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An Appropriate Technology Based Solution to Convert Waste Plastic into Fuel Oil in Underdeveloped Regions

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Abstract

Along with population and urbanization in developing countries, the amount of municipal solid waste generated is also increasing. Although programs and initiatives to recycle and manage waste can often be found in the major population centers, these technologies are slow to spread to or are not yet present in the rural areas. Heavily populated urban slums are also lacking in the infrastructure needed to collect and manage trash, particularly plastic packaging. To address this challenge, the University of Kentucky Appropriate Technology and Sustainability (UKATS) research team has developed an appropriate technology based, sustainable solution to convert plastic from Municipal Solid Waste, such as High/Low Density Polyethylene, Polypropylene and Polystyrene into a valuable hydrocarbon fuel, suitable for underdeveloped or poverty stricken communities. The UKATS Processor is designed as a waste minimization solution specifically for underdeveloped communities, comprised of a simple, non-automated, multifunctional processor built using a wood fueled rocket stove as the primary heat source. This processor is designed using the principles of appropriate technology and sustainability and can be constructed using non-standard materials commonly present in rural or underdeveloped areas. This research focuses on utilizing plastic waste to produce a fuel oil product similar to kerosene or diesel in composition.

Keywords: sustainability, municipal solid waste, pyrolysis

1. Introduction

1.1 The Waste Plastic Problem

One of the biggest challenges facing developing countries is achieving economic growth in a manner that is socially and environmentally responsible. In rapidly growing countries like India, westernization has brought increased standards of living to much of the population. However, this improvement has been disproportionately centered in urban areas. Rural communities are often left behind, particularly if the regions are remote. As a result, there is often a significant cultural and lifestyle difference between the urban, westernized cities and rural, underdeveloped villages leading to differences in how municipal solid waste is handled.

During the recent decade industrialization, migration from rural areas, urbanization, uncontrolled consumption and population growth were the causes of increasing waste and consequently the rise of the waste management problems in developing countries (Kalanatarifard and Yang, 2012). Plastic waste in particular, accounts for 20-30% by volume and 10-12% by weight of MSW, which makes it the third largest contributor after food and paper (Singh, 2016). Much of this plastic ends up in the world's oceans, where an estimated 5.25 trillion pieces of plastic are present, weighing close to 270,000 tons (Eriksen, *et al*., 2014). Plastic production has increased over time as well, with literature reporting that plastic generation has increased from 1.5 million tons (MT) in 1950 to 245 MT in 2008 (Singh, 2016). This is due to its convenience in manufacturing and variety of applications in packing, agriculture, automobile industry, construction materials, electricity and electronics (Pinto *et al*., 1999; Singh, 2016).

In recent years, mass produced prepackaged goods have also spread widely throughout both urban and rural populations of developing countries. Typically manufactured in the cities and distributed nationally, prepackaged food items are an inexpensive source of nutrition, keeping food fresher longer. This has led to countries like India increasing consumption from 3 kg of plastic per year per capita in 2000 to 20 kg per year per capita in

2016 (Singh, 2016). When multiplied with its already dense population, India generated 5.6x10^6 MT of plastic waste annually in 2013, with the city of Delhi producing 689.5 MT per day (Singh, 2016). With all this plastic, it is the disposal phase that has the biggest ecological impact (Li, *et al*., 2010). So, despite the many benefits of better food preservation, dealing with MSW accumulation due to consumption of such goods is a challenge.

Nonetheless, major cities in India such as Delhi, Mumbai, Surat and Pune have begun dealing with waste plastic through processes such as incineration, anaerobic digestion and refused derived fuel plants, recycling as much as 60% in some regions (Kalyani, 2014, Singh, 2016). But, these technologies are still new and have encountered failures leading to most of the waste being piled in landfills near slums (Kalyani, 2014). This is problematic in two ways because, incineration methods are converting the waste plastic directly into carbon dioxide, nitrous and sulfur oxides, dusts, dioxins and similar toxins, while landfilling is leading to leaching and soil impregnation along with contamination of underground waters (Pinto, *et al*., 1999; Singh 2016). Meanwhile, waste generated by rural communities is simply dumped on the streets, as sustainable technologies to recycle the waste do not yet exist in these areas. As a result, the research presented here focuses on the development of a sustainable solution based on the principles of appropriate technology that can be used to reduce the waste accumulation and disposal crisis faced by developing countries like India.

Figure 1. Landfill near Siraikkaadu, a rural village in Tamil Nadu, India

1.2 Overview of Appropriate Technology

Appropriate technology (AT) is a design philosophy first described by E.F. Schumacher in his book *Small is Beautiful* (1973). It refers to “technological choices and applications that are small scale, decentralized, labor-intensive, energy efficient, environmentally sound, and locally controlled” (Hazeltine, 1999). AT is simply technology suitable for a specific region, designed to meet specific needs of certain individuals or communities. It differs from industrial scale processes in the sense that AT is specifically intended to be used in rural or underdeveloped regions. AT is low-cost, small-scale, easy to construct, and can be operated by individuals with limited formal technical education. The purpose of AT is not to reproduce industrial technology on a small scale; instead, it is to design specific solutions based upon the resources available in a given region or for a given community (Seay, *et al*., 2012). Therefore, AT based solutions often require trading industrial scale efficiency for simpler approaches that still meet the overall goals of the projects.

The processor designed by the University of Kentucky Appropriate Technology and Sustainability (UKATS) research team has been conceived using AT principles. It is designed to be built locally in underdeveloped regions from construction materials typically present in such regions. The UKATS Processor is simple, requires no electricity to operate and has no moving parts. Therefore, it can be built and operated by individuals with little or no formal technical education. Also, since the processor can be fabricated using used or scrap parts and non-standard materials of construction, it is low in cost.

The goal of this AT based process is to convert plastic solid waste into a liquid hydrocarbon fuel in rural or underdeveloped regions where solutions to waste accumulation are few or non-existent. Overall efficiency of the technology was compromised to ensure a simpler approach such as no moving parts or electricity requirements. The product was not evaluated as an over the road motor vehicle fuel, but as a replacement for petroleum derived fuels in farming equipment and cook stoves where it can serve as a viable alternative source of energy. The research presented in this contribution describes the design and construction of the UKATS Processor and the result of field trials for converting waste plastic into fuel oil. Additionally, the results of laboratory chemical analysis of the product to ensure that its composition is similar to commercial petroleum derived fuels will be reported. This analysis will also validate that the fuel produced is consistent with results from previous research work present in the literature for this field.

The UKATS Processor used for converting MSW sourced plastic into fuel oil is fueled by wood. The required heating is achieved using the principle of a rocket stove. Originally designed for cooking, the rocket stove is an efficient way of channeling air to the combustion chamber to achieve high temperatures (Bryden, M., *et al.*, 2005). Using the rocket stove, the processor provides effective heat transfer that reduces the amount of wood input required compared with a typical open fire cook stove. However, any time a wood fueled process is proposed, deforestation must be considered. In the state of Tamil Nadu, India, where the research field trials were conducted, a governmental program has been implemented to eradicate the non-native, invasive, *prosopis juliflora* plant species that is competing with agricultural land (Imranullah, 2014). Because of the use of *prosopis juliflora* as fire wood, deforestation is of minimal concern in this region.

1.3 Recent Scholarship on Waste Plastic Conversion

Plastics commonly found in MSW such as High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE), Polypropylene (PP), and Polystyrene (PS) are all viable raw materials for this process. Plastics such as polyethylene terephthalate (PET) and poly vinyl chloride (PVC) are unfortunately not suitable for this process, due to the presence of oxygen and chlorine respectively in the polymers. LDPE was used as the waste plastic source for field trials due to its availability in the test area, however, the other plastics listed above have been validated in numerous laboratory studies (Singh and Ruj, 2016, Demirbas, 2004, Pinto, *et al*., 1999). The chemistry of converting plastics such as LDPE waste to a hydrocarbon fuel oil is simple and well established (Singh and Ruj, 2016, Demirbas, 2004, Pinto, *et al*., 1999, Al-Salem, *et al*., 2009, Miskolczi, *et al*., 2004, Wong, *et al*., 2015, Panda, *et al*., 2010). LDPE, is produced via high-pressure, high-temperature free-radical chain-growth addition polymerization of ethylene, which is originally obtained from steam cracking of higher hydrocarbon oils, such as crude oil. A branched homopolymer, LDPE is manly used for food packaging, grocery bags, housewares, and films (Chenier, 2002). Pyrolysis, heating of the plastic in the absence of oxygen, or as it is also referred to, thermal decomposition, is the most widely utilized approach for converting LDPE (Wong, *et al*., 2015), or any waste plastic, into fuel oil (Singh and Ruj, 2016, Demirbas, 2004, Pinto, *et al*., 1999, Al-Salem, *et al*. 2009, Kumar and Singh, 2011, Miskolczi, *et al*., 2004, Panda, *et al*., 2010, Sarker, *et al*., 2012). Since, the molecules of this plastic are only made up of carbon-hydrogen chains, when thermally heated to temperatures of approximately 430°C (Wong, *et al*., 2015), the hydrocarbon chains break, decomposing the polymer, and yielding a hydrocarbon gas, which is then condensed to obtain the fuel oil product. The optimum temperature and time range for these reactions was found to be 400°C - 450°C with a run time of 4 hours. These results are in agreement with literature values based on laboratory experiments (Kumar and Singh, 2011, Singh and Ruj, 2016). Therefore, the key contribution of this research is to describe the design, fabrication, operation and testing of an appropriate technology based solution for reducing plastic in MSW.

2. Fabrication of the UKATS Processor

The UKATS Processor is designed by utilizing a rocket stove heat source, which ensures efficient heat transfer throughout the processor, while minimizing wood input required to maintain temperature. The combustion chamber of the UKATS Processor is insulated with vermiculite, however any high temperature insulating product can be used. This allows the processor to reach and maintain reaction temperatures quickly and easily, thus reducing both the operation time and fire wood required. To fabricate the processor, locally sourced materials of construction, such as steel drums of two different sizes, an empty propane cylinder, sheet metal, steel rebar, piping, fittings, and insulation are used. For assembly, only welding equipment and simple machine shop skills are needed. Refer to Figure 2 and Figure 3 for a shop drawing and a photograph of the completed processor. The dimensions shown are typical and represent target values. Variation is expected for locally produced processors.

Since the processor is completely non-automated and requires no electricity, no formal technical education is required to operate it. Operation is simple and begins by loading the reaction chamber, made from a propane cylinder, with coarsely shredded, chopped, or cut waste plastic. Any of the feasible plastic types can be used, including a mixture of each. As previously described, the field trials were conducted with LDPE. Next, the reaction chamber is placed inside the processor, the lid is attached and the processor is steadily heated to 400˚C - 450˚C to ensure proper thermal decomposition of waste plastic with minimal wax formation. The main source of fuel to heat the processor is wood, although charcoal can be used as well. For the field trials in Tamil Nadu, the wood source used is the invasive, non-native tree species, *prosopis juliflora* (Imranullah, 2014). When wood or charcoal is used as a fuel source, only maintenance of a steady fire is required to obtain the desired temperatures. Vapors exiting the processor are further condensed by bubbling through a 2-3 liter, ambient temperature water bath to condense them. The top fuel oil layer from the water bath is then separated by gravity to obtain the final product. The processor is operated for approximately 4 hours for complete thermal decomposition of all the waste plastic in a typical 3-5 kg batch. This procedure is in agreement with laboratory results reported in literature (Singh and Ruj, 2016).

Heat transfer through the UKATS Processor occurs as heat from the fire radiates towards the top into the inner barrel, circulating around reaction chamber, and out to the atmosphere through the chimney. As previously described, the pyrolysis gases emitted from the reactor are piped away from the processor and bubbled through a water bath to condense the product. The product is obtained as the immiscible water and fuel oil layers are separated by gravity. The water bath is reused for multiple batches, so wastewater disposal is not required. The remaining off-gases resulting from the production of synthesis gas can also be recycled back to the processor firebox to improve efficiency and address potential air pollution concerns. Minimal residue was observed in the reactor after a batch during the field trials, although, as previously discussed, this may not be the case when using MSW sourced mixed plastics. The only other waste product then is wood ash from the fire box which should be disposed of between runs. Due to the adherence to AT principles, the system cannot be made completely air free for pyrolysis, nonetheless, the oxygen in the air is displaced by fuel oil gases as the reaction proceeds, limiting the formation of unwanted side products. Similarly, precise temperature control cannot be achieved, but the UKATS Processor is able to achieve required temperatures to support the thermal decomposition reaction, thereby minimizing wax formation and producing a viable alternate source of liquid fuel from MSW sourced plastic.

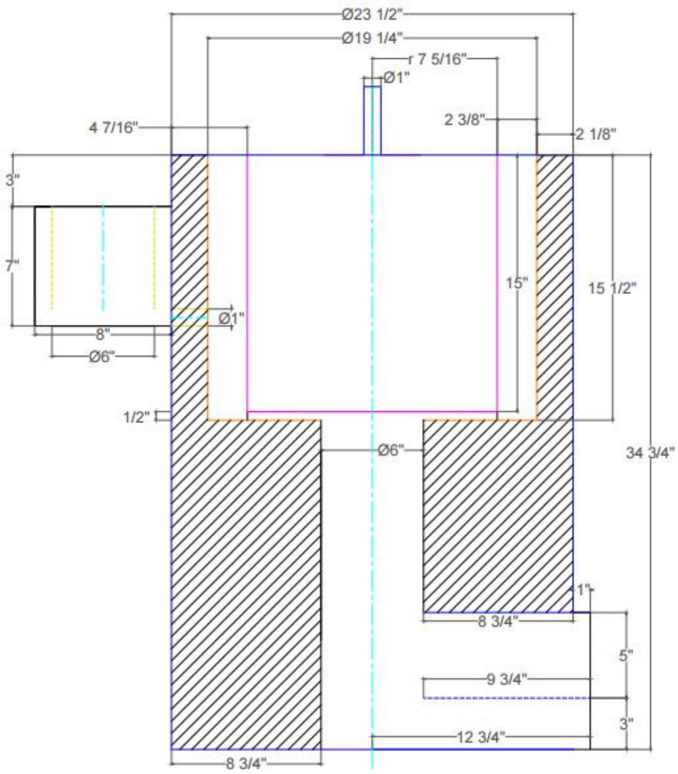

Figure 2. Dimensional sketch of UKATS processor (courtesy of Hannah Whitlock)

The safe operation of this processor is a primary concern. The principle safety hazard is burns due to contact with high temperature surfaces. To address this hazard, the processor includes a lid and is surrounded by an insulation layer that, in addition to conserving heat, maintains a safe surface temperature. A secondary potential hazard is overpressure of the reaction chamber. Although the pipe leaving the chamber is open to the atmosphere, the chamber is fitted with a safety relief device to relieve any potential overpressure as illustrated in Figure 3.

3. Implementation of the UKATS Processor Prototype in Tamil Nadu, India

Field trials were conducted in cooperation with the Organization of Development Action and Maintenance

(ODAM) in Tiruchuli, Tamil Nadu, India to test the prototype processor in a developing region. ODAM, an NGO in the region, works to address rural poverty, women's empowerment, child welfare, climate change, human rights to education, health, and safety (ODAM, 2015). The supply of LDPE waste was obtained from a grocery bag production factory in the nearby city of Aruppukottai, refer to Figure 4. This means that the waste plastic supply was clean and free of dirt and debris. MSW sourced plastic would require rinsing and drying to remove dirt and other foreign matter before adding it to the processor.

Due to the previously described eradication program for *prosopis juliflora*, ample supplies of wood fuel were available (Imranullah, 2014). The processor was operated under conditions described in literature (Al-Salem, *et al*., Kumar and Singh, 2011, Miskolczi, *et al*., 2004, Panda, *et al*., 2010, Sarker, *et al*., 2012, Wong, *et al*., 2015) and average yields of 81.22% fuel oil per batch were obtained as a result of the field trials, refer to Table 1 and Figure 5. The field trial results are in good agreement with the literature reported yields in the range of 80% (Wong, *et al*., 2015, Singh and Ruj, 2016).

Figure 3. UKATS prototype processor implemented in Tamil Nadu, India

The other products accounting for the rest of the yield were a non-condensable gas and char. Very little char was observed from the LDPE field trials. Only a small coating of residue remained in the reactor. This finding is consistent with literature results for similar experiments with LDPE (Singh and Ruj, 2016). Based on other studies, residue yields of 10% to 17% is to be expected when using mixed plastic (Singh and Ruj, 2016) (Sharma, *et al*., 2014). If running mixed plastics, this residue would have to be properly disposed of between batches.

Table 1. Field trials results of LDPE fuel oil yield per batch

Waste Plastic Input (kg)	Fuel Oil Output (kg)	Yield (%)
1.81	1.36	75.14
2.34	2.05	87.61
2.20	1.78	80.91

Average Yield – 81.22%

Based on the measured density of the fuel oil product, the average yield per 1 kg of waste LDPE was 1 L of hydrocarbon fuel oil. The liquid was yellow in color with viscosity similar to commercial combustion fuels. The fuel was further tested in local kerosene cook stoves as well as farm irrigation pumps, where it proved to be an effective replacement for both kerosene and petro diesel. Although this fuel oil has not been evaluated to determine if it meets current over-the road fuel standards, the field tests conducted in India indicate that it is certainly viable as a petro diesel alternative.

Figure 4. Waste LDPE from a grocery bag factory in Aruppukottai, Tamil Nadu

Figure 5. Fuel oil produced by the UKATS processor using waste LDPE

4. Experimental Methods and Results

Before the fuel oil produced by the UKATS Processor can be recommended as a substitute for petroleum based fuels, it is important to ensure that its quality is similar to plastic derived liquid fuels produced in a laboratory setting. Numerous laboratory studies on the properties of plastic derived liquid fuels have been conducted (Wong, *et al*., 2015, Singh and Ruj, 2016, Demirbas, 2004, Pinto, *et al*., 1999, Al-Salem, *et al*. 2009, Kumar and Singh, 2011, Miskolczi, *et al*., 2004, Panda, *et al*., 2010, Sarker, *et al*., 2012). To ensure that the quality and composition of the fuel oil produced from the UKATS processor was similar to the fuel oil properties published in literature, a series of preliminary laboratory tests were conducted.

4.1 Gas Chromatography

To compare the composition of the fuel oil produced during the field trials with petro fuels, a gas chromatograph (GC) model 7820A from Agilent Technologies was utilized. Experiments were conducted using an Agilent DB-624 UI column with a length of 30 m, diameter of 0.250 mm, and film thickness of 1.40 µm. The GC was equipped with a flame ionization detector (FID). The temperature program began with an initial temp of 75°C, held for 1 minute, then ramped at 20°C/minute to 265°C and held for 25 minutes, for a total run time of 35.5

minutes. Commercial kerosene and diesel samples were analyzed in the GC using the specified method along with the LDPE derived fuel oil from the field trials and the resulting peaks were compared to understand the composition of the fuel oil. The chromatogram of the fuel oil indicated that it is similar in composition to a mixture of heavy kerosene and light diesel fuels. The chromatogram of the LDPE fuel oil displayed peaks common to both kerosene and diesel fuel. These peaks are identified in Figure 6. The results achieved using the UKATS processor during the field trials in India are consistent with what has previously been reported in literature (Sharma, *et al*., 2014).

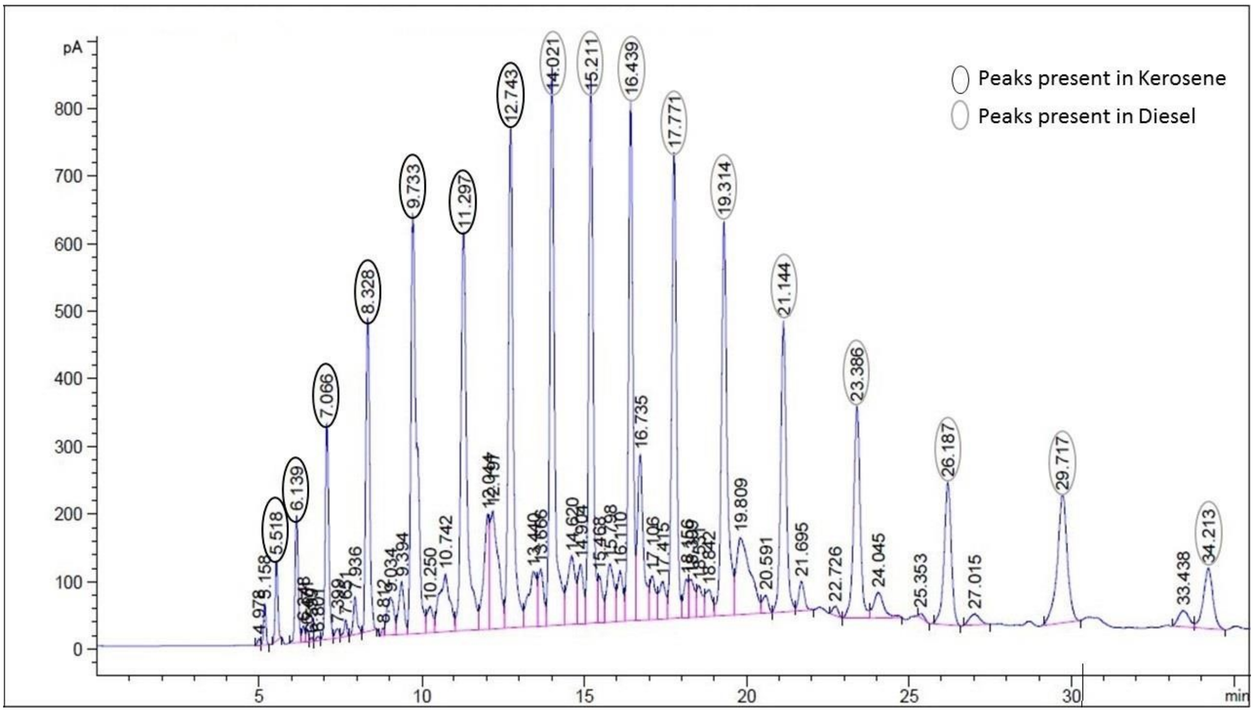

Figure 6. GC Chromatograph of the waste LDPE derived fuel oil produced during field trials in India

4.2 Density

In order to determine the mass yield, the density of the LDPE derived fuel oil produced in India was measured. Conducting a simple weight per volume experiment, the density of the fuel oil was found to be 0.742 g/mL. Results are consistent with literature reported values for mixed plastic of 0.71 – 0.73 g/mL (Singh and Ruj, 2016). Correspondingly, the density of kerosene was measured to be 0.751 g/mL and 0.732 g/mL for diesel.

4.3 Bomb Calorimetry

To determine the heat content of the fuel oil, bomb calorimeter experiments were performed. The PARR, 1341EB model was utilized with a power input of 115 Volts, 60 Hz, and 0.25 Amps. The average heat capacity of the calorimeter system was found by conducting calibration experiments with methanol. Next, the fuel oil sample was loaded in the bomb calorimeter apparatus, the apparatus was filled with pure oxygen gas, and immersed in water. A fuse in the apparatus ignited the fuel and the difference in initial and final temperature was measured to calculate the heat output value of the fuel, Q. Similar experiments were conducted with kerosene and diesel. As a result, the average Q values determined the calorific value of the samples. Each sample was run three times to obtain average values.

The experimental results verified that the heating value of the hydrocarbon fuel collected during the field trials per gram is higher than that of commercial kerosene or diesel. Specifically, the results indicate that the average calorific value of the fuel oil is 7% higher than kerosene and 17% higher than diesel. The results are illustrated in Figure 7.

4.4 Thermogravimetric Analysis

Lastly, a thermogravimetric analyzer from TA Instruments Model Q500 was used to determine the volatility per mass of the three fuels. The hydrocarbon fuel, along with kerosene and diesel were studied under a constant nitrogen flow and were heated at a rate of 10°C/min on 5-10 mg samples using platinum pans. The results indicated that the LDPE derived hydrocarbon fuel oil, was the most thermally stable and least volatile substance amongst the three. The data shows that on a per mass basis, the fuel oil sample took longer to vaporize, finishing at 225°C, compared with kerosene at 127°C and diesel 180°C. Results are illustrated in Figure 8.

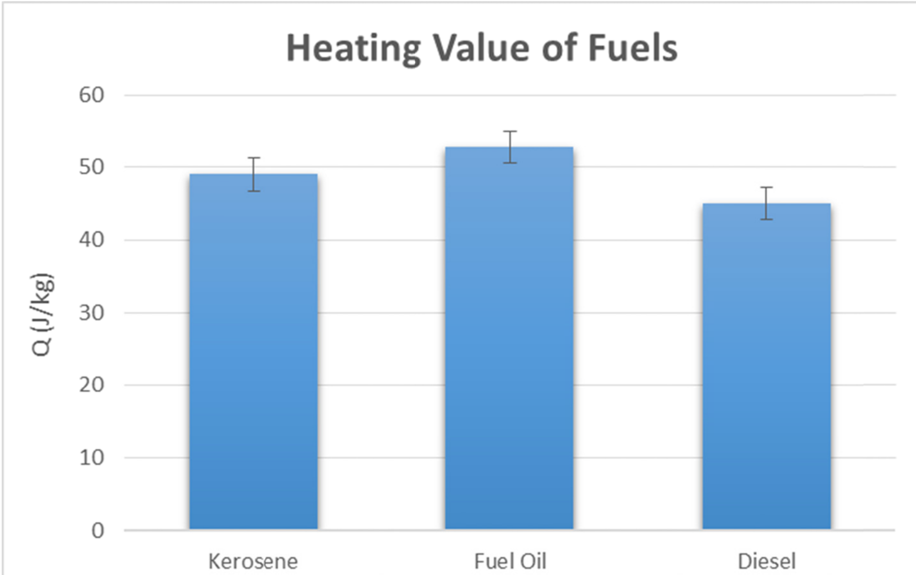

Figure 7. Heating value, Q, of the fuel samples

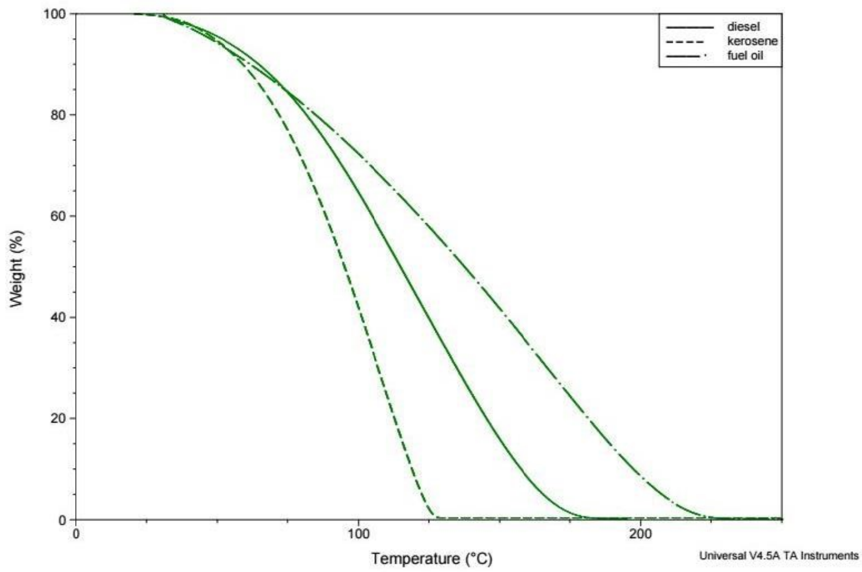

Figure 8. TGA Results of the LDPE fuel oil, kerosene and petro diesel

5. Discussion

5.1 Laboratory Results Discussion

Although AT based processing requires tradeoffs the resulting products must function as well as commercial alternatives. These results indicate that the hydrocarbon fuel oil collected during field trials has a lower volatility and higher calorific value than both petro diesel and kerosene. It is hypothesized that this may be due to the increased presence of double bonds from the LDPE feed stock. This gives the plastic greater thermal stability and higher calorific value, while still maintaining a similar composition to commercial fuels. Therefore, these results indicate that for the same volume of the hydrocarbon fuel, more energy is available, meaning it is more efficient. Hence, the amount of CO2 emissions produced per volume of fuel oil is decreased. The chemistry of the plastic molecule also leads to the fuel oil having no sulfur emissions, giving it a preference in underdeveloped regions over standard kerosene and diesel fuels due to improve environmental performance. The conclusion from this laboratory analysis is that the fuel produced using AT principles is of a consistent composition and quality as fuels produced in a controlled, laboratory setting.

5.2 Sustainability Discussion

In rural or similar underserved communities in developing countries, mass generation of prepackaged goods has led to an accumulation of waste, which often isn't recycled due to the lack of proper infrastructure to do so. This has led to increased pollution and health concerns. Therefore, the technology presented as a result of this research is designed to manage waste accumulation and produce a viable alternative fuel source, while minimizing the negative consequences from waste generation. The UKATS Processor and the hydrocarbon fuel oil product obtained from waste plastic achieve the three key principles of sustainability in that they are economically viable, environmentally benign, and socially acceptable. First, the processor can be built from used, non-standard materials of construction, reducing the cost versus new fabrication. In addition, an economic analysis was conducted on the cost of raw materials needed to produce the fuel oil. This analysis is based on the assumption that the fuel oil will be sold at the same price as the local petro diesel. The results indicated that per 3L batch of fuel oil, an average profit of 20 INR (0.29 USD) was earned after factoring in the cost of waste plastic, the cost to obtain the *prosopis juliflora* fire wood and the transportation cost of those materials. It should be noted that capital cost and labor costs have been excluded from this assessment. The omission of labor cost is based upon the assumption that entrepreneurs will be running the processors themselves and will take the 20 INR (0.29 USD) per batch as profit. If the batch size is increased, or several batches are continuously run in the processor, not only can the entrepreneur make a profit, but can also offset the capital cost of the processor within a reasonable amount of time.

As mentioned previously, since the waste plastic derived hydrocarbon fuel contains more energy per volume than petro fuels, it is more efficient. This leads to reduced CO_2 emissions compared with petroleum based fuels, aiding the environmental viability of the product. Likewise, using the rocket stove model with vermiculite insulation for heat input to the processor provides excellent heat transfer throughout the system while holding maximum amount of energy produced from the wood inside the processor itself. This means that the processor can reach desired reaction temperatures with minimal amount of wood required—an average of 3.7 kg of wood per kg of waste plastic. Although, policies in Tamil Nadu that exist to eradicate *prosopis juliflora* (Imranullah, 2014) eliminate deforestation concerns, in other developing regions the impact on deforestation must be considered, particularly if wood is scarce. Additionally, research is ongoing to consider more sustainable fuel sources for heating the processor.

Third, this technology and its hydrocarbon product are socially acceptable. The technology can be used either by communities or individual entrepreneurs, especially women. Due to its simplicity and low cost, a UKATS Processor can easily be financed via a micro loan. If it is used to bring in income to the developing community or household, gradually it can bring individuals out of poverty. In addition, the product, when utilized by the community or household, can act as an alternate source of energy for power generation, transportation and cooking in regions of limited or unreliable power generation (Whipple, *et al*., 2011). An increase in access to a reliable source of electricity also means an increase in access to education and knowledge. Similarly, the simplicity of the processor allows women in developing countries to operate it as well, thereby, improving their status in the community. Therefore, when adapted, the UKATS Processor can be a potentially transformative technology (Whipple, *et al*., 2011) that along with its hydrocarbon fuel oil product can increase the standards of living for a developing region.

In addition, there are health benefits that follow the adoption of this technology. The main purpose of the UKATS Processor is to reduce plastic MSW in developing countries. As a result, when the processor is used to remove waste plastic from landfills and off the streets of developing communities, the likelihood of it entering and contaminating water streams is decreased, as well as removing potential breeding grounds for disease carrying mosquitos. Consequently, reducing health concerns while promoting cleanliness. Hence, the UKATS Processor is an AT based solution that achieves sustainability principles by providing a low cost, simple to operate processor that results in a viable option to utilize waste in underdeveloped regions to produce an alternate source of energy.

6. Future Work

Future work for this research includes designing a modified version of the UKATS Processor that is heated by a burner using a portion of the hydrocarbon fuel oil produced from the process, thus eliminating the need for fire wood. In addition, another processor will be designed that can produce a 50L batch of MSW plastic derived fuel oil. Field trials will also be conducted on similar plastics such as High Density Polyethylene, Polypropylene, and

Polystyrene. All are potentially viable feedstock for this process, as a result, mixed plastic experiments will be conducted too. Finally, the broader goal of this research is to expand this innovative technology to other developing regions of India and other developing countries around the world where it can be used to reduce waste accumulation while obtaining a reliable, alternative source of energy.

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References

Al-Salem, S. M., Lettieri, P., & Baeyens, J. (2009). Recycling and Recovery Routes of Plastic Solid Waste (PSW): A Review. *Waste Management, 29*(10), 625-643. http://dx.doi.org/10.1016/j.wasman.2009.06.004

Bryden, M., Still, D., Ogle, D., & MacCarty, N. (2005). Designing Improved Wood Burning Heating Stoves, Aprovecho Research, Cottage Grove, Oregon.

Chenier, P. J. (2002). *Survey of Industrial Chemistry* (3rd ed.). Springer Science Business Media, LLC. pp. 117-118, 312-313. http://dx.doi.org/10.1007/978-1-4615-0603-4_8

Demirbas, A. (2004). Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. *Journal of Analytical and Applied Pyrolysis, 72*, 97-102. http://dx.doi.org/10.1016/j.jaap.2004.03.001

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C. … Reisser, J. (2014). Plastic Pollution in the World's Oceans: More than 5 Trillion Plastic Pieces Weighing over 250,000 Tons Afloat at Sea. *PLoS ONE, 9*(12). http://dx.doi.org/10.1371/journal.pone.0111913

Hazeltine, B., & Bull, C. (1999). *Appropriate Technology: Tools, Choices, and Implications*. New York: Academic Press. pp. 3, 270.

Imranullah, M. (2014). High Court Seeks Compliance Report. *The Hindu*. 10 Feb.

Kalanatarifard, A., & Yang, G. S. (2012). Identification of the Municipal Solid Waste Characteristics and Potential of Plastic Recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development, 5*(7), 11-17. http://dx.doi.org/10.5539/jsd.v5n7p11

Kalyani, K. A., & Pandey, K. K. (2014). Waste to Energy Status in India: A Short Review. *Renewable and Sustainable Energy Reviews, 31*, 113-20. http://dx.doi.org/10.1016/j.rser.2013.11.020

Kumar, S., & Singh, R. K. (2011). Recovery of Hydrocarbon Liquid from Waste High Density Polyethylene by Thermal Pyrolysis. *Brazilian Journal of Chemical Engineeirng, 28*(4), 659-67.

Li, Y., Subramanian, S. M., Hu, J. Y., Mok, P. Y., Ding, X., Wang, L., & Chen, W. (2010). Eco-Impact of Shopping Bags: Consumer Attitude and Governmental Policies. *Journal of Sustainable Development, 3*(2), 71-83. http://dx.doi.org/10.5539/jsd.v3n2p71

Miskolczi, N., Bartha, L., Deák, G., & Jóver, B. (2004). Thermal Degradation of Municipal Plastic Waste for Production of Fuel-Like Hydrocarbons. *Polymer Degradation and Stability, 86*, 357-66. http://dx.doi.org/10.1016/j.polymdegradstab.2004.04.025

Organization of Development Action and Maintenance (ODAM), Web page, accessed Oct. 2015. http://www.odamindia.org/

Panda, A. K., Singh, R. K., & Mishra, D. K. (2010). Thermolysis of Waste Plastics to Liquid Fuel. A Suitable Method for Plastic Waste Management and Manufacture of Value Added Products—A World Prospective. *Renewable and Sustainable Energy Reviews, 14*, 233-48. http://dx.doi.org/10.1016/j.rser.2009.07.005

Pinto, F., Costa, P., Gulyurtlu, I., & Cabrita, I. (1999). Pyrolysis of Plastic Wastes. 1. Effect of Plastic Waste Composition on Product Yield. *Journal of Analytical and Applied Pyrolysis, 51*, 39-55. http://dx.doi.org/10.1016/s0165-2370(99)00008-x

Sarker, M., Rashid, M. M., Rahman, M. S., & Molla, M. (2012). Production of Valuable Heavy Hydrocarbon Fuel Oil by Thermal Degradation Process of Post-Consumer Municipal Polystyrene (PS) Waste Plastic in

Steel Reactor. *Energy and Power, 2*(5), 89-95. http://dx.doi.org/10.5923/j.ep.20120205.02

Schumacher, E. F. (1973). *Small Is Beautiful: Economics as if People Mattered*, Harper & Row, New York, New York.

Seay, J., Zama, I., & Butler, B. (2012). International Partnership Helping to bring Appropriate Biofuel Technology to Rural Cameroon. *International Journal for Service Learning in Engineering, 7*(2), 35-48.

Sharma, B. K., Moser, B. R., Vermillion, K. E., Doll, K. M., & Rajagopalan, N. (2014). Production, characterization and fuel properties of alternative diesel fuel from pyrolysis of waste plastic grocery bags. *Fuel Processing Technology, 122*, 79-90. http://dx.doi.org/10.1016/j.fuproc.2014.01.019

Singh, R. K., & Ruj, B. (2016). Time and temperature depended fuel gas generation from pyrolysis of real world municipal plastic waste. *Fuel, 174*, 164-171. http://dx.doi.org/10.1016/j.fuel.2016.01.049

Suberu, M. Y., Mustafa, M. W., Bashir, N., Muhamad, N. A., & Mokhtar, A. S. (2013). Power Sector Renewable Energy Integration for Expanding Access to Electricity in Sub-Saharan Africa. *Renewable and Sustainable Energy Reviews, 25*, 630-642. http://dx.doi.org/10.1016/j.rser.2013.04.033

Vasudha Foundation. Current Status of Rural Electrification and Electricity Service Delivery in Rural Areas of India. Accessed 22 October 2015. http://www.vasudha-foundation.org/

Whipple, W., & Seay, J. R. (2011). Bridging the Gap Between Science and Engineering for High School Students through an Innovative Biofuel Research Project. *Proceedings of the 2011 American Society of Engineering Education Annual Conference*, CD Volume.

Wong, S. I., Ngadi, N., Abdullah, T. A. T., & Inuwa, I. M. (2015). Current State and Future Prospects of Plastic Waste as Source of Fuel: A Review. *Renewable and Sustainable Energy Reviews, 50*, 1167-180. http://dx.doi.org/10.1016/j.rser.2015.04.063