

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