Cambridge Prisms: Plastics

www.cambridge.org/plc

A sustainable approach to plastic waste management in the Global South

Dimitrios Karadimas, Emilye Garner and Jeffrey Seay

College of Engineering, University of Kentucky, Paducah, KY, USA

Research Article

Cite this article: Karadimas D, Garner E and Seay J (2023). A sustainable approach to plastic waste management in the Global South. *Cambridge Prisms: Plastics*, **1**, e4, 1–6 https://doi.org/10.1017/plc.2023.5

Received: 02 December 2022
Revised: 03 April 2023
Accepted: 03 May 2023

Keywords:
Pyrolysis; plastic-to-fuel; Global South; waste management; appropriate technology

Corresponding author:
Jeffrey Seay;
Email: Jeffrey.seay@uky.edu

Abstract

Although the awareness of the environmental damage caused by plastic pollution has recently increased, few steps have been taken to confront its consequences. These consequences are often most severe in the Global South where countries often lack proper waste management infrastructure. Unless the market value of plastic waste increases, it will simply be discarded, eventually making its way to the environment. It has been established that polyolefin plastic can be converted to a sulfur-free fuel oil by pyrolysis, suitable for use in diesel engines or as a clean cooking fuel. However, carrying out this chemistry in the Global South is challenging. Any process intended for use in the Global South must be safe, robust, efficient, simple to operate, low cost, and most importantly profitable for the operator. When the average daily wage in sub-Saharan Africa is less than 3 USD, an income provided from plastic waste fuel can be significant. The research presented herein focuses on the optimization of a plastic-to-fuel processor that can be built using the principles of appropriate technology. The results of this optimization and profitability assessment will be described. This research has been conducted in collaboration with the NGOs Empowered Solutions for Environmental Sustainability and UpCycle Africa.

Impact statement

Mismanaged plastic waste is a significant crisis in the Global South, where facilities to properly recycle or sequester postconsumer waste are often non-extant. Local solutions that are low cost, safe, can be easily implemented, and benefit the community are therefore needed. This research focuses on utilizing appropriate technology-based slow pyrolysis to convert plastic waste into a clean burning fuel oil that can be used locally. The primary impact of this research is found in the approach taken to enable communities in the Global South to take control of plastic waste management in a way that benefits people and the environment.

Introduction

The plastic waste crisis

Although plastic waste management is a global challenge, the problem is particularly acute in the Global South where lack of infrastructure, prioritization of economic development over human health, and lack of strong governmental institutions exacerbate the problem (Mrayyan and Hamdi, 2006; Sujauddin et al., 2008; Minghua et al., 2009; Moghadam et al., 2009; Troschinetz and Mihelcic, 2009; Seng et al., 2010; Kalanatarifard and Yang, 2012). Most environmental plastic waste clean-up efforts fail where there is no beneficial use identified for the collected environmental plastic waste (Foong et al., 2022). Without an economic value, most plastic waste will be improperly discarded, or burned in open piles. Therefore, approaches that give a value to plastic waste such as conversion to fuel oil have the best chance of being effective.

A sustainable solution

Polyolefin plastics can be converted into a liquid fuel oil via thermal decomposition by slow pyrolysis. The chemistry of this process is well understood, however, the design and operation of a slow pyrolysis processor in countries in the Global South presents specific and unique challenges. In addition, the process must be economically viable, meaning that the potential daily earnings must provide suitable income to the operators.

The primary advantage of the conversion of waste plastic into fuel oil is that it eliminates the plastic from the environment. This is in contrast to traditional recycling, which only delays the introduction of plastic to the environment. If plastic-to-fuel oil by slow pyrolysis can be carried out in a way that provides economic value, this technology can be effective in eliminating polyolefin plastics such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), and polypropylene (PE) from the environment.

Appropriate technology

The concept of appropriate technology (AT) was first described by Schumacher (1973) in his book *Small is Beautiful*. It refers to "technological choices and applications that are small scale, decentralized, labor-intensive, energy efficient, environmentally sound, and locally controlled" (Hazeltine and Bull, 1999). Although slow pyrolysis is a well-established technology, carrying it out using the principles of AT necessarily requires trade-offs. Simplicity over complexity, manual operation over automation, robust design, safety, and affordability are key hallmarks of AT. These principles have been adhered to in the design of the plastic to fuel oil processor.

Background

Plastic to fuel chemistry

The chemistry for the conversion of polyolefin plastic to liquid fuel oil is well-established (Pinto et al., 1999; Demirbas, 2004; Miskolczi et al., 2004; Al-Salem et al., 2009; Panda et al., 2010; Kumar and Singh, 2011; Sarker, 2011; Sarker et al., 2012; Wong et al., 2015; Singh and Ruj, 2016; DeNeve et al., 2017; Patil et al., 2017; Santaweesuk and Janyalertadun, 2017). Polyolefin plastic consists of long-chain polymers consisting of thousands of monomer units. These plastics can be decomposed into shorter chain lengths of 12–14 carbons. At these chain lengths, these polyolefins remain in the liquid phase and can be used as a substitute for diesel fuel or kerosene. The total energy required for the conversion of LDPE, HDPE, and PP was calculated by Joshi and Seay (2020) and is listed in Table 1.

Table 1. Pyrolysis energy for polyolefins (Joshi and Seay, 2020)

	LDPE	HDPE	PP
Pyrolysis energy (kJ/kg)	9,468 ± 593	9,097 ± 383	5,434 ± 472

To approximate real operation of the plastic to fuel oil processor in the Global South where the process will be run, experiments were carried out with a mix of LDPE, HDPE, and PP. To approximate this mode of operation, an average value for the pyrolysis energy of 8,000 kJ/kg was be used in all calculated values.

Design of the plastic-to-fuel process

The plastic-to-fuel pyrolysis processor has been designed using the principles of AT. The process consists of an electrically heated 30-liter, 30.5-cm OD inner retort made of mild steel. The operating temperature of the electric heater is controlled using a PID controller. The retort is also equipped with an analog thermometer to indicate the internal temperature. The outer housing is constructed of mild steel. The 7.6 cm annular space is filled with insulation. The vapor product is collected overhead and condensed with a 3-m aluminum coil submerged in a water bath. The processor operates at ambient pressure; however, it is equipped with a pressure relief valve to mitigate any inadvertent overpressure. A schematic of the processor previously published by Foong et al. (2022) is illustrated in Figure 1. This design is flexible and so that substitutions with locally available materials of construction are possible.

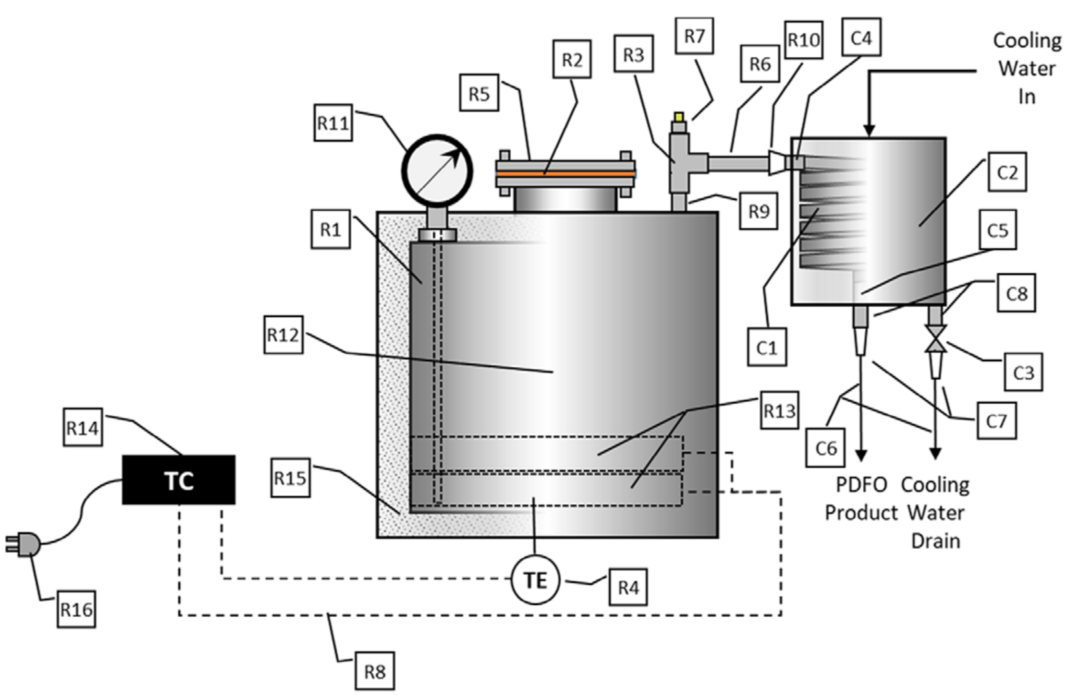

Figure 1. Schematic of electric plastic to fuel oil processor (Foong et al., 2022). R1, Fabricated retort; R2, High-temperature gasket; R3, 3/4″ CS tee fitting; R4, High-temperature thermocouple; R5, 3″ Blind flange; R6, 12″ × 3/4″ CS Pipe; R7, Pressure relief valve; R8, High-temperature wire; R9, 3/4″ CS pipe nipple; R10, 3/4″ × 3/8″ pipe reducer; R11, Analog bi-metal thermometer; R12, Fabricated processor housing; R13, Heating element, 240 V, 2,200 W (2); R14, PID controller; R15, Insulation; R16, NEMA plug w/wire leads; C1, 3/8″ Easy Bend Aluminum Tubing (10 feet); C2, Fabricated condensing vessel; C3, 3/8″ Brass Ball Valve; C4, 3/8″ compression × 3/8″ NPT fitting; C5, 3/8″ compression × 3/8″ NPT fitting; C6, 3/8″ Clear Tubing; C7, 3/8″ Hose Barb.

https://doi.org/10.1017/plc.2023.5 Published online by Cambridge University Press

Table 2. Selected global energy and fuel prices (Global Petrol Prices, 2022)

Countries and regions	Average electricity price (USD/kWh)	Average diesel price (USD/liter)
Global average	0.14	1.34
Latin America and the Caribbean	0.18	1.19
Middle East and North Africa	0.04	0.56
South Asia	0.07	1.81
Sub-Saharan Africa	0.11	1.31
India	0.07	1.16
China	0.08	1.12

Table 3. Selected average daily wages for selected Global South countries (Our World in Data, 2022)

Regions and countries	Average daily income (USD/day)
Global average	7.56
Sub-Saharan Africa	2.86
India	3.89
South Asia	4.02
Middle East and North Africa	7.52
China	10.72
Latin America and the Caribbean	11.46

Global energy price review

To be economically viable, the value of the fuel oil produced must be greater than the cost of the electricity needed to operate the process. Selected electricity and traditional diesel fuel prices for regions in the Global South as well as the global average are listed in Table 2.

Average income in Global South countries

The plastic to fuel oil processor is designed to provide sufficient supplementary income for operators in the Global South. Average daily incomes (2019 and 2022 Data) for selected regions are listed in Table 3.

Experimental methods

The experimental runs were conducted in the pyrolysis retort described by Foong et al. (2022). Mixed plastics consisting of LDPE, HDPE, and PP in equivalent amounts were used. The plastics used in these experiments were sourced from household waste. Previous results by Jangid et al. (2022), indicated that temperatures between 375°C and 425°C were appropriate for waste plastic pyrolysis. For the experimental runs conducted in this research, two temperatures in the mid-range were selected, 385°C and 395°C. Temperatures below 375°C produced almost no product and temperatures above 400°C tended to generate wax.

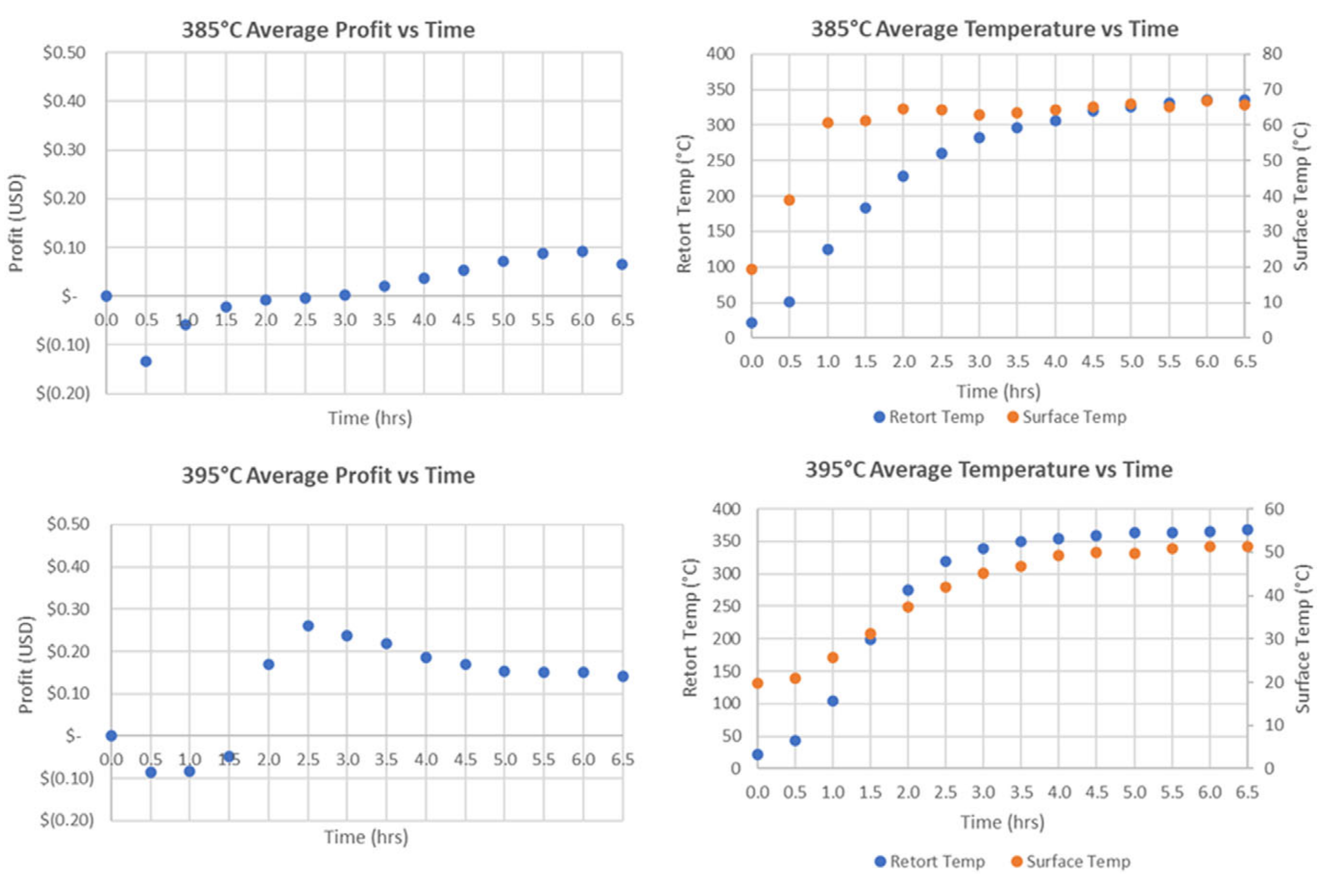

Figure 2. Average profit versus time for mixed plastic pyrolysis using Mineral Wool insulation.

To assess the efficiency of the processor, the measured electricity input in kWh, the fuel oil production in grams, the heater temperature, temperature at the surface, and the temperature in the retort were all recorded at 30-minute (0.5-hour) intervals. Data for each run were collected for 390 minutes (6.5 hours). This time was selected based on an 8-hour workday, allowing time for shredding plastic, loading the processor, and cooling and clean-up time at the end of the workday. Two insulation materials were tested, mineral wool (thermal conductivity = 0.055 W/m-K at 400°C) and Pyrogel XTE Aerogel composite blanket (thermal conductivity = 0.046 W/m-K at 400°C). In both cases, 7.65 cm of total insulation thickness was used.

Results and discussion

Experimental results are reported in Figures 2 and 3. These results indicate that higher *R*-value insulation results in improved efficiency, reduced heat loss, and higher profitability.

Based on the measured experimental data, the average daily profitability has been calculated and is reported in Table 4. Profitability is based on an average diesel fuel price of 1.63 USD/liter and an electricity price of 0.12 USD/kWh. Calculations are based on an 8-hour workday with a total processor operating time of 6.5 hours. The profitability calculation is based on the assumption that in the Global South, waste plastic can be purchased from waste pickers at 0.15 USD per kg. If the waste plastic is collected from the environment by the operator at no cost, the profitability will be increased.

Table 4. Summary of pyrolysis profitability experimental results

	Average profitability @ 385°C	Average profitability @ 395°C
	(USD/day)	(USD/day)
Mineral wool insulation	0.15	0.51
Aerogel insulation	1.25	1.46

Based on the measured data from the experimental results, the heat loss to the environment can be calculated. This heat loss to the environment is calculated as follows:

$$Q = h \cdot A \cdot \Delta T, \tag{1}$$

where: Q is the average heat loss in kJ/h, h is the convective heat transfer coefficient in W/m^2-K, and ΔT is the temperature difference between the processor surface and the ambient air.

The heat transfer coefficient for convective heat loss to the environment in still air at an ambient temperature of 25 °C is estimated to have an average value of 5.0 W/m^2-K (Kosky et al., 1999). The surface area for heat transfer from the outer housing is 1.2 m^2. The heat loss calculation results are listed in Table 5.

The efficiency, η, of the AT plastic to fuel processor is calculated as follows:

$$\eta = \frac{\text{Theoretical pyrolysis energy}}{\text{Total electric energy input}} \cdot 100\%. \tag{2}$$

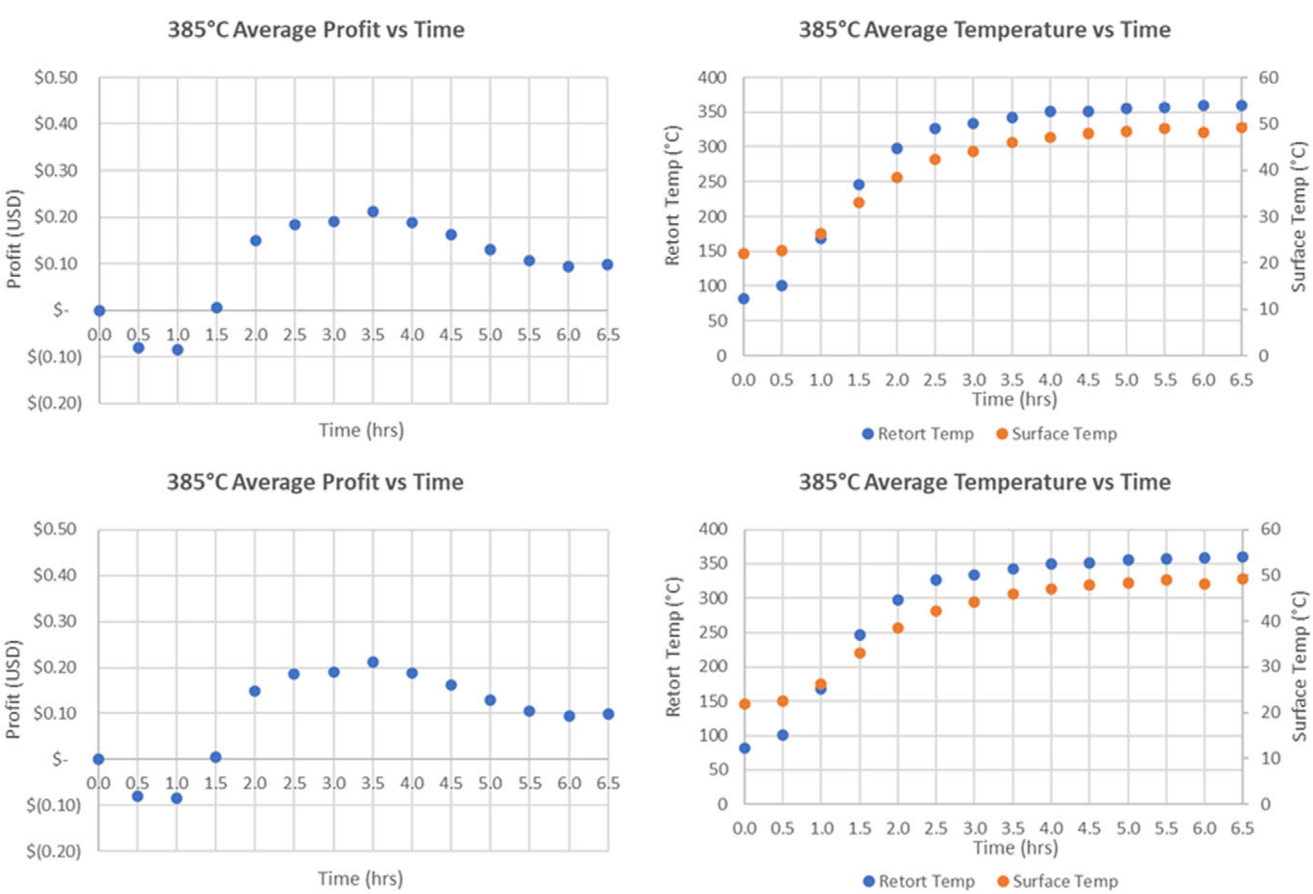

Figure 3. Average profit versus time for mixed plastic pyrolysis using Aerogel insulation.

Table 5. Summary of heat loss from pyrolysis runs

	Average heat loss at 385°C	Average heat loss at 395°C
	(W)	(W)
Mineral wool insulation	239.1	251.9
Aerogel insulation	131.2	145.7

Table 6. Summary of efficiency from pyrolysis runs

	Average efficiency at 385°C (%)	Average efficiency at 395°C (%)
	(kJ/h)	(kJ/h)
Aerogel insulation	50.8	54.3
Mineral wool insulation	20.0	30.3

The results of the efficiency calculations are reported in Table 6. As can be seen, there is a significant efficiency improvement with the use of Aerogel.

It should be noted that Aerogel is significantly more expensive than mineral wool insulation and may not be easily available in countries in the Global South. This highlights the trade-offs that must often be made when designing processes using the principles of AT. However, the insulating benefits of Aerogel can be achieved by increasing the thickness of the mineral wool insulation used. This research demonstrates that plastic to fuel oil by slow pyrolysis can be carried out in an economically viable manner in the Global South. Furthermore, the design flexibility allows room for future improvement.

Conclusions and future work

This work has demonstrated that polyolefin can be successfully converted into liquid fuel oil using AT. The results are significant in that they demonstrate that converting plastic waste into liquid fuel can be a viable endeavor for people in communities in the Global South. Based on these results, it can be observed that the average profitability provides sufficient income for many Global South countries. The AT design requires trade-offs; however, this proposed design does provide sufficient income for operators in the Global South. As shown in the results, the effectiveness of the insulation is critical to the efficiency and profitability of the plastic-to-fuel oil process. Additional work to improve the efficiency is therefore needed to improve the overall sustainability of the process.

Open peer review. To view the open peer review materials for this article, please visit http://doi.org/10.1017/plc.2023.5.

Acknowledgments. The authors gratefully acknowledge the contributions of Mr. Dewayne Burnett of the University of Kentucky, Mr. Paul Kiwanuka of Empowered Solutions for Environmental Sustainability in Kampala, Uganda, Mr. David Monday and Mr. John Mary Kavuma of Upcycle Africa, and Mr. Kobee Seay for their critical contributions to this research.

References

Al-Salem SM, Lettieri P and Baeyens J (2009) Recycling and recovery routes of plastic solid waste (PSW): A review. *Waste Management* **29**, 2625–2643.

Demirbas A (2004) Pyrolysis of municipal plastic wastes for recovery of gasoline-range hydrocarbons. *The Journal of Analytical and Applied Pyrolysis* **72**, 97–102.

DeNeve D, Joshi C, Higgins J and Seay J (2017) Optimization of an appropriate technology based process for converting waste plastic in to liquid fuel via thermal decomposition. *Journal of Sustainable Development* **116**(10), 116.

Foong Y, Browning S and Seay J (2022) An appropriate technology approach for utilizing plastic waste derived cooking fuel to reduce indoor air pollution from solid fuel cooking. *Journal of Appropriate Technology* **8**(3), 101–108.

Global Petrol Prices (2023) Available at https://www.globalpetrolprices.com/electricity_prices/; https://www.globalpetrolprices.com/diesel_prices/ (accessed 29 November 2022).

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

Jangid C, Miller K and Seay J (2022) Analysis of plastic derived fuel oil produced from high- and low- density polyethylene. *Recycling* **7**, 29.

Joshi C and Seay J (2020) Total generation & combustion emissions of plastic derived fuels: A trash to tank approach. *Environmental Progress and Sustainable Energy* **39**(5). https://doi.org/10.1002/ep.13151.

Kalanatarifard A and Yang GS (2012) Identification of the municipal solid waste characteristics and potential of plastic recovery at Bakri Landfill, Muar, Malaysia. *Journal of Sustainable Development* **5**, 11.

Kosky P, Balmer R, Keat W and Wise G (1999) *Exploring Engineering*, 3rd Edn. Boston: Academic Press.

Kumar S and Singh RK (2011) Recovery of hydrocarbon liquid from waste high density polyethylene by thermal pyrolysis. *Brazilian Journal of Chemical Engineering* **28**, 659–667.

Minghua Z, Xiumin F, Rovettac A, Qichang H, LiuBingkai FV, Giustic A and Yi L (2009) Municipal solid waste management in Pudong New Area, China. *Waste Management* **29**, 1227–1233.

Miskolczi N, Bartha L, Deak G and Jover B (2004) Thermal degradation of municipal plastic waste for production of fuel-like hydrocarbons. *Polymer Degradation and Stability* **86**, 357–366.

Moghadam MRA, Mokhtarani N and Mokhtarani B (2009) Municipal solid waste management in Rasht City, Iran. *Waste Management* **29**, 485–489.

Mrayyan B and Hamdi MR (2006) Management approaches to integrated solid waste in industrialized zones in Jordan: A case of Zarqa City. *Waste Management* **26**, 195–205.

Our World in Data (2022) Median Income or Expenditure Per Day, 1977 to 2019. Available at https://ourworldindata.org/grapher/daily-median-income (accessed 29 November 2022).

Panda AK, Singh RK and Mishra DK (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**, 233–248.

Patil L, Varma AK, Singh G and Mondal P (2017) Thermocatalytic degradation of high density polyethylene into liquid product. *Journal of Polymers and the Environment* **26**, 1920–1929.

Pinto F, Costa P, Gulyurtlu I and 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.

Santaweesuk C and Janyalertadun A (2017) The production of fuel oil by conventional slow pyrolysis using plastic waste from a municipal landfill. *International Journal of Environmental Science and Development* **8**, 168–173.

Sarker M (2011) Converting waste plastic to hydrocarbon fuel materials. *Energy Engineering* **108**, 35–43.

Sarker M, Molla M, Rashid MM and Rahman MS (2012) Production of valuable heavy hydrocarbon fuel oil by thermal degradation process of post-consumer municipal polystyrene (PS) waste plastic in steel reactor. *Energy Power* **2**, 89–95.

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

Seng B, Kaneko H, Hirayama K and Katayama-Hirayama K (2010) Municipal solid waste management in Phnom Penh, capital city of Cambodia. *Waste Management & Research* **29**, 491–500.

Singh RK and Ruj B (2016) Time and temperature dependent fuel gas generation from pyrolysis of real world municipal plastic waste. *Fuel* **174**, 164–171.

Sujauddin M, **Huda MS and Hoque RATM** (2008) Household solid waste characteristics and management in Chittagong, Bangladesh. *Waste Management* **28**, 1688–1695.

Troschinetz AM and Mihelcic JR (2009) Sustainable recycling of municipal solid waste in developing countries. *Waste Management* **29**, 915–923.

Wong SI, **Ngadia N**, **Abdullahb TAT and Inuwac IM** (2015) Current state and future prospects of plastic waste as source of fuel: A review. *Renewable and Sustainable Energy Reviews* **50**, 1167–1180.

https://doi.org/10.1017/plc.2023.5 Published online by Cambridge University Press