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Low density polyethylene sachets waste: Fuel conversion, characterization and life cycle analysis

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Abstract

Pyrolysis of plastic waste is a practical solution for plastic waste pollution in our environment here in Ghana. Pyrolysis, which is decomposition at high temperatures in the absence of oxygen, enables the conversion of polyethylene (PE) into liquid fuel and flammable gas. The selected pyrolysis temperatures in this study were ~ 300 °C, 350 °C, 400 °C, and 450 °C. Acquired fuels were then analysed via FTIR and GC–MS. These indicated the presence of aromatic compounds, alkenes and peaks of alkanes. The density, cetane index, viscosity at 40 °C, and flash point tests were carried out on each fuel product obtained at the different temperatures. The standardized life cycle assessment methodology according to ISO 14040/44 was carried out to provide a first insight on the savings in Global Warming Potential (GWP) associated to fuel produced from the pyrolysis process compared to that from fossil fuel. Results show a reduction of about 10% in GWP of the PE derived fuel compared to conventional fuel production.

Introduction

Plastic pollution has emerged as one of the main urgent environmental challenges, with the rapid increase in manufacturing of plastic products. Most plastics which ended up in the environment do not decompose due to their structure and chemical composition making them resistant to the natural decomposition processes and hence, slow deterioration rates [1].

The African Maritime Trash Network estimates that by 2035, Africa would be the continent with the most waste input into the world's seas, ranking second in terms of pollution [2]. Due to the most sought properties of plastics, Ghana for instance now imports about 15,000 tonnes of various plastics annually which mainly contains bottles and sachets, all of which are eventually disposed of as garbage. Just around 10% of the estimated 12,710 tonnes of solid trash that are produced daily in Ghana are collected and disposed of in appropriate facilities [3]. The poor recycling statistics means that the country is missing out on the benefits that plastic waste can yield; among which are job creation and energy generation both of which are lacking in the continent [4]. Hence there is the need to promote the utilization of waste plastics to produce energy and fuels via processes such as pyrolysis which in turn can be considered as a transition towards a circular economy which is another way to accomplish SDG 7 [2].

Polyethylene (PE) is widely utilized for packaging (plastic sacks, containers, toys, bottles, bags, films, etc.) [5]. Polyethylene is a homopolymer, as it is made out of a single monomer constituent [6]. Ethylene monomer (CH_2), is a

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vaporous hydrocarbon normally produced by the breaking and cracking of ethane. Ethylene particles are fundamentally made from two methylene units (CH_2) associated together by a two-fold bond between the carbon atoms; a construction represented by the chemical formula $CH_2{=}CH_2$ [7]. Influenced by polymerization catalysts, the double bond can be disintegrated and the resultant extra single bond used to connect to a carbon atom in a different ethylene particle [8]. This basic structure of the ethylene monomer, repeated several number of times, is the main property of polyethylene. The long, chainlike particles, and bonds, where hydrogen atoms are linked with a carbon backbone, can be created in branched or linear structures.

The cost effective nature and extreme usefulness of PE in our everyday life accounts for its high demand. As at 2019, in excess of a million tonnes of polyethylene resins are being created yearly, representing ~ 34% of the entire plastics market. Over the next five years, the capacity for polyethylene production is expected to rise significantly, potentially rising to 173.55 million tonnes per annum in 2024, representing a total growth of 52% [9]. Unlike industrialized nations, where over 90% of solid trash is collected through official channels, countries unlawfully burn or dump over 90% of their solid waste, which has harmful effects on both humans and the environment. This is especially true in underdeveloped countries. Municipal plastic waste treatment technologies have advanced significantly in the shift towards more sustainable development such as the waste to energy technology. The ISO 15270 (2008) [10] states that plastic waste may be recycled, processed to create raw materials, and converted into high-calorific compounds that can be utilized as fuels for energy generation [11]. This study seeks to control the pollution being created by waste plastics by converting them to useful fuels. One of the most popular waste-to-energy chemical recycling methods called pyrolysis, is still in the early phases of commercialization. Pyrolysis is an efficient method for successfully converting plastic wastes to fuels, which can be used in everyday life for various purposes. This has the potential of reducing the ever-increasing demand for fossil fuels and energy. Pyrolysis, which is also the initial stage of gasification and combustion, takes place when there is little to no oxygen present, making it distinct from combustion (burning), which can only occur when there is enough oxygen available [12]. Between 350 °C and 900 °C, the process typically produces high calorific value (CV) gas, condensable hydrocarbon oil, and carbonized solid char. [11]. The primary advantage of pyrolysis is its capacity to recover both the chemical and energy value of the waste by creating potentially useful molecules during the pyrolysis process. The traditional methods for handling post-consumer plastics have been landfills or incineration [13]. However, given the scarcity of available land and the high durability of plastics, landfilling of post-consumer plastics could provide issues. Incomplete incineration on the other hand can produce hazardous by-products and have a major negative impact on health and the environment. The most popular waste treatment option for generating energy from garbage and reducing the amount of solid waste dumped in landfills is to use waste-to-energy plants that use incineration systems. However research has shown that these waste-to-energy systems frequently emit significant amounts of greenhouse gases. [14]. Yet, the life cycle assessments (LCAs) as explored in this study can provide a more comprehensive framework for analysing waste management strategies, detecting environmental implications, and flagging problem areas in connection to the waste treatment hierarchy. [11] For organic materials, other techniques like gasification and bioconversion are primarily used. Hence, the need for pyrolysis of plastic waste [15]. Pyrolysis of polymers results in final products such as liquid, solid, and gas known as bio-oil or liquid fuel, char, and combustible gas, respectively. In all, the operational parameters and process variables of the pyrolysis process are crucial for maximizing the final product yield and its composition. These crucial variables can be summed up as follows: temperature, reactor type, heating rate, pressure, chemical composition of feedstock, residence time, cooling process, catalysts, degradation rate, and duration of pyrolysis process [16–18].

An increasing amount of research is being done in Africa on the sustainable use of waste plastics to generate energy and recover materials. For example, in Ghana, large proportions of mixed polymers from Polyethylene terephthalate (PET), Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyvinyl chloride (PVC), and other composite plastics have been found as ideal for developing plastic recycling employing thermal methods and extrusion to make pellets. Mechanical recycling has also grown, particularly for PP, HDPE, white, and blue PET materials. Recently, Ghana has installed a pilot-scale (waste-to-energy) thermochemical waste processing plant to produce pyrolysis oils from a variety of waste. However, large scale pyrolysis technology units and combined capacity completely dedicated to plastic garbage are absent [3].

Life cycle assessment (LCA) according to ISO 14040744 [19] can be used to assess, compare, and highlight environmental hotspots of various waste management options in order to identify the environmental impacts and problem areas of these waste treatment processes. [20]. Although comprehensive LCA studies for different waste management methods such as pyrolysis, gasification, and hydrocracking have been mostly conducted in the developed countries, such analysis is rare, and need be done in full scale in countries such as Ghana as they are in the initial phase of implementing these waste treatment methods. Hence, this paper provides a good insight of the environmental impacts of converting plastic to fuel through pyrolysis which can inform the decision makers in Ghana on low impact pathways to define and deploy the country's waste treatment strategies.

Experimental

Materials and methods

Materials and equipment used in this study includes a batch type reactor with two collection chambers, liquefied petroleum gas (LPG), gas burner, PerfectPrime TC9815 4 Channels Thermocouple Thermometer and polyethylene waste (water sachets) acquired from the environs of Accra, Ghana.

The pyrolysis setup (see Fig. 1) consisted of a 15 kg capacity stainless-steel batch cylindrical reactor sealed at one end and a stainless-steel condensation tube (90 cm long) outlet at the other end leading to two reservoirs (chambers) for liquid fuels and an outlet pipe for gas products collection. The reactor was equipped with a pressure gauge and heated externally via a gas burner, with a K-type thermocouple fixed inside the reactor and connected to an external PID controller (PerfectPrime TC9815).

Waste polyethylene sachet materials were shredded into pieces (2–3 cm) and then dried at 50 °C for three hours to get rid of any moisture. Three kilograms of the as-dried raw plastic waste materials were then fed into the pyrolysis reactor and air tightly sealed for the pyrolysis process. The temperature in the reactor operating at atmospheric pressure was quickly increased from room temperature to a temperature range of 300 °C to 450 °C at a rate of 10 °C/min. At this point in the pyrolysis process the waste plastic quickly changed into hazy gaseous vapour flowing that condensed to produce a liquid hydrocarbon fuel under ambient temperature and pressure. The denser vapour condensed into the first collection reservoir (chamber) whiles the less dense vapour condensed into the second collection reservoir (chamber). The non-condensable vapour moved into the gas collector. The process was completed within 2 h. The condensed liquid fuels, noncondensible gases, and residue were collected and weighed for their weight percentage yield as well as for further analysis. The weight percentage yield of each product was determined as a ratio of the weight of the feedstock and the weight of final product multiplied by 100.

Characterization of pyrolysis products and life cycle assessment

The pyrolysis liquid fuel (oils) were analysed using a Perkin Elmer Clarus 580 Gas Chromatography and Mass Spectroscopy (GC–MS) machine which had a flame ionization detector and a TurboMass™ V6.1.0 software with a Selected Ion and Full Ion (SIFI) scanning Optimization Tool. Prior to the analysis, the liquid test sample (≈ 0.1 g) was mixed with a measured quantity of N-heptane (≈ 2 mL), then ultrasonicated for ≈ 2 min; after which a portion of the solution (0.1 µL) was injected (*splitless mode*) into an Elite-5 ms (PEN9316282) capillary column with a length (L) of 30 m, internal diameter (Ø) of 0.25 mm, and a film thickness (e) of 0.25 µm. The GC's heating source (oven) was raised from 50 to 280 °C at a heating rate of 5 °C/min and held for 10 min at 280 °C under helium carrier gas (1 mL/ min) atmosphere. During the determination of the mass spectra data, the temperatures of the quadrupole analyser and the ion source were set at ≈ 220 °C while the solvent delay time was set at ≈ 3 min. At an electron ionization voltage of 70 eV, mass spectrometric ionization was conducted. The NIST library software was used to collect and analyse data while performing the multiple reaction monitoring (MRM) in the scan mode within the mass range of 50–600 amu. Fourier Transform Infrared spectroscopy (FTIR) data of the pyrolysed oil

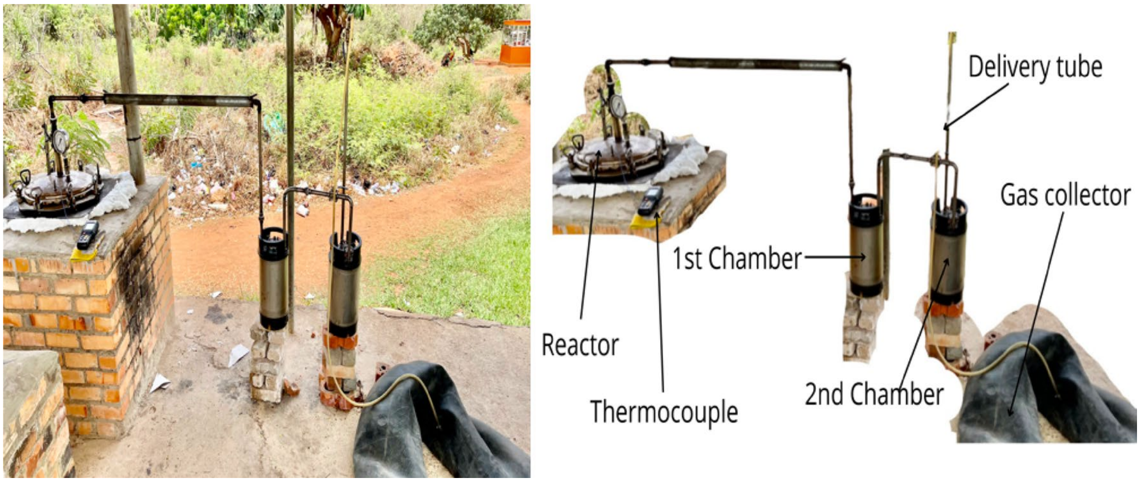

Fig. 1 Pyrolysis setup

samples were obtained within the 400–4000 cm^{-1} range with a 4 cm^{-1} resolution on a Bruker ALPHA II Spectrometer equipped with an OPUS Multi Evaluation software.

Physical properties of pyrolysis products

The density of acquired liquid fuels was found with a hydrometer using the ASTM-D-1298 standard test method for density. This test procedure included a glass hydrometer and a number of calculations to determine density in the lab. The experiment was conducted at a reference temperature of 15 °C. Distillation of liquid fuels was performed according to the ASTM-D-86 test method, the standard test procedure for distillation of liquid fuels and petroleum products at atmospheric pressure. The atmospheric distillation of liquid fuels acquired using the laboratory batch distillation unit OptiDist pac was used in this test technique to quantitatively identify each sample's features related to its boiling range. The temperature for initial boiling point, 10%, 50%, 90% evaporated as well as final boiling point was recorded for each liquid fuel sample. The ASTM-D-93 standard test procedures for flash point by pensky-martens closed cup was used to determine the flash point of liquid fuels obtained. This was achieved using the GD-3536DT auto COC flash point tester. The kinematic viscosity of liquid fuels at 40 °C was determined using the ASTM-D-445 test procedure for determination of kinematic viscosity of liquid petroleum products, both opaque and transparent. A calibrated viscometer's capillary was used to measure the amount of time it took for a fixed volume of liquid to flow through it while falling to the ground, under a repeatable driving head, at a tightly regulated temperature, and inside a viscosity bath. The calculated kinematic viscosity value is the result of multiplying the recorded flow time by the viscometer's calibration constant [17]. To calculate a kinematic viscosity result that is the average of two valid determined values, two such determinations were needed. The behaviour of each sample determined the outcome of this test technique. Cetane index calculation by the four variable equation from the ASTM-D-4737 test method was carried out for further characterization and analysis of liquid fuels obtained from pyrolysis at the different temperatures. The calculated cetane index by the four variable equation presented a method for calculating the distillate fuels' ASTM cetane number from measurements of density and distillation recovery temperature.

Life cycle assessment

The life cycle assessment (LCA) of the pyrolysis of plastic waste to fuel was carried out considering a cradle-to-gate system boundary. LCA is the standardized methodology to compile and evaluate inputs, outputs and environmental impacts of a product throughout its lifecycle. The main purpose of an LCA is to inform decision making, especially at design or pilot phase, on the environmental performance of products or services and alternatives to minimize the impacts. In this study, the four phases of LCA according to ISO 14040/44 [19] were applied, namely Goal and Scope definition, Life cycle inventory, Life cycle impact assessment and interpretation. The Goal of the LCA is to compare the Global Warming Potential (GWP) contribution of producing fuel from plastic waste against conventional fuel production. A cradle-to-gate system boundary was considered for both fuel types and 1 kg of fuel was used as the functional unit, made up of 60% diesel and 40% petrol. It was assumed that quality and hence function of the fuel from the pyrolysis and conventional production are similar. In line with the defined goal, the GWP contribution was evaluated following the IPCC 2013 GWP 100a method. This is also the rationale behind the choice to exclude the use phase in the comparison. The LCA was modelled using primary data for foreground processes and the ecoinvent database for background processes. It is assumed that the collection of the plastic waste and transportation to the pyrolysis site occurs without any material or energy input and output.

Results and discussions

Product yield and physical properties of fuel samples

After each experiment, the percentage yields of condensed liquid fuels, noncondensible gases, and residue was calculated as the percentage ratio of the weight of the feedstock and the weight of final product multiplied by 100. Typically, the following product yields were observed: 300 °C (liquid 75.14%, gas 6.29%, residue 18.57%); 350 °C (liquid 65.71%, gas 5.71%, and residue 27.86%); 400 °C (liquid 74.29%, gas 6.71%, and residue 19.0%); 450 °C (liquid 64.29%, gas 7.14%, and residue 28.57%). Table S1 displays the physical characteristics of each fuel, including its density, viscosity, flash point, and cetane index. The liquid product's pour point of 20 °C is suitable for the majority of geographical areas, and its flash point is in a similar range. According to the distillation report for the liquid fuels, the range of boiling points for the fuels is between 57 °C and 366 °C. This suggests the presence of a blend of various fuel ingredients, including petrol, diesel, and kerosene. Given that the liquid products' initial boiling point is less than 100 °C, they include a significant amount of volatiles. So, these might serve as potential feed stocks for the production of lighter compounds for use as diesel or for improving low grade fuels. The density, cetane index, viscosity, and flash point of each sample was compared with that of diesel, petrol, and kerosene [18, 19].

Liquid fuel from C2 was synonymous to petrol while that of C1 was similar to diesel. Pyrolysis at 350 °C and 400 °C provided the best match.

Characterization of the liquid fuel products

Fourier transform infrared spectroscopy (FTIR)

Fourier transform infrared spectroscopy (FTIR) is an essential characterization tool utilized in the study of various distinguishing molecular functional groups contained in organic samples such as oils when they interact with an infrared light radiation. This infrared light interaction with the molecules, results in the absorption infrared radiation in a specific wavelength range irrespective of the molecular structure of the compound; leading to vibrational stretching or contraction of the chemical bonds. The FTIR spectra data (*see* Fig. 2) of the condensed liquid fuels collected from both storage chambers (C1 and C2) produced under the different temperatures conditions, display distinct frequency bands around $\sim 3078\ \text{cm}^{-1}$ which could be attributed to the C–H stretching vibrations of alkene groups. The other frequency bands were found around $\sim 2918\ \text{cm}^{-1}$ (*C–H stretching vibrations of alkanes*), $\sim 1647\ \text{cm}^{-1}$ (*C=C stretching vibrations of alkenes*), $\sim 1440\ \text{cm}^{-1}$ (*C–H scissoring and bending vibrations of alkanes*), $\sim 907\ \text{cm}^{-1}$ (C–O stretching vibrations of alcohols, ethers, carboxylic acids, and esters), and $\sim 720\ \text{cm}^{-1}$ (C–H bending vibrations of phenyl ring substitution bands). These observations compare favourably with the confirmatory Gas Chromatography–Mass Spectrometric (GC–MS) results presented in Fig. 3.

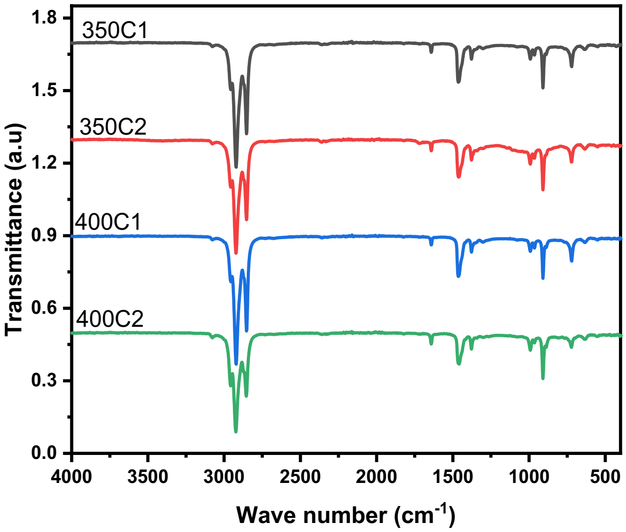

Fig. 2 FTIR of liquid fuel from first and second collection chambers

Gas chromatography-mass spectrometry (GC–MS) of the liquid samples

Gas Chromatography-Mass Spectrometry (GC–MS) analysis was carried out on the liquid fuel samples to determine and confirm the constituent compounds (Fig. 3a and b). The library search chromatogram/spectrum peak report of the GC–MS tests presented the peak and retention time of each identified compound in all the seven (7) different liquid fuel samples. Each sample revealed the presence of over thirty different compounds. Several alkanes, alkenes and alkynes can be found in the GC–MS analysis of all the liquid fuel variants as seen in the FTIR results as well. However, liquid fuel found in C2 for all the different temperatures had relatively shorter carbon–carbon and carbon-hydrogen chains as compared to liquid fuel found in C1. Liquid fuel in chamber C2 presented cyclopentene, 1-(1-methylethyl)- compound C_8H_{14} as the shortest chained compound whiles liquid fuel found in C1 had 2,4-Dimethyl-1-heptene C_9H_{18} as the shortest chained compound. Pyrolysis at 350 °C presented the longest carbon–carbon and carbon-hydrogen chain with the compound Hexatriacontane $C_{36}H_{74}$.

Life cycle assessment

The Global Warming Potential (GWP) of the pyrolysis fuel is compared with an equivalent low sulphur fuel (60% and 40% diesel and petrol, respectively. As illustrated in Fig. 4, the results show an almost 10% reduction of the impact in the case of pyrolysis fuel.

This result, apart from the climate change mitigation potential, suggests other benefits related to the valorization of PE waste through fuel product. This could include material resource reduction and human toxicity related impacts.

Conclusion

Pyrolysis of PE waste led to the creation of end products: liquid fuel, combustible gas, and char. The main focus of this study was the valuable liquid fuel produced. FTIR and GC–MS analysis revealed the existence of significant amounts of alkanes, alkenes, and alkynes. Liquid fuels found in C1 were denser since they had heavier compounds with longer carbon–carbon and carbon-hydrogen chains. It was also observed that, pyrolysis at the various temperatures gave the following yields:300 °C (liquid 75.14%, gas 6.29%, residue 18.57%); 350 °C (liquid 65.71%, gas 5.71%, and residue 27.86%); 400 °C (liquid 74.29%, gas 6.71%, and residue 19.0%); 450 °C (liquid 64.29%, gas 7.14%, and residue 28.57%). In general, comparative study of the liquid fuel with everyday petroleum fuel revealed more similarities than differences. These

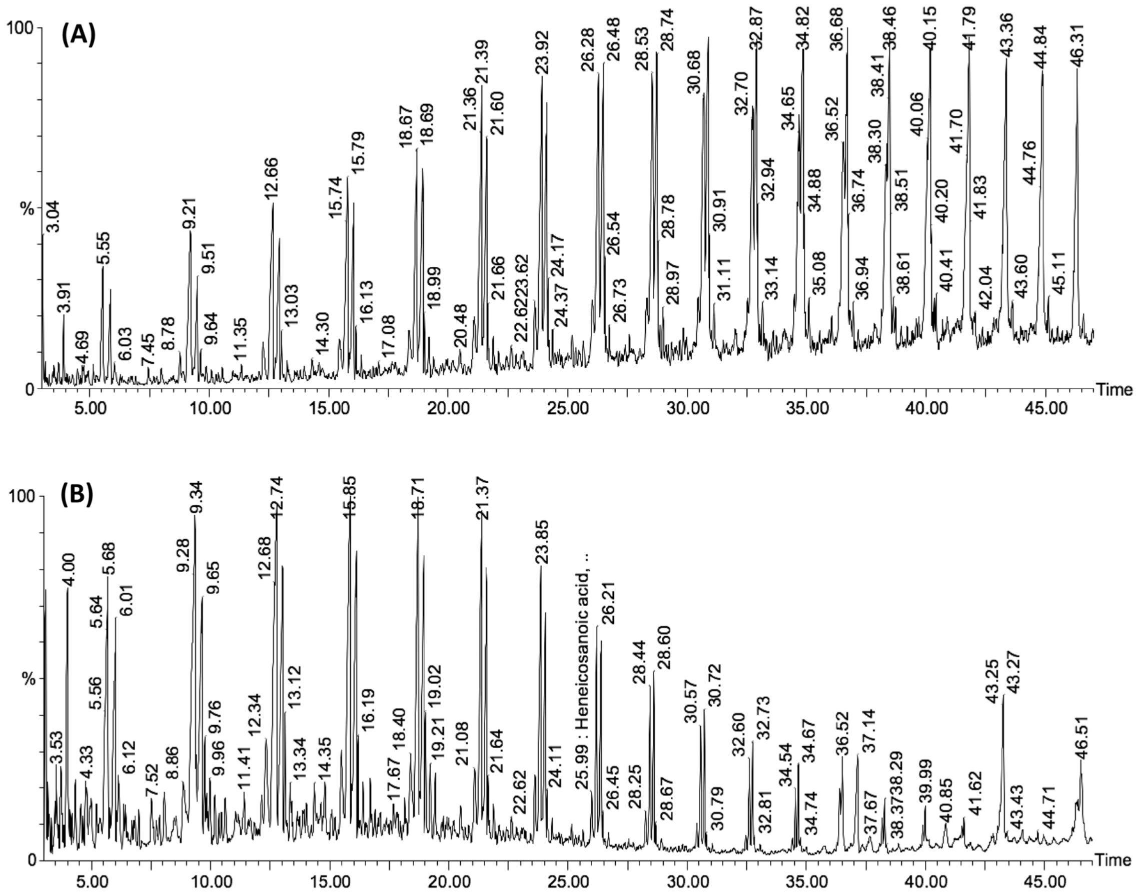

Fig. 3 GC–MS of liquid fuel from first (**a**) and second (**b**) collection chambers

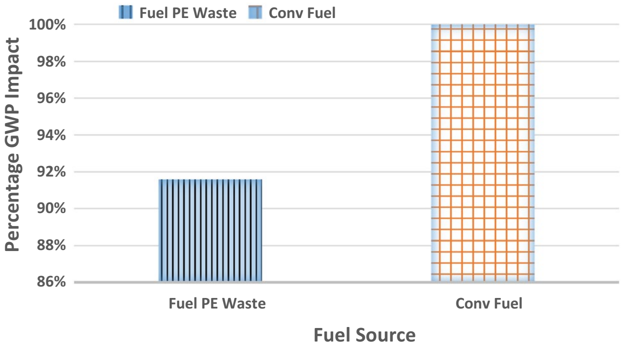

Fig. 4 Global Warming Potential (GWP) impact of PE waste derived fuel against Conventional fuel

petrol-like and diesel-like fuels produced will help solve the problem of both plastic pollution and fuel shortage by reducing the demand for petroleum fuel. In addition, LCA results show significant potential in the reduction of environmental impact compared to that of conventional petroleum derived fuel in use today. The optimized process of plastic pyrolysis will help communities and individuals who intend to venture into this value-added field reduce cost and save energy while making the environment a safer and better place.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1557/s43580-023-00571-9.

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Data availability All data generated or analysed during this study are included in this published article (and its supplementary information files).

Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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