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(RESEARCH ARTICLE)

Electricity generation potential of synthetic human hair, water nylon sachet and plastic waste mixtures

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Abstract

In order to address two critical challenges, including ineffective waste management and unreliable power supply faced by many developing countries; this study explored the electricity generation potential of three polymeric wastes (synthetic human hair, water nylon sachets, and plastic waste mixtures), using pyrolysis process. The study employed a pilot-scale batch pyrolysis system, consisting of a charcoal-fired furnace, a cylindrical galvanized iron pyrolysis reactor, a condenser, a gas scrubber, and a gas storage bag; for the wastes conversion into gaseous fuels to power a generator for electricity generation. The objective was to measure the composition of the gas produced during pyrolysis and assess the generator runtime when powered by the gas to determine the feasibility and efficiency of the polymeric waste-derived gases as an alternative fuel source for electricity generation. The pyrolysis process, conducted at temperatures ranging from 236°C to 488°C, was carried out as a batch process over three cycles, with 5 kg of each waste material used in every cycle. The pyrolysis gas produced was stored for compositional analysis and the gas mixture used as generator fuel. The results showed that plastic waste mixture contained hydrogen (20.21%), methane (17.62%), and ethane (25.17%); artificial woman hair contained hydrogen (18.93%), methane (21.43%), and ethane (23.86%); and pure water nylon sachets contained hydrogen (22.89%), methane (16.31%), and ethane (23.78%). This indicated that all the three waste types had significant electricity generation potential due to the high calorific values of their pyrolysis gas compositions.

Keywords: Waste Management; Electricity Generation; Pyrolysis; Sustainability; Environment

1. Introduction

Waste disposal in many developing countries is often carried out using harmful methods, such as open burning, improper landfilling, and ocean dumping, leading to significant social, economic, and environmental repercussions. Over the years, it has been noted that the waste generated daily in many developing countries, including Nigeria, is largely underutilized and not effectively converted into valuable resources, including energy and other valuable product, On the contrary, the wastes often litter roads, gutters, and waterways. Nigeria, the most populous country in Africa, has the potential to generate huge amount of wastes daily [1]. Additionally, frequent energy crises, driven by rising oil prices in countries like Nigeria, have resulted in environmental, social, and economic consequences. Meanwhile, the wastes generated could be effectively managed through valorization into electricity generation, which will have a significant impact on human beings, especially the majority of people living in developing countries where the power supply is unstable.

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To address the challenges of ineffective waste management and unreliable power supply, affordable and eco-friendly waste management and energy generation techniques integrated into the economic framework of the developing countries are essential. In developed countries, various sustainable techniques, such as pyrolysis, anaerobic digestion, and gasification, are employed for efficient waste management and concurrent energy production [2, 3]. However, fully developed waste management techniques are still lacking in many developing countries like Nigeria. Pyrolysis, a thermal decomposition process that occurs in the absence of oxygen under an inert atmosphere, is an effective method for converting combustible waste, such as discarded plastics and rubber, into valuable resources, including energy. Plastic wastes are attractive for energy conversion because when they are burnt, they release a significant amount of heat, making them effective for generating energy.

Furthermore, plastic wastes are appealing for energy conversion due to their widespread availability. Plastic wastes are abundant in the environment, especially in urban areas, where large amounts of plastic are discarded daily. The most commonly used plastics can be categorized into six distinct types, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polyvinyl chloride (PVC), polypropylene (PP) and polystyrene (PS). PET plastics are primarily used for packaging food products, including food juice containers, mineral water bottles, soft drink bottles, electrical insulation, printing sheets, magnetic tapes, and x-ray and photographic films. HDPE plastics have a wide range of uses, such as in the production of milk bottles, detergent bottles, oil containers, and toys. PVC is commonly used for electrical insulation while LDPE is used in bags and film packaging, as well as, electrical insulation. PP plastics have diverse applications, including flowerpots, office folders, car bumpers, buckets, carpets, furniture, and storage boxes. PS is utilized in various applications, such as food packaging, electronics, construction, medical equipment, appliances, and toys [4]. This widespread availability makes plastic waste an easily accessible and potentially sustainable resource for energy production.

Many researchers have studied plastic wastes valorization into valuable products using pyrolysis technique. Pyrolysis is a process in which a material is heated to temperatures between 250°C and 500°C in the absence of oxygen, causing it to volatilize and decompose into oil, gas, and char [5]. The yield, distribution, physical and chemical properties of the pyrolytic products (non-condensable gas, condensable liquid oil, and char) are influenced by various pyrolysis conditions including temperature, heating rate, particle size, residence time, feedstock composition, carrier gas type and flow rate, the presence of catalysts, reactor type, and atmospheric pressure [6]. Temperature plays a critical role in pyrolysis, as it controls the cracking of polymer chain molecules. The degradation of polymeric materials, such as plastics, is also impacted by the pyrolysis process mode (batch, semi-batch, or continuous). Meanwhile, the usage of pyrolysis process for waste valorization has been widely researched and commercially implemented in developed countries and valuable products such as fuel gases, liquid oil, and carbon black have been extracted from the waste materials [7].

Razzaque [8] investigated the design, fabrication, development, and evaluation of a laboratory-scale fluidized bed pyrolysis reactor for the production of bio-oil, syngas, and bio-char from various feedstocks. Hazrat et al. [9] explored thermo-catalytic degradation to produce clean transportation fuel and reduce plastic wastes. Samarasiri [10] focused on reactor design for converting waste plastic into fuel oil and gas. Ellens [11] developed an innovative biomass fast-pyrolysis reactor aimed at improving the inefficiencies of traditional reactors while maintaining high bio-oil yields. Low et al. [12] designed and built a recycling apparatus capable of operating at low temperatures (below 550 °C) and atmospheric pressure to convert mixed plastic wastes into usable liquid fuel. Ademiluyi and Adebayo [13] examined fuel gases produced from the pyrolysis of waste polyethylene sachets using a fabricated batch reactor with lagging for enhanced heat transfer. Ademiluyi and Akpan [14] investigated the pyrolysis of low-density polyethylene water sachet waste for the production of fuel oil. Manjunath et al. [15] designed and constructed a pyrolysis reactor while considering key design factors such as metal material type, wall thickness, and reactor volume.

Buah et al. [16] developed a novel gas-fired static bed pyrolysis system for activated carbon production through a gasification reaction. Tsuji et al. [17] explored the gasification of polyethylene, polypropylene, and polystyrene plastic pellets in a two-stage thermal degradation process. Mohammad et al. [18] studied the design and fabrication of a fixed bed batch pyrolysis reactor for pilot-scale pyrolytic oil production from waste tyres. Furthermore, Cudjoe et al. [19] examined the scientific strategies for optimal investment and decision-making on the environmental sustainability of plastic waste-to-energy pyrolysis projects while Jawale et al. [20] studied pyro-cycling technique for conversion of plastic waste into electrical energy. In the review made by Cuevas et al. [21], pyrolysis was highlighted as a promising technique for managing waste materials to produce energy. Iglinski et al. [22] reviewed studies conducted by many researchers regarding large-scale pyrolysis for production of low-cost renewable energy sources with broad applications in the energy, chemical, agricultural, and transportation industries. Hasan et al. [23] reviewed pyrolysis technologies for plastic waste management and their efficiency, economic potential, and environmental impact. It was stated in their review that the pyrolysis gas, with a market value of $200–$300 per ton, could generate up to 800 kWh of electricity per ton of waste. It was added that pyrolysis could convert 60 %–80 % of plastic waste into liquid fuels, with yields of up to 85 % in fast pyrolysis processes conducted at temperatures between 450 ∘C and 600 ∘C. The process could also reduce greenhouse gas emissions by 40 %, mitigating 3.5 tons of CO_2-equivalent per ton of plastic waste processed.

While there has been considerable research into the potential of using the pyrolysis technique for waste valorization into valuable products, there is limited work on pilot-scale conversion of polymeric wastes (such as pure water nylon sachets, synthetic human hair, and a shredded plastic waste mixture consisting of polyethylene terephthalate bottles, polypropylene and polyethylene plastics) into electricity, particularly in developing countries like Nigeria. Therefore, the purpose of this study was to develop a pilot-scale pyrolysis system for effective management and conversion of polymeric wastes generated at Lagos State University, Epe Campus, Lagos, Nigeria; into gaseous fuels for electricity generation [3, 4]. The project on waste valorization of combustible wastes is essential for sustainability. The initiative will have positive impact on environmental sanitation, poverty reduction, health improvement, clean water access, gender equality, affordable clean energy, resource management, and climate change mitigation, as well as, employment generation [5-10].

2. Materials and Methods

2.1. Experimental material

The feedstock materials used for the study included pure water nylon sachets, synthetic human hair, and a shredded plastic waste mixture consisting of polyethylene terephthalate (PET) bottles, polypropylene (PP), and polyethylene (PE) plastics. During the pyrolysis experiment, several instruments were utilized, such as a chemical balance, spring balance, measuring cylinder, and stopwatch; to measure feedstock weight, gas weight, cooling water volume, and the reaction time, respectively. Additionally, clean containers and gas bags were prepared to collect the condensed liquid oil and char, as well as, the pyrolysis gas produced during the pyrolysis process. The pyrolysis system consisted of a charcoal-fired furnace, a pyrolysis reactor, a condenser, a gas scrubber for cleaning, and a gas storage bag (Plate 1). The reactor was a cylindrical vessel made from galvanized iron, with an internal diameter of 300 mm and a height of 720 mm. It was sealed at the loading point with a flange. Attached to the top of the reactor was a gas exit pipe, which led the gas to the condenser and then to the scrubber.

Plate 1 Pyrolysis system set-up

2.2. Experimental Procedure

The pyrolysis process was conducted in three distinct cycles, each using a different type of plastic waste material. The temperature during the pyrolysis ranged from 236 °C to 488 °C. In the first cycle, 5 kg of shredded plastic waste mixture was introduced into the pyrolysis reactor and the pyrolysis gas production began 49 minutes after initiating the process. The non-condensable gas produced was collected in a gas storage bag, and samples of this gas were sent to CTX-Ion Analytics Ltd, Lagos, Nigeria, for composition analysis. In the second cycle, 5 kg of synthetic human hair was placed into the reactor and the gas production began 51 minutes after the process commenced. As with the first cycle, the non-condensable gas was captured in a gas storage bag, and samples were sent to CTX-Ion Analytics Ltd for analysis. During the third cycle, 5 kg of pure water nylon sachets were loaded into the pyrolysis reactor and the gas production was observed to begin 40 minutes after the process began. The non-condensable gas was captured in a storage bag, and samples were sent to CTX-Ion Analytics Ltd for composition analysis. At the conclusion of the pyrolysis experiment, the gas products stored in the three gas bags were transferred into a large storage bag. The gas in the large storage bag was then used as fuel for a 6.5 HP generator to produce electricity, which powered a 5 W light bulb for 2 hours and 16 minutes.

3. Results and Discussion

3.1. Gas compositional analysis

The results of the compositional analysis of the gas obtained from the use of experimental pyrolysis to evaluate the waste-to-energy potential of different polymeric materials (pure water nylon sachets, synthetic human hair, and a shredded plastic waste mixture) are given in Table 1. The gas compositions are important because the gases released from these materials can be analyzed to estimate their potential for electricity generation through pyrolysis process. The gases produced are combustible, and are primarily hydrocarbons, including hydrogen (H_2), methane (CH_4), ethane (C_2H_6), ethylene (C_3H_4), propane (C_3H_8), butane (C_4H_{10}), and butylene (C_4H_8), along with some carbon dioxide (CO_2) and carbon monoxide (CO). The electricity generation potential of these gases largely depends on their calorific value or energy content.

Table 1 Gas Analysis Result from Pyrolysis of the feedstocks

S/No	Gas Composition	Plastic Wastes Mixture Gas Composition (Vol %)	Synthetic Human Hair Gas Composition (Vol %)	Pure Water Nylon Sachet Gas Composition (Vol %)
1	Hydrogen, H2	20.21	18.93	22.89
2	Methane, CH4	17.62	21.43	16.31
3	Ethane, C2H6	25.17	23.86	23.78
4	Ethylene, C3H4	14.30	15.40	14.65
5	Propane, C3H8	11.23	10.19	12.16
6	Butane C4H10	1.84	4.30	3.47
7	Butylene C4H8	1.32	2.66	3.83
8	Carbon dioxide CO2	2.02	1.70	1.64
9	Carbon monoxide CO	1.28	1.54	1.27

Hydrogen is a high-energy gas and is excellent for electricity generation. It produces only water vapor when combusted, making it an environmentally friendly fuel. A significant percentage of hydrogen in the waste mixture enhances the electricity generation potential. Methane is the main component of natural gas and has a high calorific value. It can be effectively burned in gas turbines or internal combustion engines to generate electricity. Ethane and ethylene are light hydrocarbons, which also have a relatively high energy content; while not as high as methane, they can still be used for electricity generation, typically in a gas turbine or engine. Propane and butane are liquid petroleum gases that are commonly used for heating but can also be used in internal combustion engines or gas turbines for electricity generation. The energy content of propane and butane is lower than methane, but it is still significant. Butylene C_4H_8 is another light hydrocarbon with good energy content, but it is generally more challenging to process. It would require refining or processing before being used in energy production. While CO_2 is a non-combustible gas and does not contribute to energy generation, CO can be used as a fuel in fuel cells or combustion engines, but it is less common. It is also hazardous and requires careful handling.

3.2. Electricity generation potential of polymeric waste feedstock

The electricity generation potential of the polymeric wastes is influenced by the gas composition of the gaseous fuel produced from the waste pyrolysis. Plastic waste mixture has a good potential for electricity generation due to its high levels of methane (17.62%), hydrogen (20.21%) and ethane (25.17%). Ethylene (14.3%) and Propane (11.23%) contribute a moderate amount of energy. The remaining gas compositions (butanes, CO_2, CO) add some energy but it is less significant for electricity generation. Regarding synthetic human hair, it also has good electricity generation potential due to its methane (21.43%), the key energy source, and ethane content (23.86%). Hydrogen content (18.93%) is good but slightly lower than plastic waste mixture. Ethylene (15.40%) and propane (10.19%) contribute moderately to electricity generation. Meanwhile, pure water nylon shows strong electricity generation potential, mainly due to its high hydrogen (22.89%) and ethane (23.78%) content. Methane (16.31%), Ethylene (14.65%) and propane (12.16%) contribute moderately to the energy generation.

Based on the gas compositions, all three waste mixtures have notable potential for electricity generation, but plastic waste mixtures and synthetic human hair have slightly higher methane content, which is a very efficient fuel for energy production. Pure water nylon sachet contains slightly less methane but has higher hydrogen and ethane levels, which are still valuable for electricity generation. In summary, plastic waste mixture has high potential due to hydrogen and methane content; synthetic human hair has high potential with methane and ethane as key contributors, while pure water nylon has good potential, especially with high hydrogen and ethane content.

4. Conclusion

The results from the pyrolysis of various polymeric materials, including plastic waste mixture, synthetic human hair, and pure water nylon sachets; demonstrate notable potential for electricity generation based on their gas compositions. Plastic waste mixture and synthetic human hair have high energy potential, primarily due to their high levels of methane, hydrogen, and ethane, which are valuable for electricity production. Pure water nylon sachets also show good potential, driven by their high hydrogen and ethane content, despite having slightly lower methane levels. Overall, while all three materials show promise, the plastic waste mixture and synthetic human hair have slightly higher methane content, making them more efficient for energy generation

Compliance with ethical standards

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Disclosure of conflict of interest

Authors declare that there is no conflict of interest.

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