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Sustainable Plasma Gasification Treatment of Plastic Waste: Evaluating Environmental, Economic, and Strategic Dimensions

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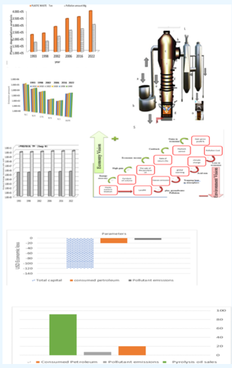
ABSTRACT: The conversion of waste to energy is an essential process in the Middle East, especially in Saudi Arabia, where it plays a crucial role in waste management. The annual analysis of the decomposition hazards of the landfills in the city of Makkah showed that they ranged from 168,000 Mg in 1994 to 297,000 Mg in 2022. The emission costs of pollution ranged from 4 million in 1994 to 7 million in 2022. The number of gas emissions of plastic waste accumulating in the analyzed landfill has increased from 128,000 Mg in 1994 to 227,000 Mg in 2022. The thermal plasmas used were produced by air plasma torches, which are an essential part of plasma reactors. The operational characteristics of air plasma torches were investigated at a flow rate of 10−30 g/s, including current−voltage characteristics, applied power, applied flow rate, average temperatures of the exiting plasma jet ranging from 15,000 to 19,000 K, average velocity of the exiting plasma jet (1677.3−2763.2) m/s, wavelength of the emitted radiation ranging from 153 to 193 nm, and the corresponding beam lengths ranging from 400 to 450 mm. The proposed plasma gasification is the greenest method for processing plastic waste in the light of ecological, economic, and strategic visions with an amount of recovered pyrolysis oil in the year 2022 of 3.17×10^5 tons with an equivalent energy of 12.55 × 109 MJ, with an output efficiency value equal to 81%. A roadmap for the economic and environmental visions was introduced, where the economic return on investment (ROR%) was 80%, the payback period (PBP) was 1.2 years, and the gross profit reached 129%.



1. INTRODUCTION

The Kingdom of Saudi Arabia 2030 Vision for Environmental Sustainability has identified waste as a serious concern. Plastic waste data for the past 20 years show that it is the second largest municipal waste after scrap tire waste, and energy recovery from plastic waste is regarded as a strategic vision in the K.S.A. as a source of industrial fuel oil (such as pyrolysis oil and diesel oil).[1−3] The city of Makka in western Saudi Arabia was selected for this study. It is one of the most important places in the world for Muslims, with millions of Muslims from all over the world making a pilgrimage at least once in their lifetime, resulting in the appearance of all kinds of waste.[4]

Waste streams refer to the flow of specific waste from its source to recovery, recycling, or disposal. These waste streams collectively constitute the overall waste treated. Waste streams can be categorized into two primary types: material-related streams, which include metals, glass, paper and cardboard, plastics, wood, rubber, textiles, biowaste, and slaughterhouse waste, and product-related streams, such as packaging, electronic waste, batteries and accumulators, end-of-life vehicles, and mining, construction, and demolition waste. To assess different waste streams, various aspects must be taken into account, such as the sources of waste to be treated and the uses of treated waste, applicable recycling and recovery methods, specific opportunities and challenges related to recycling, and relevant legislation of K.S.A. and its implementation.[5−7]

Landfills are an old-fashioned way to eliminate accumulated plastic waste. Due to the city of Makkah's high atmospheric temperature, more polluted gases are produced in landfills in the first few months owing to the degradation of plastics.[8] Over time, these gases accumulate and damage the surrounding environment, because of the escalation of self-igniting vapors. In addition, the emission of polluted gases from the landfill into the air causes pollution and according to scientific studies also cancers.[9] According to statistics from the Saudi Center for Energy Efficiency (SCEE), the share of domestic energy consumption will reach 50% by 2030. By 2022, the K.S.A. will consume 3 million barrels of petroleum per day, or 24% of its domestic energy reserves, where wasting energy of all kinds is estimated to cost the Kingdom USD 36 billion.[10,11] Although the Kingdom of Saudi Arabia is considered one of the richest countries in the world in terms of its oil economy, there are serious problems in terms of the environment. According to the Saudi Ministry of Environment regulations from 2022 (before the COVID-19 pandemic), unsustainable waste management is the main environmental deterioration factor

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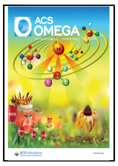

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in the K.S.A. Environmental degradation costs USD 22 billion per year, equivalent to 3% of the gross domestic product (GDP). The different impact factors for the high cost of environmental degradation and pollution in USD billion can be classified as waste (0.25), natural disasters (0.3), coastal resources (0.33), soil (1.15), water (1.3), climate change (7), and air (10).[12] The landfill in Makkah is located about 13 km from the city center and is designed as a sanitary dump for waste, including plastic. This is a well-planned and developed waste treatment facility that uses modern engineering principles to protect the environment and improve the living standards of local communities in the surrounding areas. During the intense heat that characterizes Makkah's atmosphere, waste and pollutants can escalate quickly. In addition, the wind carries the emitted pollutant gases into the city.

According to the 2022 Global Burden of Disease Study, exposure to air contaminated with plastic waste is an extremely dangerous cause of death. In recent years, there has been growing global concern about the harmful effects of air pollution on respiratory health. The lung is the main organ affected by direct exposure to air pollution. These impacts can be divided into short- and long-term. Short-term exposure to air pollution worsens respiratory illnesses including wheezing, coughing, chest tightness, and asthma. Long-term effects are chronic and last for years or the patient's lifetime. It can lead to chronic laryngitis, chronic lung disease, and respiratory cancer.[13]

Research into infectious diseases caused by plastic waste pollution can be classified into direct and indirect diseases. Direct infectious diseases are arthropod-borne diseases that generate suitable habitats for their vectors. The most obvious example is *Aedes albopictus* mosquitoes, which transmit chikungunya, dengue, yellow fever, Zika virus, and numerous other arboviruses.[14]

The exposure to sunlight of toxic gases released from plastic waste, collected in landfills for a long time, can make them harmful and affect human health by indirect infectious diseases of (1) the brain: headache, dizziness, and unconsciousness; (2) the eye: irritation in the eyes and visual disturbances; and (3) the nose, breathing problems, asthma, and respiratory problems; (4) the thyroid: cough and throat problems; (5) the lung, lung problems; (6) the liver: liver dysfunction, diarrhea, vomiting, indigestion, and typhoid; (7) the stomach: pain and food poisoning; (8) the skin: disorders, dandruff, allergy, and skin cancer; and (9) the penis: birth effect, infertility, hormonal changes, and decreases in sperm number and cancer.[15,16]

In many developing nations, plastic waste is disposed of using various methods such as landfilling, incineration, recycling, and pyrolysis. These options offer numerous advantages such as financial benefits, employment opportunities, resource preservation, economic gains, energy savings, and partial environmental friendliness. However, there are also drawbacks that need to be addressed. Owing to Makkah's increasing production of plastic waste and hot weather, landfills in the city pose significant risks to the environment and public health. As more plastic debris fills the deepest part of the landfill, the oxygen ratio drops, causing degradation and smoke. Recycling often leads to harmful gases, including carbon dioxide, methane, hydrogen sulfide, and dioxins, being released into the surrounding soil.[14,15] Additionally, due to rising pollution and energy consumption, the financial rewards of recycling are becoming less profitable and more costly.[16]

The process of incinerating waste to produce energy has adverse effects owing to the release of pollutants, such as sulfur oxides, nitrogen oxides, and fly ash. Furthermore, the utilization of the resulting energy products is inflexible and approximately 30% of the original waste volume is represented by the remaining tar and ash.[17] Pyrolysis is a completely nonoxidative thermochemical process that converts raw materials to coal, oil, and combustible gases in an inert environment. Pyrolysis causes more air and soil pollution than incinerators.[18]

The process of flow gasification has been recognized as a highly promising technique for the efficient and clean production of syngas on a large scale.[19,20] A variety of materials can be used in the different stages of this process, including biomass gasification in the early stages of technology development, reverse multiburner gasification of coal-water slurry, and noncatalytic partial oxidation utilizing natural gas or coke oven gas. In addition, solid fuels can be converted into cleaner gaseous fuels through steam gasification. However, steam gasification reactions typically require high temperatures to achieve optimal reaction rates, as they are highly endothermic.[21] Furthermore, in a typical steam gasifier, at least 35% of the feedstock must be combusted to drive the gasification reaction, which results in additional NOx emissions. In recent years, the significance of gasification procedures, particularly efficient microwave heating methods, has increased. When exposed to external microwave radiation, carbonaceous fuels often exhibit rapid nanoscale thermal changes.[22] Gasification can also address the release of mercury (Hg) into the environment and the diffusion of process byproducts. It is crucial to understand the behavior of mercury in thermal waste treatment, as the temperature, residence time, and purge gas flow rate affect the amount of mercury released from the waste. Each type of waste has different mercury release rates during thermal treatment. The easiest way to release mercury is from plastic samples owing to the great potential of producing low-mercury alternative fuels from waste through thermal processing.[23] The initial mercury concentrations of waste coal, sludge, fly ash, paper ash, biomass waste ash, and other wastes had mercury contents of 523.16 527.81, 6.02, 1.45, and 6, respectively. In total, 47 g/kg Hg was emitted during the combustion process. The addition of up to 10% polymer reduces mercury emissions by 53.72% for coal fuel and 26.36% for coal sludge.[24]

Plasmas can be easily distinguished from solids, liquids, or gases owing to the presence of charged species in plasmas, making them highly reactive.[25] Charged electrons collide with gas molecules at high energies, forming a plasma that is sometimes called the fourth state of matter. Thermal plasma is used in waste processing, which is characterized by very high temperatures and energy densities. High-temperature plasma jets can be produced by passing an electric current through a gas.[26] During high-temperature plasma heat treatment, the starting material is completely decomposed into simpler material compounds in a process called plasma gasification, which occurs in a partially oxidizing environment. The organic partial conversion of solid feedstocks produces high-quality syngas that can be used as fuel for power generation or to manufacture chemicals.[27] The chemical bonds of all materials are broken by the high-temperature plasma, which releases a large number of extremely active free radicals, electrons, ions, and excited molecules into the system and generates high-intensity plasma radiation. There is a significant increase in response rate.[28] Thermal plasma is used to completely decompose waste, turning the organic portion into synthetic gas and the inorganic part into vitrified slag.

Over the past few decades, several researchers have focused on waste gasification for clean energy production as well as safe and efficient waste management using thermal plasma.[29,30] The thermal plasma waste gasification process is a viable solution for the treatment of waste with the potential to recover energy, reduce environmental costs, and create employment opportunities. This process is capable of handling waste of any chemical composition due to its high temperature and energy efficiency, ensuring environmental safety. The organic components in the raw materials are gasified and converted into industrial gases with high calorific values and high material yields, while the inorganic components are converted to lava through a thermal plasma process. The feedstock is processed to produce syngas that can be used for generating electricity or heat and producing useful byproducts such as methanol or hydrogen for fuel cells. Additionally, the production of synthetic fuel from plastic that has undergone plasma treatment is cost-effective compared with producing energy from fossil fuels, resulting in net profit. Thermal plasma treatment occurs at high speeds and temperatures and produces chemical reactions in which all complex chemical elements are broken down into simple substances and converted into synthetic gases that are combustible fuels.[31−33]

Our project aims to use plasma gasification technology in Makkah to treat plastic waste, which is a modern and cost-effective method of converting plastic waste into renewable energy. Our approach results in emission-free pyrolysis oil, a clean and safe fuel alternative to petroleum, and does not produce toxic emissions that could harm humans or the environment. The project is focused on achieving sustainability in three dimensions: environmental, economic, and social. In addition, the economic feasibility of our plastic waste to pyrolysis oil energy recovery process as the most sustainable solution is evaluated and an algorithmic model is developed to predict environmental pollution and an economic indicator to assess the impact of plastic waste in Makkah. This project aims to redraw the vision for converting plastic waste into energy in a sustainable manner with a focus on Makkah City. Specifically, it examines four out of the five aspects of the vision for plastic waste-to-energy conversion (PWTE): environmental impact, energy recovery, economic feasibility, and profitability.

2. MATERIALS AND METHODS

2.1. Statistical Survey of Plastic Waste. The challenge of managing waste during the Arabic months of IX and XII in Makkah (see Table S1) has proven to be a difficult problem for authorities. During these months, religious rituals are performed in enclosed areas within Al-Haram and Al-Masha'ir. The peak period of waste production occurred between the 8th and 16th days of the Arabic month of XII, with a large amount of plastic waste being generated.[34] It is crucial to properly dispose of plastic waste to prevent pilgrims from facing inconvenience or problems. The nearby Makkah Holey Community, General Administration of Cleanliness, Management of Quality Assurance, and Performance Evaluation provided information on the amount of plastic waste generated, which was measured in tons over a 27-year period. This information also includes statistics on the average rate of plastic waste production during months IX and XII.[35]

The environmental vision will focus on the Zam-Zam plastic (Zz-PW) of the holy mosque of the Muslim community (Al-Masjid Al-Haram), and the environment represented by the regions of Arafat, Muzdalifah, and Mina (Al-Masha'ir); these regions represent the rituals of religious pilgrim Muslim areas. Zz-PW disposable plastic cups and bottles are classified as polystyrene polymer type by the Society of the Plastics Industry (SPI) with Code 6 PS (see Figure S.1 shows the annual output of Zz-PW in tons for Makkah over a 27-year period).

2.2. Proposed Plasma Reactor. The experimental setup adopted the previously proposed stages of plasma treatment (PTP) projects for green energy generation in pilgrimages, and it was designed to test and validate the plasma treatment of Zz-PW with energy recovery before scaling up to 200 t/day.[36] A schematic representation of the plasma treatment reactor is depicted in Figure 1. The plastic feedstock is fed into the plasma furnace reactor and propelled downward by gravity into the high-temperature plasma zone, where it undergoes breakdown and gasification. The reactor chamber was lined with a heat-resistant insulating refractory material.

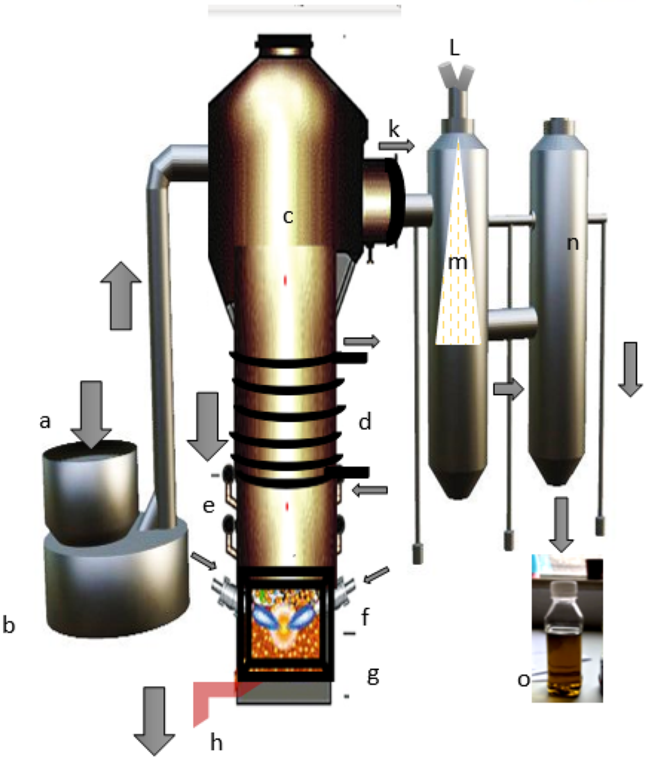

Figure 1. Plasma treatment furnace for the PWTE process: (a) chopping unit; (b) grinding unit; (c) furnace; (d) water inlet and outlet; (e) air; (f) plasma torch; (g) windows; (h) slag; (k) syngas; (L) air and water; (m) cylindrical quenching chamber; (n) cylindrical pyrolysis oil chamber; and (o) pyrolysis oil sample.

Before feeding Zz-PW into the plasma reactor, it must undergo pretreatment (such as grinding, chopping, or shredding) to facilitate quick processing in a combustion-like chamber at temperatures ranging from 1500 to 5000 °C. Zz-PW is converted into one of three products: syngas, pyrolysis oil, and slag. The active operational gas of the plasma treatment reactor is air, which significantly affects the oxidation process without causing environmental pollution. The final product, slag, is collected at the bottom of the reactor, and the manufacturing fuel (pyrolysis oil) is removed, intensified, and filtered.[37] In the final phase, liquid fuel (pyrolysis oil) can be utilized as an energy source,[38] which represents the objective of the present study.

In the present study, thermal plasma jet generated by a DC air plasma torch (non-transferred arc), previously discussed in our article[39] was used to treat waste. The plasma torch had a power of 125 kW and an airflow rate of 10−30 g/s. In the plasma torch, the electrical energy is converted to heat and the pressure of the compressed air stream ejects the hot plasma jet out of the torch, transferring heat to the Zz-PW and the inner wall of the reactor. The performance of a plasma-chemical reactor is influenced by the power, torch type, electrodes, and operating conditions. Two plasma torches were used for each of the five reactors, allowing for easy demonstration of the Zz-PW plasma-assisted combustion process, adjustment of the chemical composition of the plasma, and removal of various byproducts.[40] The reactor had two water-cooling systems: the first was designed to work with walls as hot as 1500 °C, and the second was designed to work with hot syngas already created and flowing out of the furnace reactor through a cylindrical cooling chamber. In addition, the gas entered the condensation chamber at a low temperature and exited through the quenching chamber.

2.3. Plasma Torch and Thermal Process.

The primary technical component of a plasma furnace is the torch, as depicted in Figure 2, which is powered by a direct current. The air torch (non-transferred arc) schematic diagram has been previously discussed in our articles.[41−43] The characteristics of the plasma torch, summarized in Table 1, enable the generation of a highly versatile plasma jet that transforms electrical energy into the thermal energy required for a variety of eco-friendly processes.

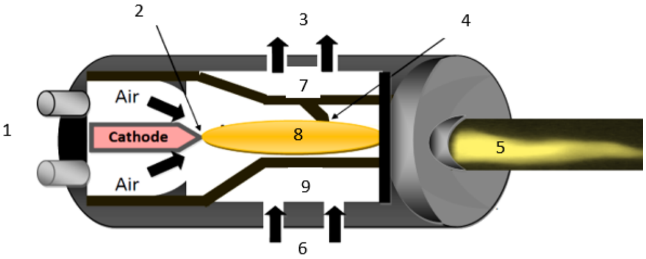

Figure 2. Schematic diagram of plasma furnace, the air torch (non-transferred arc): (1) gas in; (2) cathode spot and boundary layer; (3) outlet water; (4) anode spot and boundary layer; (5) plasma jet; (6) inlet water; (7) anode; (8) arc; and (9) anode.

Table 1. Air Plasma Torch Parameters

parameter	amount
power	direct current
the working active gas	air
V_{max}	500 V
I_{max}	250 A
$P_{max.out}$	125 kW
$T_{plasmajet}$	10,000 to 19,000 K
gas flow rate	30 g/s
cooling system	inlet and outlet water

The cooling system in the plasma torch comprises several key components, including the specific heat value for water (C_p), the mass flow rate, and the inlet and outlet water temperatures. The heat losses to the walls and electrodes are accounted for by calculating ΔT, which is then removed by the cooling water.[44] The electrical discharge between the cathode and anode is essential to prevent gradual erosion, and the thermal plasma jet stream is expelled from the torch due to the pressure of the compressed air flow as it passes between the gas column and the surface of the inner anode.

Temperatures of the inner wall of the reactor and the gas are measured using thermocouples, while the flow rate of the reaction gas is determined using a pitot tube flow meter. This study, which focuses on the plasma treatment reactor, has a working active gas air range of 10−30 g/s. The high-temperature plasma jet at the nozzle of the torch has a significant impact on oxidation.[45]

The enthalpy probe, made up of three concentric tubes, operates by cooling the system using water. This device takes gas samples and measures the stagnation pressure. Additionally, the probe features three thermocouples, one measuring the gas temperature at the probe's end and the other two measuring the temperature rise of the cooling water.

$$h_{tip} = m_{water} m_{gas} C_p(\Delta T_{GF} - \Delta T_{NGF}) + h_{exit} \quad (1)$$

The temperature increase of the cooling water (ΔT_{GF}) in the presence of gas flow is influenced by two important parameters: the enthalpy at the tip of the probe (h_{tip}) and at the exit of the probe (h_{exit}). Additionally, the temperature rise in the absence of gas flow (ΔT_{NGF}) is a crucial measurement that is obtained through tare measurement. The mass flows of the cooling water (m_{water}) and gas (m_{gas}) are both important factors, with the specific heat of the water (C_p) being assumed constant. The isokinetic sampling law requires that the velocity in the measuring tube be as close as possible to the free stream velocity and the mass flow of the gas must be adjusted accordingly to ensure that the temperature difference ($\Delta T_{GF} - \Delta T_{NGF}$) is large enough to measure but remains constant during the measuring cycle.

As the gas flow rate increases, the ratio of the gas mass flow to the cooling water decreases while the heat flux to the cooling water increases. These two effects offset each other, resulting in the plasma enthalpy remaining constant over a specific range of gas mass flows. The exit temperature (h_{exit}) is determined by the temperature at the probe exit and does not exhibit significant variations with changes in the gas mass flow. By knowing the gas composition at the probe exit, we can determine the mass of the gas through the mass flow rate. The plasma temperature (T) can be calculated using the dependency of h_{tip} on temperature.

2.4. Energy Recovery Analysis.

An energy recovery analysis was conducted to evaluate the effectiveness and energy requirements of the plasma treatment for the Zz-PW streams. The study involved a parametric analysis of Zz-PW streams, with a focus on identifying the plastic type with the highest heating value (HHV) or carbon and hydrogen content for treatment at the plasma facility.[46] In our example, we used the following formulas to calculate the conversion and percent pyrolysis oil while excluding the percent residue and percent syngas, which will be addressed in future research.

$$\text{conversion(wt\%)} = \frac{\text{mass of the feedstock plastic} - \text{mass of the residue}}{\text{mass of the feedstock plastic}} \times 100\% \quad (2)$$

The liquid yield is as follows:

$$\text{pyrolysis oil(wt\%)} = \frac{\text{mass of oil}}{\text{mass of the feedstock plastic}} \times 100\% \quad (3)$$

The current paper presents a new modeling approach that outlines how to obtain a reduction in greenhouse gas emissions and minimize Zz-PW in landfills in Makkah while considering the environmental vision for plastic waste. To achieve this, this research conducts a statistical study of plastics, the release of toxic substances in landfills, the proportions of these substances, the impact of Zz-PW on public health, and the costs associated with plastic pollution. Furthermore, this study explores the use of plasma reactors to recover energy from Zz-PW for sustainable development in the industrial fuel (EEIF) sector.

2.6. Environmental and Economic Indicator Models. The pollutant emissions from the Zz-PW from the Al-Haram and Al-Masha’ir regions accumulated in the sanitary landfill were calculated using SimaPro7 software (version 7.1.0),[47] which focuses on sustainable development for climate change through counting and management. It provides the amount of decomposition emissions from landfills, the cost of the emissions, and the amount of gas pollution and moisture content per ton and per year. The SimaPro program (Ecopoints method) can help measure the environmental impact and automatically calculate group emissions for accuracy in any sustainability program (see S.I.3). Furthermore, an algorithmic model was used to estimate the economic evaluation of the energy recovery process[48−50] from Zz-PW to pyrolysis oil as the greenest alternative solution. The algorithmic model for environmental pollution vision with a negative indicator and economic vision with a positive indicator of Zz-PW in Makkah was evaluated as follows:

```
• Net losses algorithm
• Call amount of Zz-PW ($P$)
• Call amount of gas emission ($G$)
• Call global warming cost ($W$)
• Call climate change cost ($C$)
• Call consumed fuel (CF)
• // Calculate pollution cost = $P + G + W + C + \text{CF}$
• // Calculate net losses = pollution cost
• Net gains algorithm
• Call product sales ($S$)
• Call economic gain ($E$)
• Call manufacturing expenses ($M$)
• Call tax ($T$)
• // Calculate revenue gains = $S + E - M - T$
• // Calculate net profit = revenue gains
• Call rate of return (ROR%)
• Call payback period (PBP)
• Call gross profits (%)
• // C++ program
• //Include < iostream>
• // Calculate net losses
• // Calculate net profit
• The total volume of product sales ($S$) − expenses operating expenses − employee costs, administrative costs, research, and development (R&D) costs ($E$) − tax cash flow federal, state, local income, and payroll taxes ($T$)
• Float net profit (float $S$, float $E$, float $M$, float $T$)
• {
• Float net losses (float $P$, float $G$, float $W$, float $C$, float CF)
• {
• // Iterate for $n$ number of iterations
• for (int $i = 1$; $i \leq 12$; $i$++) {
• // Update next value of Net profit
• $N_g = S + E - M - T$
• // Update next value of $N$
• // Update next value of $x$
• }
• Return $N_g$
• }
• Update next value of net losses
• $N_l = P + G + W + C + \text{POE}$
• // Update next value of $N_l$
• // Update next value of $x$
• }
• Return $N_l$
• }
```

3. MODELING RESULTS AND DISCUSSION

3.1. Environmental Vision. *3.1.1. Analysis of Toxic Emissions from Landfills.* The environmental vision for the sustainable treatment of Zz-PW is presented through an annual statistical survey and the amount of decomposition emissions from landfills from 1993 to 2022. Figure 3 presents the results of the analysis conducted using the SimaPro software program model on the annual amount of landfill degradation emissions in megagrams from contaminated landfill gases due to accumulated plastic waste, according to Figure S2 (see the SI). The results indicate that the average production of polluted landfill gas varies from 168,000 Mg in 1994 to 297,000 Mg in 2022.

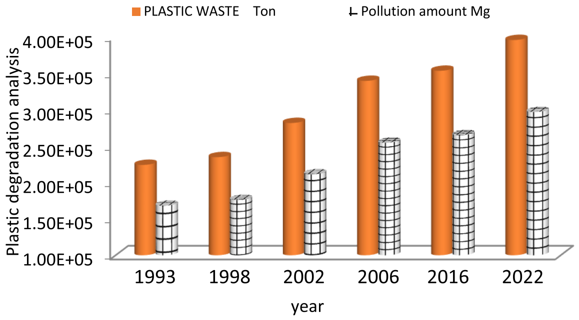

Figure 3. Analysis values of the output gas emission pollution from the landfill and the pollution cost due to the accumulated plastic waste.

3.1.2. Ratios of Emission Categories for Toxic Substances. Figure 4 shows the amount of polluted gas emitted from the landfill used to evaluate pollution from plastic waste. An emission analysis was performed for a parametric study of the amount and type of polluted landfill gas from Zz-PW.[51−53] The highest emission levels are carbon and hydrogen,[54,55] with

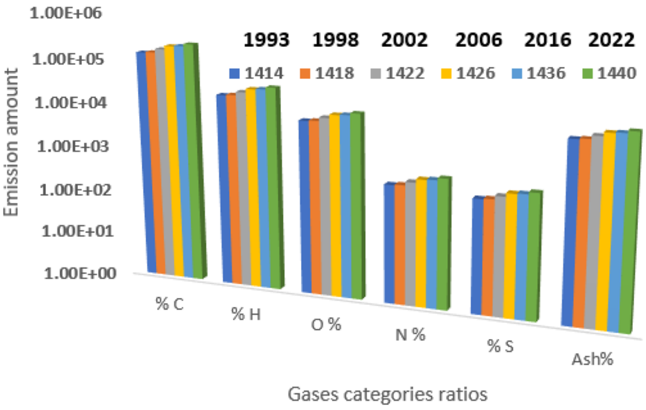

Figure 4. Logarithmic scale of gas category amounts emitted from landfills due to plastic waste.

emissions of 128,000 Mg in 1994 and up to 227,000 Mg in 2022 for carbon emission pollution with a ratio of 76.3% of all gases emitted, and with emissions of 193,000 Mg in 1994, to 342,000 Mg in 2022 for hydrogen, with a ratio of 11.5% of all gases emitted.

In addition, as shown in Figure 4, the SimaPro program can help measure environmental impact and automatically calculate emissions from other polluted landfill gas groups, such as oxygen, nitrogen, phosphorus, and ash, with ratios of 4.4, 0.26, 0.2, and 5.3% for the annual landfill emissions data survey from 1994 to 2022, respectively.

3.2. Greenest Alternative Solution. The plasma gasification reactor represents the greenest alternative solution for waste-to-energy technology.[54] Plasma jet emerging from the air plasma torch is considered the corner stone for environmentally friendly processes, and plasma jet characteristics will be discussed as follows.

3.2.a. Current–Voltage Characteristics. Plasma is typically generated by subjecting a gas or vacuum to an electric current, which creates a conducting path known as a breakdown between the electrodes. This process is utilized by a plasma torch to generate an air plasma jet with an extremely high temperature. The current–voltage characteristics of the plasma torch for various air flow rates ranging from 10 to 30 g/s are shown in Figure 5. Furthermore, from the current–voltage characteristics, the applied input torch power into the jet ($I_{\text{ampere}} \times V_{\text{volt}}$) can be estimated as 25–125 kW, considering as discussed before in our previous work that the ability of the plasma torch to convert electric energy into thermal energy represents the electrothermal efficiency of the plasma torch.

3.2.b. Plasma Jet Temperature and Wavelength. Figure 6 illustrates the temperature of the plasma jet in relation to the air flow rate for different current values. It is evident from the figure that as the air flow rate increases, the temperature of the plasma jet decreases. Furthermore, the curves indicate that at higher current, the temperature increases for a fixed flow rate.

The emission spectra of the plasma jet along its axis were measured using an AvaSpec-2048 spectrometer, and the wavelength $\lambda_{\max}$ of the radiation with the highest intensity was determined using Wien's displacement law, which can be expressed by eq 4.

$$\lambda_{\max} = {}^{d}\!/_{T} \tag{4}$$

The temperature, T, and a constant, d (2.9 mm K), play a critical role in the flow rate of air and the temperature of the jet outlet from the nozzle of the torch. As the flow rate of air increases, the temperature of the jet outlet from the nozzle of the torch decreases, leading to an increase in $\lambda_{\max}$. Additionally, due to the high temperature of the jet, it serves as an intense source of ultraviolet radiation, providing the plasma jet with a powerful gas cleaning effect. The connection between the airflow rate and the temperature of the jet emerging from the nozzle of the torch is demonstrated in Figure 7.

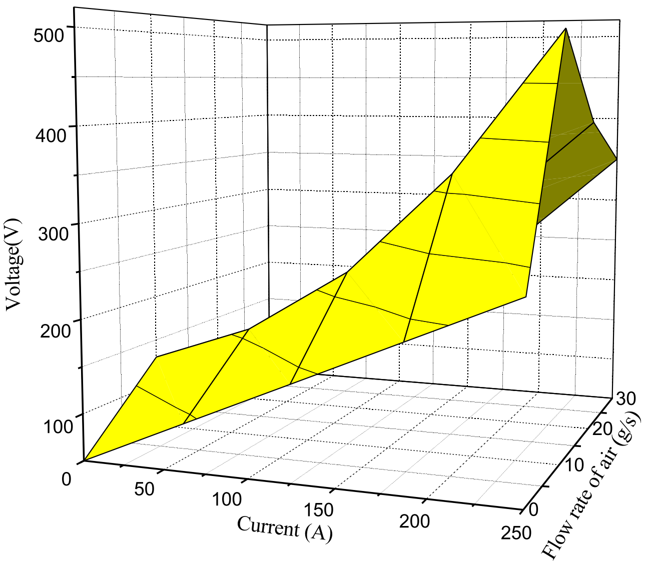

Figure 5. Voltage (V) versus current (A) characteristics of the plasma torch at different flow rates of air.

3.2.c. Plasma Jet Velocity and Length. In a plasma that is isothermal and exhibits laminar flow, the mean plasma temperature, as determined by Figure 6,[56,57] is utilized to calculate the sound velocity of the plasma, as specified by eq 5.

$$v_s = \sqrt{\gamma RT} \tag{5}$$

The corrected value for the mean molar mass of the plasma gas is represented by the symbol R, with a reference value of $R_{\text{air}} = 287.05$, and the adiabatic coefficient γ is set at 1.4.[58] According to eq 5, the plasma sound velocities are influenced by the temperature of the plasma plume and the applied current, which varies from 100 to 250A. Furthermore, the applied power, airflow rate, temperature, wavelength of radiation, sound velocity, and efficiency of the plasma torch are crucial factors for the formation of the plasma jet and the design of the experimental equipment with stable operating parameters. The characteristics of the plasma torch are heavily dependent on the dimensions of the electric arc chamber and the type of plasma-forming gas and its mass flow rate.[59]

According to the data, the temperature of the jet typically falls within the range of 7000 to 19,000 K at the torch nozzle, with an average velocity of 1677.3 to 2763.2 m per second. The findings suggest that this plasma technology can be employed for ecologically friendly applications, including the treatment of all types of waste into their fundamental components: carbon, syngas, pyrolysis oil, and slag.[60]

The images of plasma jets at various gas flow rates and arc currents, as shown in Figures 8a,b, indicate that an increase in energy supply results in a longer plasma jet (mm). As the temperature of the jet rises, so does the heat exchange between the plasma and the surrounding environment. At lower gas flow rates, the plasma jet is in a laminar flow state with a

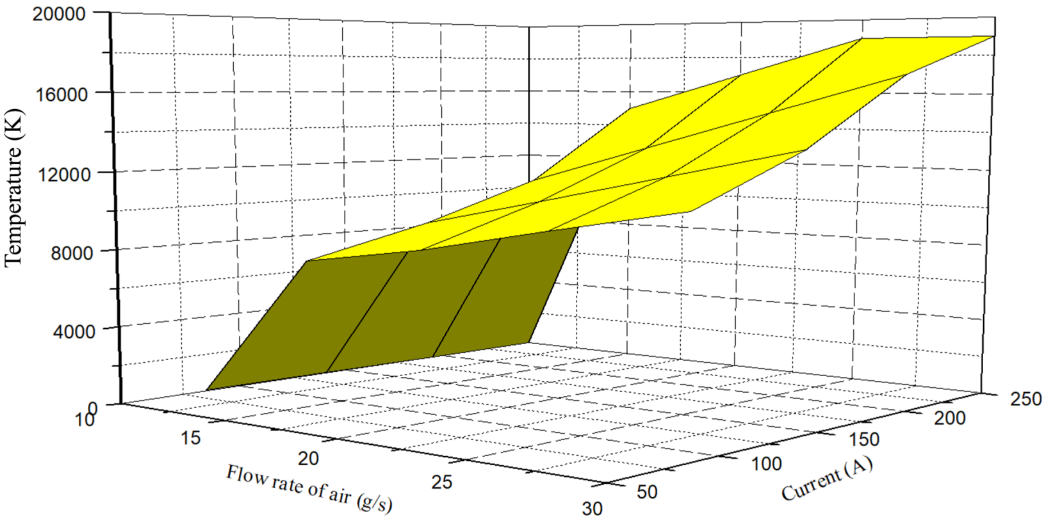

Figure 6. Plasma jet temperature (°K) vs flow rate of air (g/s) characteristics at different applied currents.

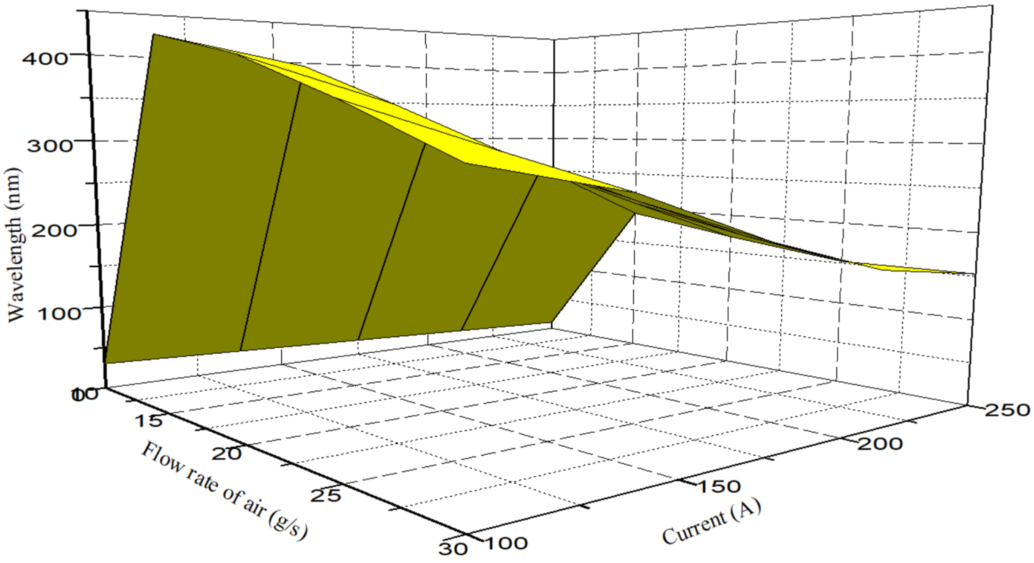

Figure 7. Relation between the wavelength emitted plasma (nm) and the flow rate of air (g/s) at different currents.

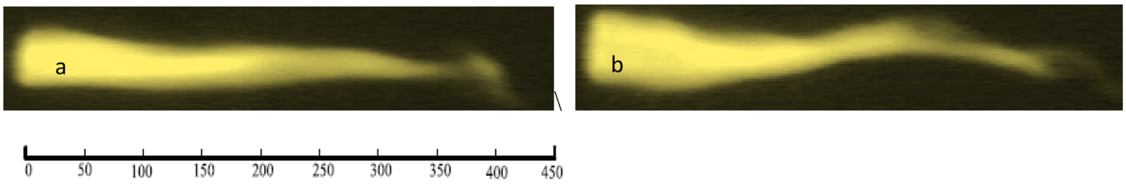

Figure 8. (a, b) Jet *length* images (mm) with a gas flow rate G_{gas} from 10 to 40 L/min, and with an arc current I = 100 A.

corresponding jet length of 400 mm. However, when the gas flow rate is increased from 10 to 40 L/min, and the arc current is held at 100 A, as illustrated in the figures, the plasma jet draws in more air, with a corresponding jet length of 450 mm, leading to a greater heat loss. This causes the plasma jet to transition progressively from a laminar flow state (mode) to a turbulent flow state.[61]

3.3. Energy Recovery.

Toxicity reduction and environmental remediation prompted K.S.A. to move away from landfills as a conventional method of Zz-PW management and to replace them by nonconventional plasma gasification technology to evaluate energy recovery from plastic.[62,63]

The organic components of Zz-PW are gasified in the plasma reactor at high temperature and in the presence of air and converted into high calorific gases and materials at high yields. According to the chemical conversion process, the reaction of plasma treatment with air where m is the moles of air (O_2 + 3.76 N_2) and the feedstock Zz-PW with a moisture content equal to zero[64,65] can be written as

$$\begin{aligned} &C_5H_{7.1}O_{1.4} + m(O_2 + 3.76N_2) \\ &\quad \xrightarrow{\Delta} n_1H_2 + n_2CO + n_3CO_2 + n_4H_2O + n_5CH_4 + n_6N_2 \\ &\qquad + n_7C \end{aligned} \tag{6}$$

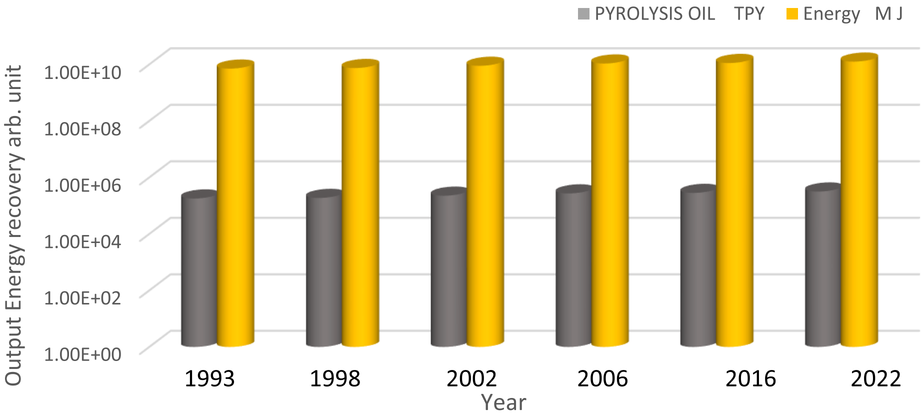

Figure 9. Energy recovered from Zz-PW through the plasma gasification system is represented on a logarithmic scale.

The Zz-PW is converted into seven products, ranging from $n1$ to $n7$, with n representing the moles of the various plasma treatment products. Among these products, CO and H_2 are the primary products of interest in syngas whereas CH_4 is present to a lesser extent.[66] Owing to its high ash and wax contents, pyrolysis oil cannot be used directly as an energy source. However, the condensate of oil can be utilized as a fuel oil once the hot exhaust syngas is cooled. The collected pyrolysis oil resembles crude oil, with a brownish-black and viscous appearance, a density of 0.81 g/cm^3, a gross calorific value of 10,500 kcal/kg, a sulfur content of 0.03%, and a moisture content of 0.05%. Several distillation steps are required to enhance their suitability for use in engines.

This study conducted an energy recovery analysis of Zz-PW streams to determine the amount of energy produced (Table S2). The output energy was assessed in terms of pyrolysis oil, which was found to be 0.8 times the input energy of plastic waste. The analysis revealed that 1 kg of mixed plastic (PE, PP, and PS) yielded 0.8 kg of oil. Additionally, the energy equivalent of pyrolysis oil was determined to be 39.6 MJ/kg. Figure 9 illustrates the energy recovery findings of Zz-PW through a plasma gasification system using the data from Table 2. These findings highlight the significance of fuel oil derived from Zz-PW pyrolysis as a valuable energy source.[67] During pyrolysis, Zz-PW is broken down within a plasma gasification furnace system, reaching temperatures of up to 1500 °C. This results in the formation of fuel oil, slag, and syngas in the form of oil, solids, and gaseous substances, respectively.[68] Table 2 further demonstrates the range of energy output, measured in MJ, from the Zz-PW input. In 1994, the range was 7.10×10^6 MJ/ton, while in 2022, it increased to 1.25×10^7 MJ/ton. The input of Zz-PW also ranged from 2.24×10^5 tpy in 1994 to 3.96×10^5 tpy in 2022. Similarly, the quantity of pyrolysis oil ranged from 1.79×10^5 tpy in 1994 to 3.17×10^5 tpy in 2022.

Table 2. Quantity of Pyrolysis Oil and Energy Yield from the Zz-PW Recovery Process between 1994 and 2022

	output energy	
year	pyrolysis oil TPY	energy MJ/ton
1994	1.79×10^5	7.10×10^6
1998	1.88×10^5	7.44×10^6
2002	2.26×10^5	8.93×10^6
2006	2.72×10^5	1.08×10^7
2016	2.83×10^5	1.12×10^7
2022	3.17×10^5	1.25×10^7

The efficiency of Zz-PW energy recovery through plasma gasification, known as "GasifEq", was developed by AQMountouris et al.[69] to model thermodynamic and chemical equilibrium processes in plasma treatment. The production efficiency η can be calculated using this model, as shown in eq. 7.

$$\eta = \frac{\text{heating value produced(J)}}{\text{heating value feedstock(J)}} \tag{7}$$

or by substituting the values of the high heating value (HHV) and lower heating value (LHV), as in eq 8, as follows:

$$\eta = \frac{\mathrm{HHV_{oil}}}{(P_{\mathrm{torch}} + \mathrm{HHV_{refuse}})} = \frac{\dot{m}_{\mathrm{oil}} x \mathrm{LHV_{oil}}}{[P_{\mathrm{torch}} + (\dot{m}_{\mathrm{feedstock}} x \mathrm{LHV_{feedstock}})]} \tag{8}$$

The mass flow rate of oil and input plastic waste, denoted by $\dot{m}$, and the electrical power of the plasma torch, represented by P_{plasma}, are factors that influence the process. The ratio, denoted by η, is calculated based on the heating value of the produced $\mathrm{HHV_{oil}}$ and the waste input $\mathrm{HHV_{refuse}}$, as well as the electricity used by the plasma torches P_{plasma}:

$$\mathrm{LHV} = \mathrm{HHV} - 0.212(H + 118M - 0.038Y)(\mathrm{GJ/T}) \tag{9a}$$

and

$$\mathrm{HHV} = 1.423[H + 0.214C - 0.108Y] \tag{9b}$$

where H is the hydrogen content (%), M is the moisture content (%), C is the carbon content (%), and Y is the oxygen content (%).[70]

The efficiency of our plasma treatment system for processing Zz-PW was determined by using the GasifEq model. In 2023, this system was expected to input 3.96×10^5 tons of Zz-PW per year, produce 3.17×10^5 tons of pyrolysis oil, and extract an equivalent amount of energy at 1.25×10^7 MJ/ton. The efficiency, represented by the value of the third bar HHV oil (1.25×10^7 MJ/ton), can be calculated by dividing it by the sum of the values of the first two bars for each feedstock (HHV refuse at 0.92×10^7 MJ/ton and P_{plasma} at 0.63×10^7 MJ/ton), resulting in an annual efficiency of 81% (Figure 10).[71]

3.4. Economic Indicators.

3.4.1. For Plastic Pollution Cost. The accumulation of Zz-PW in landfills generates

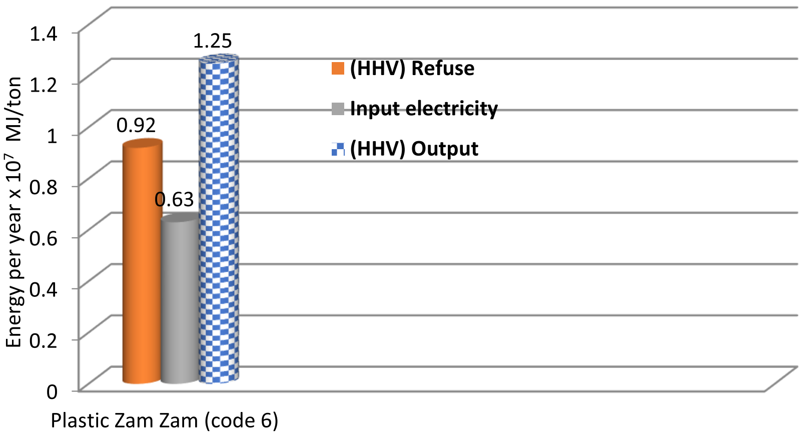

Figure 10. Output heating values are produced, and the input heating values are required for the efficiency of the plasma treatment system.

harmful pollutants that pose a significant threat to the health of pilgrims. To mitigate this risk, it is essential to monitor, calibrate, and detect the volume and type of contaminants present. Air pollution is a major contributor to deaths because Zz-PW releases gases such as carbon, hydrogen, nitrogen, phosphorus, and sulfur. These gases have a significant impact on human health and are considered the fourth most common risk factor for death.

According to Figure 11, the cost of Zz-PW pollution is expected to range from 4 million in 1994 to 7 million in 2022.

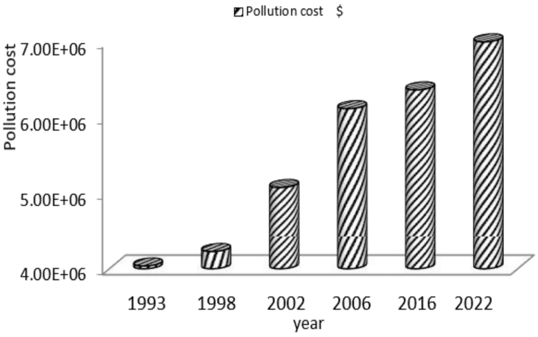

Figure 11. Average cost of pollution from Zz-PW ranges from USD 4 million in 1994 to USD 7 million in 2022, over a period of 26 years.

The Saudi Arabia Index[72,73] and the SimaPro program were used to determine that an average of 297,000 Mg of landfill gas is produced by 2022, resulting in an annual cost of 7 million from plastic pollution alone. However, treating Zz-PW in a plasma reactor can reduce all pollution costs and eliminate toxins, air pollution, and climate change.[74]

3.4.2. For Pyrolysis Oil Profits. Zz-PW processed in a plasma reactor to produce pyrolysis oil provides the same energy and lower cost as petroleum[61] with a gross profit margin. One of the goals of this study was to evaluate the gross profits of the cheapest oil extracted from pyrolysis oil after the energy recovery process, because it has a high energy value for production purposes. The demand for pyrolysis oil has grown steadily amid growing awareness of the need for alternative sustainable energy sources. Pyrolysis oil represents a smart environmental solution and a renewable and cheaper fuel energy alternative to petroleum.[75] As the number of pilgrims in Makkah increases, the amount of waste increases and exceed expectations.[76] Table 3 shows that 4.6 million barrels of pyrolysis oil are extracted from the annual amount of Zz-PW reaching 0.4 megatons in 2023 in Makkah city.

Table 3. Pyrolysis Oil Volume Was Extracted from Zz-PW Annually by 2023 in Makkah City

parameter	amount
plastic amount	0.4 megatons
pyrolysis oil amount	962 million liters
pyrolysis oil volume	4.6 million barrels

To evaluate the economic indicator of the energy recovery process,[76] we must estimate (a) economic losses with a negative indicator and (b) the economic gain indicator with a positive outcome.

a. Economic Losses with Negative Indicator. Figure 12 shows the annual economic losses with negative indicators owing to the degradation process of Zam-Zam Zz-PW in the landfill, including the following:

1. USD 120 million represents the cost of five plasma reactor manufacturing (total capital of the plant) including the costs of 200 t/day of raw material, transportation, utility, labor, waste treatment fixed, capital investment, and workers salary.
2. USD 20 million represents the cost of 0.2 million BOE petroleum oil consumption in Makkah for energy purposes through Hajj and Umra seasons, where according to the annual OPEC basket In January 2023, the price was USD 100.8 per barrel (equivalent to 159 L).

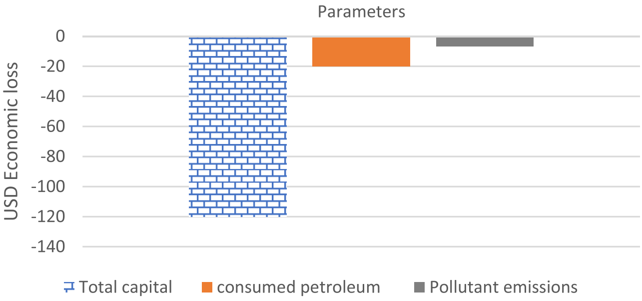

Figure 12. Annual economic losses with negative indicator due to the annual degradation process in 2023 in Makkah city.

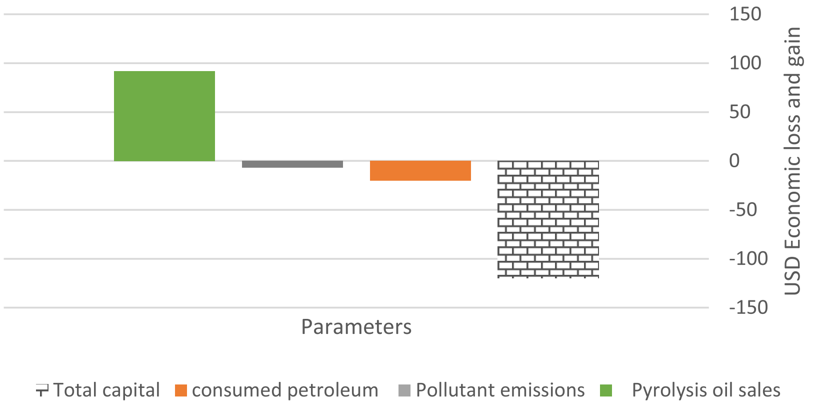

Figure 13. The annual economic indicator within 2023 in Makkah City, with a positive outcome indicator due to the energy recovery process and negative indicators due to consumed petroleum, pollutant emissions, and total capital.

3. USD 7 million represents the cost of landfill pollutant gases, climate change, greenhouse gas effect, and global warming due to Zz-PW, as discussed and mentioned in Section 3.4.1.

b. Economic Gain with a Positive Indicator.[77−79] Figure 13 shows the annual economic gain indicator for 2023 in Makkah City, with a positive outcome indicator owing to the energy recovery process mentioned in Section 3.3, including the following:

1. USD 92 million represents the sale of 4.6 million barrels of the pyrolysis oil product due to the energy recovery process, where according to the pyrolysis oil market (extracted from Zz-PW), the price was in the range USD 25−20 per barrel (barrel, equivalent to 210 L) with density; 0.81 g/cm^3, gross calorific value; 10,500 kcal/kg, sulfur content; 0.03%, and moisture content 0.05%.
2. At the end of 2023, USD 27 million economic losses with negative indicators changed into economic gain indicators with positive outcomes in the ECO program, and the profits will be gross to USD 109 million, as shown in Figure 14.

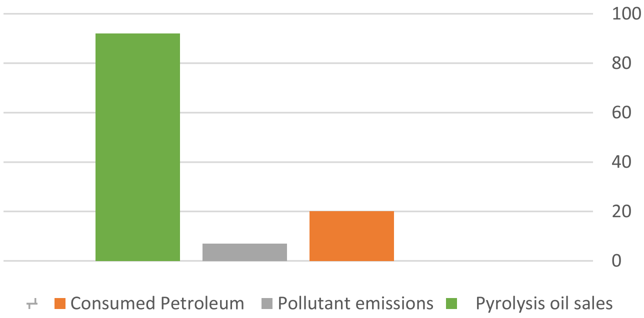

Figure 14. Gross profits and economic gains indicator sources in Makkah City, for the PWTE process.

3. The rate of return (ROR%) of the project reaches 80%.
4. In the perspective future in 2024 and 2025, the payback period (PBP) will reach 1.2 years, and with gross profits reaching 129%.

3.4.3. Roadmap for Zz-PW Management.

a) Makkah is expecting 30 million pilgrims by 2030, putting the city in a dire situation: more pilgrims and more Zam-Zam plastic waste. Landfill site selection is a difficult puzzle: landfill waste management selection, using a geographic information system and analytical hierarchical process according to political, social, economic, and environmental factors.[79]
b) Even though K.S.A. tries to solve the problems created due to the accumulation of Zz-PW in landfills, it is still considered a source of public health problems due to the breakdown of plastic waste. With the expectation of completion by 2030, more landfills with large-scale areas are needed.
c) The following items represent the deficiencies of landfills, which prompted K.S.A to move away from landfill as a conventional method of Zz-PW management and replace it by nonconventional plasma gasification technology:[80]
d) The thermal and combustion processes are growing, with impossible thermal control.
e) Landfills are harmful to public health due to indirect infectious diseases.
f) Climate change is caused by the large volume of emissions from gas toxics.
g) Negative economic indicator evaluation due to pollution costs without any profit, income, or cash back.
h) Figure 15 shows an experimental roadmap and conclusion for the gain in the positive economic indicator ending in payback, cashback, and gain gross profit stages owing to the use of thermal plasma to prove the energy recovery from plastic waste. On the other hand, there is a degradation of the environmental vision by gas emission and groundwater pollution due to the accumulation of Zz-PW in the landfill for a long time. Gas emissions, in turn, trap heat to produce global warming plus acid rain, ending in climate change stages that represent economic losses, zero outcome, and a negative economic indicator.[81]

4. CONCLUSIONS

The remapping of environmental and public health visions for chemical agents emitted from landfills represents health challenges in the Kingdom of Saudi Arabia's (K.S.A.) 2030 vision. The environmental vision on Zz-PW is described as the rapid transformation of sustainable development from Zz-PW management in landfills to energy recovery technology as the best environmentally friendly method by exploring the operating characteristics of air torches, including applied

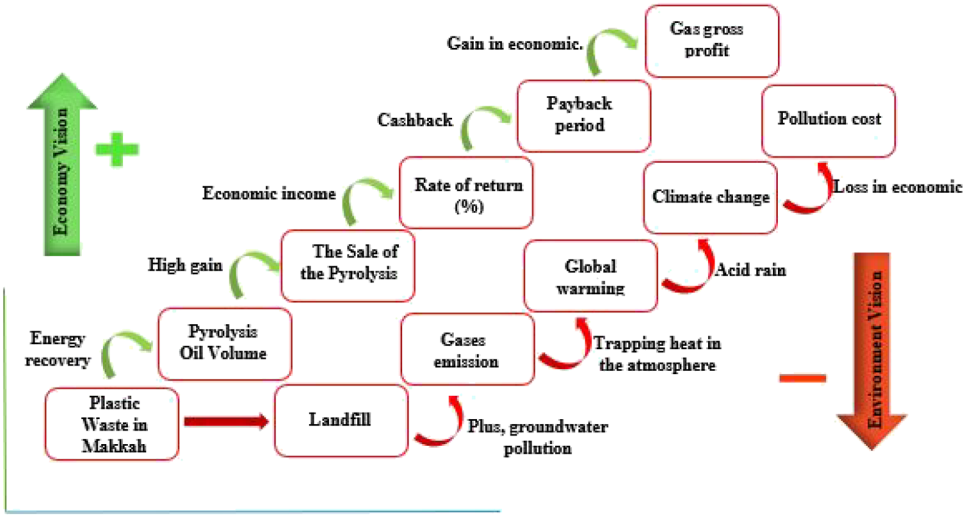

Figure 15. A roadmap for economic and environmental indicators.

power, applied flow rate, torch efficiency variations, and the characteristics of the emerging jet, such as mean temperatures, velocities, and radiation wavelengths.

Furthermore, using the SimaPro program provides counting and managing plastic waste, polluted emissions from landfills, and pollution costs; an annual statistical survey of plastic; and analysis of landfill emissions, emission category ratios, and moisture content percent per ton and per year.

Additionally, environmental, economic, and strategic sustainability dimensions of plasma treatment of Zz-PW in Makkah City were evaluated for the period from 2004 to 2022. The annual decomposition emissions from landfills and pollution costs from Zz-PW were calculated using SimaPro software and the hazard analysis model. It was found that the amount of gases emitted by Zz-PW in landfills increased from 128,000 Mg in 1994 to 227,000 Mg in 2022. Plasma gasification was determined to be the greenest method for Zz-PW treatment in terms of environmental, economic, and strategic visions, as it resulted in the recovery of 3.17×10^5 t of pyrolysis oil in 2022, with an equivalent energy of 12.55×10^9 MJ. Additionally, a roadmap for the economic and environmental visions was introduced, which resulted in an economic gain with a rate of return (ROR%) of 80%, a payback period (PBP) of 1.2 years, and a gross profit of 129%.

Our research directions for future sustainable waste treatment solutions will be characterized by PWTE recovery using a plasma reactor and based on the following visions: the first vision will be related to the economic evaluation of carbon and slag using PWTE technology, with reduced CO_2 emissions from the oxidation of plastic as a strategic view; the second vision has to do with the prospect of testing and validating the conversion process of slaughterhouse waste and later diverse difficult waste streams into usable energy products with the same test setup. The SimaPro software and hazard analysis model will be validated.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.4c01084.

> Amount of plastic *Zam-Zam* waste in the city of Makkah from 1994 up to 2022, tons per year; values and amounts of energy parameter units; and Ecopoints method in the SimaPro method (PDF)

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Notes

The authors declare no competing financial interest.

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