Feasibility and Optimization of Plastic Waste Energy Recovery Process as a Plastic Waste Management Tool in Zimbabwe

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Abstract

Post-use disposal of non-biodegradable plastic waste is a major challenge world-wide resulting in unprecedented accumulation of plastic waste in the environment. This poses hazards to the environment and health of human beings. Solutions to this challenge are still being sought. In this study, therefore, the feasibility of employing plastic waste energy recovery process as a plastic waste management tool was investigated and optimised. Polypropylene, polyethylene, and a mixture of the two plastics were used in the investigation. Energy recovery was done using the pyrolysis process. The Taguchi method was used for process optimisation and parameter design. Feedstock composition, temperature and heating rate are the parameters investigated. The energy was recovered in liquid form as oil. Optimum conditions were found using polypropylene plastic and a temperature of 500 ºC and a heating rate of 15 ºC/min were found to be the optimum conditions. Parameter interaction analysis showed increase in the oil yield as temperature increased from 450 °C to 500 °C, after which the yield decreased.

Keywords
Energy recovery, optimisation, plastic waste, waste management, Taguchi

1. .Introduction

Plastics production has increased by an average of almost 10% every year on a global basis since 1950 (Daugaard and Brown, 2003). The increased consumption of plastic in modern society is inevitable due to their versatile utilities, functional values, and a relatively small amount of energy required for their production compared with other materials (Ng et al., 1995).. Plastic wastes can be classified into two categories based on their origins as municipal (post-consumer) and industrial (pre-consumer) plastic waste. These groups have different qualities and properties; thus, they are subject to different management strategies. Of the total plastic waste, over 78% of this total corresponds to thermoplastics and the remaining to thermosets (Panda et al., 2010). Thermoplastics are composed of polyolefin such as polyethylene, polypropylene, polystyrene, and polyvinyl chloride (Mudzengerere and Chigwenya, 2012) and can be recycled. On the other hand, thermosets mainly include epoxy resins and polyurethanes and cannot be recycled (Panda et al., 2010). Pre-consumer plastic wastes, which are also known as primary (industrial) waste, emanate from manufacturing, processing, and packaging industries (Patni et al., 2013). They are a result of process purging and scrap during virgin plastic manufacture. Post-consumer plastic wastes are a fraction of municipal solid waste (MSW) whose life cycle range from medium to short term (Chanda, 2017). The composition of municipal plastic wastes (MPW) vary with the lifestyle and economy of the people as well as the season of the year. MPW is a heterogeneous mixture that includes items such as disposable plastic plates, food containers, packaging foam, disposable cups, compact disks, cutlery, cushioning foams, carbonated drink bottles and plastic pipes.

Most plastics are not biodegradable, and hence disposing them after use has become a major problem worldwide. This increase in plastic burdens financial resources of local authorities tasked with solid waste management and

sanitation. Plastics litter communities and block sewerage systems, among other negative impacts on the environment and public health (Klar et al., 2014). Disposing of the waste to landfill is becoming undesirable due to legislation pressures, rising costs and the poor biodegradability of commonly used polymers. A typical legislation is that waste to landfill must be reduced by 35% over the period from 1995 to 2020 (Geyer et al., 2017). Incineration is slowly becoming unpopular due to the greenhouse gases produced during the process.
Recycling emerged as a better method; however, only about 20% of the total waste plastic is recycled, leaving the rest to incineration and landfilling (Lebreton and Andrady, 2019). There are several options available for managing waste plastics which include, primary recycling, secondary or mechanical recycling, chemical or tertiary recycling and quaternary recycling as shown in Figure 1.

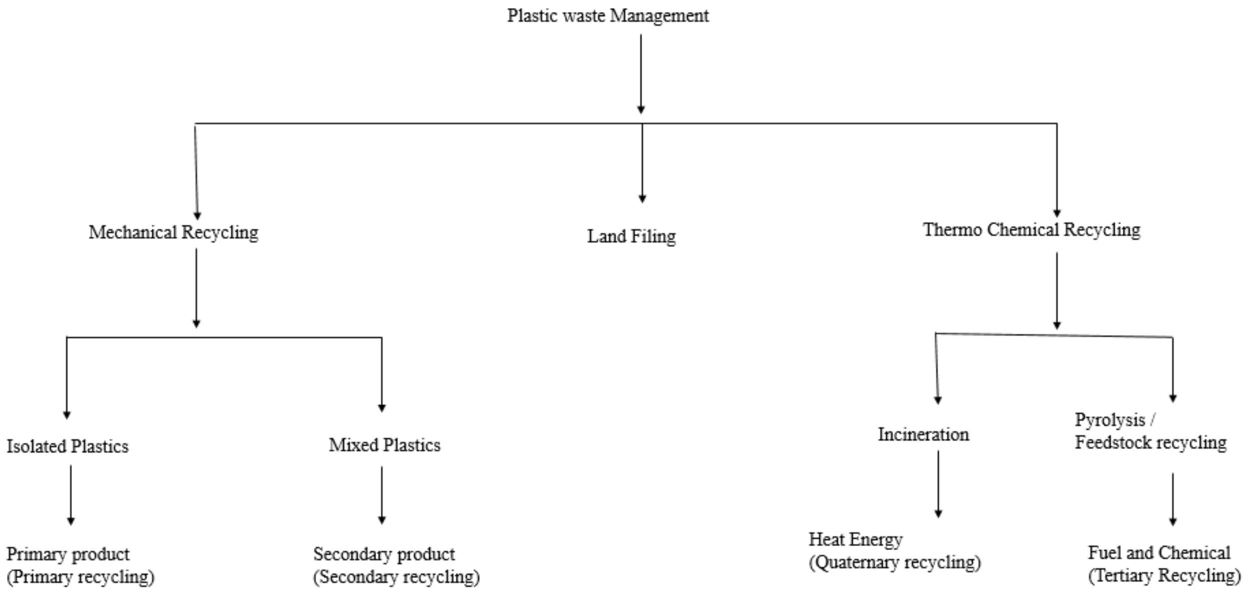


Figure 1. Plastic waste management methods

Plastic waste in Zimbabwe is mainly landfilled, indiscriminately dumped, and incinerated (combusted). There are only two landfills in Zimbabwe, one in Harare and the second one in Bulawayo, making it a challenge for waste management using the landfilling method. Therefore, this work sought to investigate the feasibility of using plastic waste energy recovery process as a plastic waste management tool in Zimbabwe.

The plastic waste energy recovery process needs to be optimised in order to make it economical. There are different optimisation techniques such as artificial neural network (ANN), particle swam optimization ., genetic algorithms (GA), design of experiments (DEO), and fuzzy logic (Agrawal et al., 2019). There are different approaches to DOE such as factorial method, Plackett-Buman method, Taguchi method and response surface method (RSM) (Benoit et al., 2017), of these the Taguchi and RSM are widely used optimisation techniques when dealing with polymers (Agrawal et al., 2019). Taguchi method is a statistical approach to optimise the process parameters and improve the quality of components that are manufactured (Porro et al., 2007, Kukovecz et al., 2005). The method affirms the role of product design and development by reducing the occurrence of defects in the products (Rao et al., 2013) thus optimizing the quality of the product. The Taguchi method has been used for the optimisation of process parameters in improving the surface roughness of the lathe facing operation. It was also employed to optimise the mechanical properties of Manicaria Saccifera fabric (MF) reinforced by the poly-lactic acid matrix.

2. Materials and Methods

A survey and experimental approach were employed in this study. Interviews were conducted with staff at the landfilling site and the senior management in the waste management section of the city council. Questionnaires made up of open-ended types of questions were distributed to the team of the waste management department. Onsite visits to some illegal dumping sites around the city were carried out. Samples were collected from the dumping sites which represent the waste generated in the city. Experimental work was used to assess the thermal decomposition behaviour of the plastics and energy that can be recovered from waste plastics. Pre-treatments processes which included sorting, washing, and shredding of waste plastics were done prior to other experiments. Thermogravimetric analysis of the plastics at different heating rates of 10, 15 and 20°C/min at a temperature range of 30-8000°C under an inert environment was done to determine the transition temperature of each plastic. The thermal stability of the plastics was also investigated using a thermogravimetric analyser. A vertical pyrolysis batch reactor with an electrically powered furnace was used to carry out pyrolysis experiments.

To optimise the energy recovery process the Taguchi method was employed. Optimisation experiments were done in accordance to the L9 Taguchi orthogonal array to standardise the experimental designs. The method aids in formulation of quality loss when quality loss /gain is expressed on a simpler manner, quality characteristic can be for a specific target value (nominal is best), high as possible (bigger is best) or low as possible (smaller is best). The performance characteristic for this study was bigger is best. Careful selection of process parameters, bifurcating them into control and noise factors is essential when using the Taguchi method. Three factors were considered for the study, feed composition, temperature, and heating rate. Taguchi method uses a statistical measure of performance called the signal to noise (S/N) ratio. The S/N ratio is the ratio of the mean (signal) to the standard deviation (noise). It takes both the mean and variability into account. The S/N ratio is a special kind of data summary that can combine two characteristics into the desired one, and it is often used in analysing the data for parameter design (Panda et al., 2010). The S/N equation depends on the criterion for the quality characteristic to be optimised.

3. Results and Findings

3.1 Waste stream characterisation

The survey revealed that there is no material recovery facility and composting facility in the city and not all waste is dumped at the landfill as some are dumped at legal and illegal dumping sites. It was also observed that plastic waste contributes most to the city waste stream as shown in Figure 2

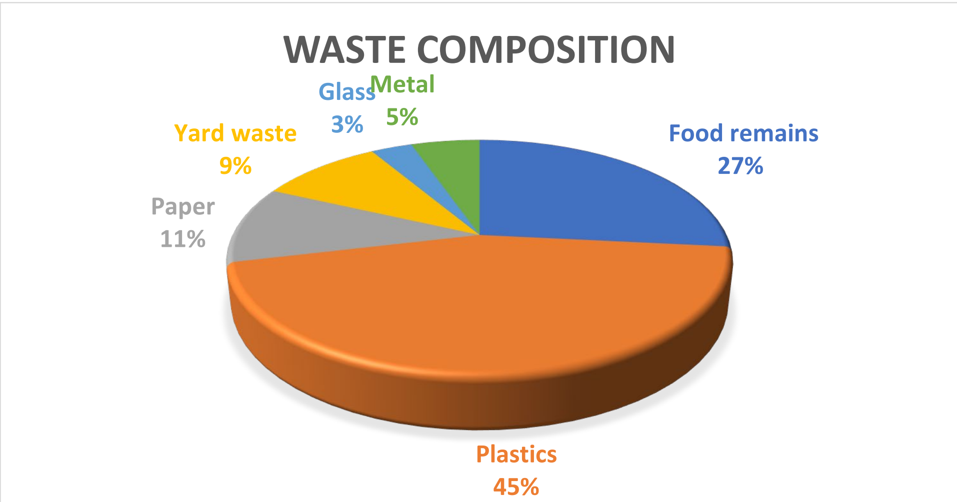


Figure 2 City waste composition

The composition of the city waste is shown in Figure 3.

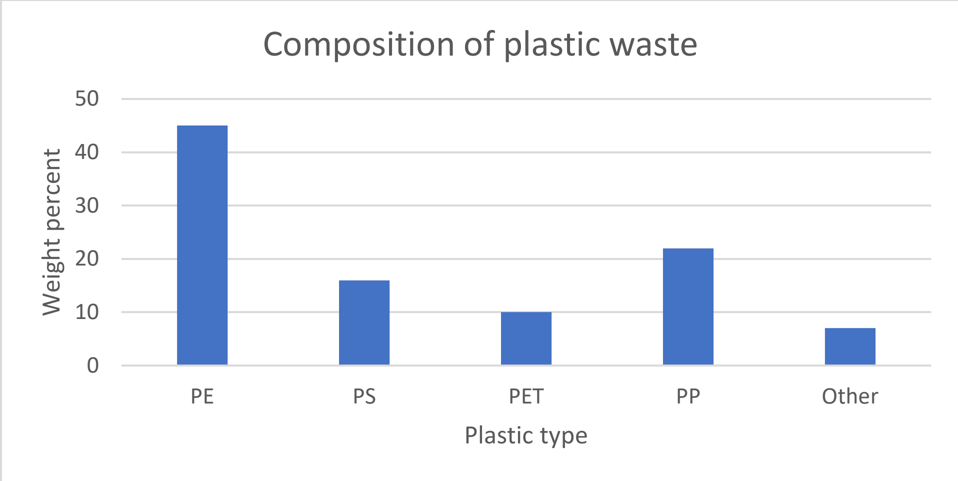


Figure 3. Plastic waste composition
PE- polyethylene, PS- polystyrene, PP- polypropylene, PET- polyethylene terephthalate

Figure 3 shows that PE is the most common plastic in the plastic waste stream and constitute about 45% of the plastic waste. This is because PE has wide use in plastic carrier bags and wrapping paper for different commodities. PP constituting about 23% is the second common plastic in the waste stream as it is mostly used for domestic plastic utensils because of its strength. PET constituting about 10% is found in minimum amounts as it is mostly reused in the informal sector recycled by the private sector. PS constitutes 15% as it is commonly used in fast food outlets. The other types of plastics constitute about 6% of the plastic waste stream.

3.2 Proximate analysis

A proximate analysis using the TGA results gave an overview of the moisture content (MC), volatile matter (VM), fixed carbon (FC) and ash content in plastic polymers. Plastics have very low moisture content. Plasticisers, moisture and other low boiling compounds which are highly volatile make up the moisture content of the plastics. Volatile matter are materials such as oil and polymer degradation products. The amount of volatile matter shows an approximate amount of energy that can be recovered from the plastics. Fixed carbon is made up of combustible material which oxidises at temperatures as high as 750°C. Ash consists of nonvolatile residues which may include metal components and filler content. Table 1 summarises the proximate analysis of the plastics under investigation.

Table 1 Proximate analysis

Polymer	MC	VM	FC	Ash
PE	0.10	92.01	0.13	7.76
PP	0.07	98.06	0.07	1.80
Mixture	0.15	91.32	0.52	8.01

3.3 Energy recovery

Energy was recovered in liquid form as an oil. Experiments to recover the energy embedded in plastic waste were done and optimized following the Taguchi L9 orthogonal array. The collected oil was expressed as a weight percentage of the mass of plastics fed into the reactor. Each experiment was done in triplicate. A mean value of oil recovered for each trial was calculated. The objective function for this study was to maximise the oil yield. Table 2 shows results for the experiments, mean and SN value for each trial.

Table 2 Orthogonal array experiment results

Experiment	A	B	C	Trial 1	Trial 2	Trial 3	Mean	SN Value
1	PE	450	10	61.1	60.9	60.6	60.9	35.687
2	PE	500	15	62.4	62.0	61.9	62.1	35.862
3	PE	550	20	57.9	58.5	57.6	58.0	35.253
4	PP	450	15	63.9	64.4	64.8	64.4	36.173
5	PP	500	20	64.7	65.0	64.9	64.9	36.240
6	PP	550	10	62.4	63.2	62.7	62.7	35.954
7	Mixture	450	20	60.5	60.1	59.2	59.7	35.552
8	Mixture	500	10	61.6	61.2	60.8	60.8	35.734
9	Mixture	550	15	59.7	59.0	58.3	58.6	35.415

A- Feedstock composition B – temperature C – heating rate

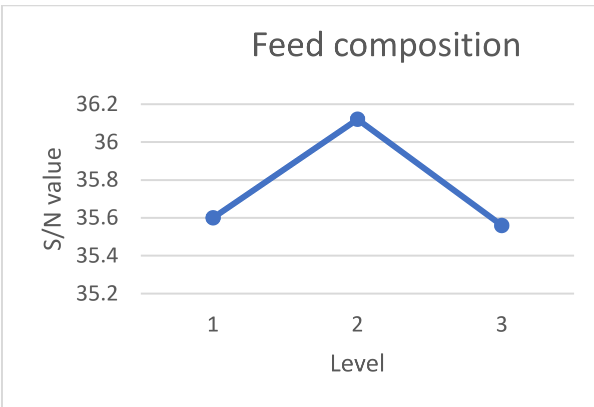
To assess the effect of each factor the S/N value for each factor at each level was calculated. The R-value (R= high SN – low SN) for every factor was calculated to indicate the effect of the factor on the process. Temperature (factor B) has the largest R-value signifying its significant impact on the process. Table 3 shows the S/N value for each factor and the R-value. A change in the temperature causes an effect on the amount of oil obtained during the plastic waste pyrolysis process.

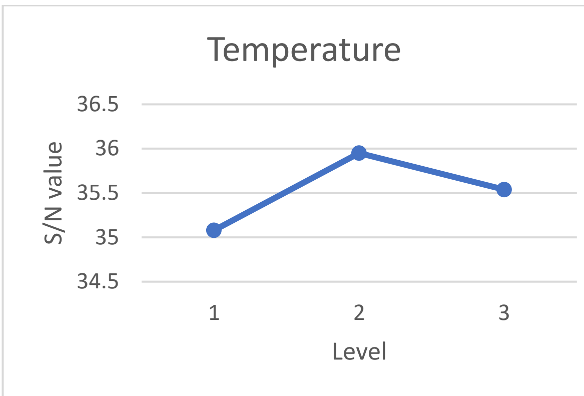
Table 3 Factor S/N value and R

Level	SN_A	SN_B	SN_C
1	35.60	35.08	35.79
2	36.12	35.95	35.81
3	35.56	35.54	35.68
R	**0.56**	**0.87**	**0.13**

3.4 Main Effect plots

Main effect plots were plotted to give the optimum level for each factor so as to determine the optimum condition for recovering maximum oil.





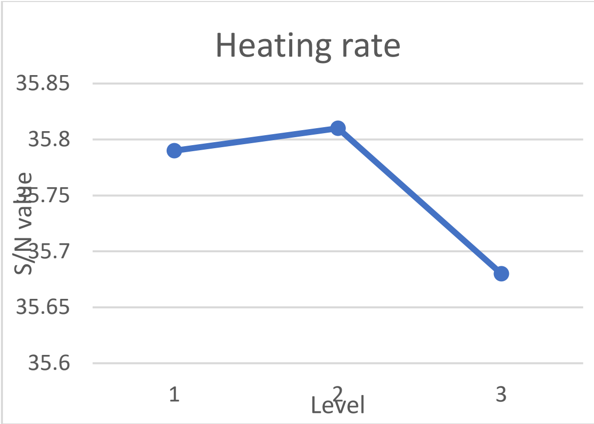


Figure 4. Main effect plots

Figure 4 shows that oil yield increases as the feedstock is changed from PE to PP and decreases when the two polymers are mixed. Also, as the temperature and heating rate increase from 450-500°C and 10-15°C/min oil yield increase respectively continual increase in the two factors is marked with a decrease in oil yield. Using these plots optimum conditions were determined as feed composition of polypropylene at a temperature of 500°C and heating rate of 15°C/min.

4 Conclusion

The amounts of oil obtained during the pyrolysis experiments are evidence that energy embedded in the plastic waste can be recovered. Energy can be reclaimed in liquid form as oil, solid form as char, or as a gas. Plastic waste is bulky, occupying a larger volume; pyrolysis reduces the bulk of the trash. All products obtained from pyrolysis can be put to good use, making pyrolysis an efficient method/tool for waste management. In conclusion, pyrolysis is effective in recovering energy from plastic waste as a tool for waste management

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Biographies

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