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Examining the environmental and economic dimensions of producing fuel from medical waste plastics

Tıbbi atık plastiklerden yakıt üretiminin çevresel ve ekonomik boyutlarının incelenmesi

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Abstract

The increasing challenge of managing medical waste plastics has spurred the exploration of various waste management strategies. This comprehensive study delves into the environmental and economic aspects of different approaches to medical waste management; incineration, landfilling, and pyrolysis, with a specific focus on plastics-to-fuels conversion. The study provides a critical assessment of these methods, highlighting their sustainability and environmental implications. In this study, it was conducted a Life Cycle Assessment (LCA), with a particular focus on comparing greenhouse gas (GHG) emissions. Notably, landfill, a commonly employed method for medical waste disposal, was found to produce lower GHGs than incineration and pyrolysis. However, it does have the drawback of leaving waste as a final product, and its long-term environmental consequences are uncertain, emphasizing the need to explore new technologies. Moreover, this study envisions the conversion of pyrolysis oil from medical waste plastics into a viable fuel source for circular economy, providing a sustainable solution to the growing problem of medical waste plastics. It predicts that in 2030, 799,163 kg of fuel can be obtained from medical waste plastic pyrolysis in the Adana province. As a result, the implementation of a circular economy through the utilization of medical waste plastic pyrolysis oil is projected to yield annual economic profits of up to $4,794,979. Furthermore, this approach has been verified to effectively reduce greenhouse gas (GHG) emissions compared to incineration. Moreover, this innovative strategy has been scientifically validated to substantially reduce greenhouse gas emissions, making it an environmentally responsible and economically promising solution for the future.

Keywords: Pyrolysis oil, Vehicle fuel, Life cycle assessment (LCA), Greenhouse gas (GHG) emissions, Medical waste plastics

Öz

Tıbbi atık plastiklerin yönetiminde giderek artan zorluklar, çeşitli atık yönetimi stratejilerinin araştırılmasını teşvik etmiştir. Bu kapsamlı çalışma; plastiklerin yakıtlara dönüştürülmesine özel olarak odaklanarak, tıbbi atık yönetimine yönelik farklı yaklaşımların (yakma, düzenli depolama ve piroliz) çevresel ve ekonomik yönlerini incelemektedir. Çalışma, bu yöntemlerin detaylı bir değerlendirmesini sunarak sürdürülebilirlik ve çevresel etkilerini vurgulamaktadır. Bu çalışmada, özellikle sera gazı (GHG) emisyonlarının karşılaştırılmasına adına bir Yaşam Döngüsü Analizi (LCA) yapılmıştır. Özellikle, tıbbi atık bertarafı için yaygın olarak kullanılan bir yöntem olan düzenli depolamanın, yakma ve pirolize göre daha düşük sera gazı ürettiği tespit edilmiştir. Bununla birlikte, atığı nihai ürün olarak doğaya bırakma dezavantajına sahiptir ve uzun vadeli çevresel sonuçları belirsizdir, bu da yeni teknolojilerin araştırılması ihtiyacını ortaya koyar. Ayrıca bu çalışma, tıbbi atık plastiklerden elde edilen piroliz yağının döngüsel ekonomi için uygun bir yakıt kaynağına dönüştürülmesini ve büyüyen tıbbi atık plastik sorununa sürdürülebilir bir çözüm getirilmesini öngörmektedir. Adana ilinde 2030 yılında tıbbi atık plastik pirolizinden 799.163 kg yakıt elde edilebileceği öngörülmektedir. Sonuç olarak, tıbbi atık plastiklerinden elde edilen piroliz yağının kullanılması yoluyla döngüsel bir ekonominin uygulanmasının yıllık 4.794.979 $'a kadar ekonomik kazanç sağlayacağı öngörülmektedir. Ayrıca, bu yaklaşımın sera gazı (GHG) emisyonlarını yakmaya kıyasla etkili bir şekilde azalttığı doğrulanmıştır, bu da yakıt eldesini gelecek için çevresel açıdan sorumlu ve ekonomik açıdan umut verici bir çözüm haline getirmektedir.

Anahtar kelimeler: Piroliz yağı, Taşıt yakıtı, Yaşam döngüsü analizi (YDA), Sera gazı (GHG) emisyonları, Tıbbi atık plastikleri

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1 Introduction

In the past 65 years, of the 8.3 billion tons of plastic produced worldwide, only 12% was burned, 9% was recycled, and a staggering 79% remained in the environment. According to the World Economic Forum, without intervention, by 2050, there will be more plastic waste in the oceans than fish [1].

Approximately 33% of plastic waste finds its way into terrestrial environments or freshwater ecosystems. The majority of this plastic undergoes degradation, forming particles smaller than five millimeters, referred to as microplastics, and these degrade even further into nanoparticles, measuring less than 0.1 micrometers in size. The concern lies in the fact that these particles are infiltrating the food chain [2]. With current plastic consumption and waste management practices, it is expected that plastic waste reaching oceans and seas will further increase. After Egypt and Italy, Türkiye ranks as the third-largest contributor of plastic waste to the Mediterranean, according to a 2018 report by the World-Wide Fund for Nature. This report states that 144 tons of plastic waste from Türkiye, enters the Mediterranean daily. Plastics, particularly disposable plastic packaging and items, discarded cigarette filters, abandoned fishing nets, and nearly invisible microplastic particles measuring less than 5 millimeters in size, are frequently encountered in environment. The significant increase in plastic imports in Türkiye, particularly following China's bans on plastic imports in 2018, is a significant factor contributing to plastic pollution [3]. In 2015, while 381 million tons of plastic were produced, 55% of plastic waste was disposed of in landfills, 25% was incinerated (leading to carbon emissions), and only 20% was recycled. Without any intervention, United Nations Environment Programme (UNEP) estimated that by 2040, the annual accumulation of plastic waste in the oceans would increase from the current 11 million tons to 29 million tons, nearly tripling. Heads of state, environmental ministers, and representatives from 175 countries made a historic decision in March 2022 at the UN Environment Assembly in Nairobi, Kenya, to end plastic pollution and create an internationally legally binding agreement by the end of 2024 [4].

The swift build-up primarily results from the exponential growth in virgin plastic manufacturing, the protracted decomposition of discarded plastic waste, and the limited utilization of incineration (12%) and recycling (9%) [5]. It is evident that the world produces huge amount of plastic annually, and most of it poses harm to the environment and society after use. Scaling up the circular economy for plastics requires systematic changes in waste management and recycling, adopting a holistic approach to reduce, reuse, and recycle plastics [6].

1.1 Medical waste

Waste generated within healthcare facilities during diagnostics, treatment, and immunization constitutes a distinct category referred to as healthcare waste [7]. Healthcare waste can be categorized into two primary types; hazardous waste and non-hazardous or general waste. The World Health Organization (WHO) estimates that approximately 10-15% of healthcare waste falls into the hazardous category, encompassing infectious waste, pathological waste, sharps waste, chemical waste, pharmaceutical waste, cytotoxic waste, and radioactive waste [8]. Managing healthcare waste entails a series of steps, including segregation, collection, storage, transportation, treatment, and final disposal. This aspect demands particular attention in developing countries due to a lack of awareness and limited resources [9]. Effective segregation forms the foundation of appropriate healthcare waste management and involves sorting waste at the point of origin. Inadequate segregation leads to the mingling of general waste with hazardous waste, resulting in an increase in the volume of hazardous waste. Consequently, the lack of awareness regarding the benefits of segregation presents a substantial challenge to efficient healthcare waste management [10-13]. The healthcare sector was responsible for a substantial 4.4% of global carbon emissions in 2019, an alarming figure for a single source. Among this, an estimated 70% was attributed to medical waste [14].

Furthermore, the COVID-19 pandemic has significantly increased the amount of plastic waste due to single-use plastic sources such as personal protective equipment, test kits, and vaccine syringes [48]. The COVID-19 pandemic has had a profound impact on the generation and management of medical and plastic waste on a global scale. A stark example is seen in Wuhan, China, where hospitals experienced a daily production of approximately 240 tons of medical waste during the pandemic, a substantial increase from the pre-pandemic daily average of under 50 tons. To address this surge, China initiated the construction of waste facilities and deployed 46 mobile waste treatment plants. Meanwhile, the United Kingdom faced its own waste challenges, as research from University College London estimated that an individual using one disposable mask daily for a year could generate an astonishing 66,000 tons of plastic waste [15]. On a worldwide scale, it is estimated that the pandemic has led to the consumption of approximately 194 billion dis-posable masks and gloves each month, as reported in a study published in the Environmental Science and Technology journal. In response, countries like the UK delivered two billion units of personal protective equipment to healthcare workers within the first few months of the pandemic. Moreover, industries related to acrylic sheets and plexiglass saw a remarkable surge in production and sales, underscoring the global demand for protective materials [16].

The exponential growth in medical and plastic waste during the COVID-19 pandemic has presented an urgent and global challenge. Cities grappling with high COVID-19 infection rates have been strained in managing the massive increase in medical waste generated by healthcare facilities. The scale of waste production has overwhelmed waste management and processing capabilities. Given the persistence and high infectivity of the SARS-CoV-2 virus, many countries classify all hospital waste as infectious, necessitating high-temperature incineration, sterilization, and subsequent storage of the remaining ash. However, uncontrolled incineration of medical waste, often containing plastics, poses environmental risks, including greenhouse gas emissions and the release of potentially hazardous compounds such as heavy metals, dioxins, polychlorinated biphenyls, and furans. In response to concerns about COVID-19 transmission, some nations have suspended re-cycling programs and instead prioritized incineration and landfilling for medical waste [17]. Amidst the ongoing COVID-19 pandemic, the generation of medical waste has seen a substantial surge. Effectively managing the disposal of medical waste is vital in order to mitigate the virus's transmission. Given these circumstances, it is imperative to reassess the management of medical waste in urban areas within the context of the COVID-19 pandemic. In numerous hospitals worldwide, a comparative analysis of medical waste generation during the COVID-19 period reveals an escalation ranging from 40% to 50% [18].

The use of single-use plastics has increased significantly with the COVID-19 pandemic. In 2020, it was approximated that 52 billion single-use facial coverings were manufactured, with 72% of these masks disposed of in landfills and 3% finding their way into the oceans [19]. These single-use masks, comprising various polymers such as polypropylene, polyurethane, polyacrylonitrile, polystyrene, polycarbonate, polyethylene, or polyester, contribute significantly to the challenge of managing pandemic-related waste [20].

1.2 Conversion methods of medical waste

In recent times, rapid urbanization has led to a rise in the production of healthcare waste. This upswing is influenced by various socio-economic and environmental factors, including the Human Development Index, life expectancy, mortality rates, and CO_2 emissions [21]. Handling medical waste plastics requires specific strategies due to their health risks. Several methods are employed for the conversion and treatment of medical waste plastics. The selection of waste treatment technologies, such as microwave irradiation, auto-claving, incineration, and chemical disinfection, depends on considerations such as health hazards, environmental consequences, societal acceptance, and economic feasibility. In numerous developing nations, straightforward yet inefficient and high-emission technologies are utilized for healthcare waste treatment due to factors like cost, accessibility, and practicability [22]. In certain instances, medical waste plastics can be incinerated in specialized facilities designed to minimize emissions and recover energy. Incineration is the most well-established and prevalent method for treating healthcare waste; however, it is not environmentally friendly or energy-efficient due to operational inefficiencies in incinerators [23]. Landfilling is a cost-effective and uncomplicated option for waste disposal. Although landfill technologies have progressed in developed nations in recent years, these advancements are limited in developing countries. In these regions, the management of disposal sites is often neglected, and open dumping remains the predominant method of waste disposal. Landfill sites release landfill gases, including methane (CH_4), contributing to global warming, and generate leachate that contaminates underground water sources. Improper landfill management poses risks to both human health and the environment [24]. Landfills can have long-term environmental impacts, including groundwater contamination and space limitations. Landfilling waste plastics has significant and multifaceted environmental consequences. As plastics degrade within landfills, they produce leachate, releasing harmful chemicals into the soil and groundwater, posing risks to water quality. Moreover, anaerobic decomposition of plastics generates methane, a potent greenhouse gas, contributing to climate change. This practice also contaminates soil, rendering it unsuitable for various uses, and poses a threat to wildlife, as animals may ingest or become entangled in plastic debris. Landfills containing plastics are visually unattractive, emit unpleasant odors, and contribute to noise pollution. Additionally, the long-lasting nature of plastics exacerbates their persistence in the environment, making it crucial to reduce plastic consumption, promote recycling, and develop alternative materials while implementing proper waste management practices to mitigate these adverse effects [25].

Autoclaving utilizes high-temperature steam for disinfection and sterilization, this method ensures safety but does not address resource recovery or GHG emissions. Chemical treatment processes neutralize hazardous components in medical waste plastics. Proper disposal of treated waste minimizes environmental impact. Using microwave technology efficiently disinfects medical waste plastics, reducing infection risks. Mechanical recycling involves sorting and recycling medical waste plastics, such as containers and equipment, after proper decontamination [26,27].

Disposing of plastic waste on land or in landfills results in the abiotic and biotic deterioration of plastics, during which plastic additives (such as stabilizers, detrimental colorants, plasticizers, and heavy metals) may seep and eventually penetrate different parts of the environment, resulting in contamination of soil and water. Research indicates that even after five years of being incorporated into sewage sludge and soils, microplastics [28] and synthetic polymer fibers are still observable [29].

The production of oil from waste plastics has faced challenges in commercialization, primarily due to the difficulty of producing liquid fuel on a smaller scale and meeting commercial fuel requirements. The process of obtaining fuel from plastic waste requires highly skilled personnel and advanced technology. Findings also show that the mixed composition of plastic waste and its variable quality pose challenges to producing liquid fuel from plastic waste [30].

Onwudili et al. emphasized the need for pre-processing of plastic waste before it enters the process of producing fuel or oil. The highly volatile nature of these plastics requires vaporization to be carried out at higher safety measures. In these aspects, kinetic models and reaction data are crucial in designing reactors [31].

Hossain et al. reported the highest achievable pyrolysis oil yield from medical plastic waste was 53% by weight, obtained at a temperature of 260 °C with a feed size of 0.65 cm^3. Remarkably, the fuel properties of the resulting pyrolysis oil were found to be on par with those of diesel and furnace oil [32].

Aydin and Un stated that medical waste plastic oil can be seamlessly blended with diesel fuel at a 10% ratio and employed in waste collection trucks without necessitating any modifications. Furthermore, this 10% oil addition to diesel not only allows for the use of medical waste plastic as an oil source but also leads to a reduction in CO and CO_2 emissions [33].

Pyrolysis stands as a transformative method for managing plastic waste, involving the thermal decomposition of plastics through a process known as destructive distillation. This process essentially reverses the physical phase and chemical composition of waste plastics. Long-chain polymer molecules within plastics undergo conversion into shorter and less complex molecules. Pyrolysis necessitates the application of high temperatures for a brief duration while excluding oxygen. The key determinant of the range of pyrolysis products lies in the design of the pyrolysis reactor itself. Various types of pyrolysis reactors are employed in processing waste plastics through pyrolysis. When crafting a pyrolysis reactor, two primary criteria come into play: the maintenance of efficient heat transfer and the minimization of residence time. A lower heat transfer rate and an extended residence period can lead to an increased production of char and gas products. Among the commonly reviewed types of reactors used in plastic waste treatment through pyrolysis are batch and semi-batch reactors, fixed bed reactors, fluidized bed reactors, conical spouted bed reactors, auger reactors, and microwave-assisted reactors [34,35]. Pyrolysis is a method used to thermally break down large polymeric molecules found in medical waste into smaller molecules, typically in an environment with limited oxygen or completely devoid of oxygen. Plastic waste can be subjected to thermal degradation within the temperature range of 540–830 °C in the absence of oxygen [36]. Thermal pyrolysis requires an energy input since it is an endothermic process. On the other hand, catalytic pyrolysis involves the use of catalysts to accelerate the chain-breaking reactions. Variations in the feedstock and operational conditions during pyrolysis can result in different final product states, including solid, liquid, and gas [37]. Researchers demonstrated that pyrolysis technology has the potential to convert medical waste into valuable products, such as biofuel for alternative energy sources and biochar for adsorption purposes [38]. The pyrolysis of medical waste can yield liquid fuels that can be utilized as an energy source for powering tur-bines and generators, leading to electricity generation [39].

The FTIR analysis indicated that face masks are composed of polypropylene, while gloves are made of PVC thermoplastic polymer. These materials can be readily converted into fuel energy through the process of pyrolysis. Notably, we observed endothermic peaks at approximately 431 ℃ for medical gloves and 175 ℃ for surgical masks, which correspond to the respective melting points of PVC and polypropylene plastic polymers [40]. Singh et al. stated that for studies; at elevated temperatures, a substantial increase in gaseous components were observed, resulting in a reduction in char content and a concurrent rise in the wax fraction within the oil product. Gas production was assessed through time-dependent pressure analysis of the procedure. The primary gases generated were alkene compounds, including methane, ethane, propane, and n-butane [41]. Additionally, it has been suggested that pyrolysis technology could potentially create more job opportunities based on a social management analysis [42].

The oil derived from plastic waste typically contains a higher sulfur content when compared to traditional fuel oil. This necessitates users of pyrolysis oil to install environ-mental protection devices to cleanse the emitted flue gases. This has raised concerns among users and environmental advocates due to the potential for sulfur emissions leading to increased instances of acid rain. Pyrolysis oil exhibits a higher sulfur content in contrast to conventional gasoline, kerosene, and commercial-grade diesel. As an example, the sulfur content in waste pyrolysis oil was measured at 0.246%, whereas diesel oil contains 0.15% and gasoline just 0.014%. When mixed plastics are utilized, studies have re-ported a 4.8% sulfur content in thermal pyrolysis and 4.36% in catalytic pyrolysis liquid fuel derived from mixed waste plastics [43,44].

The primary products of plastic pyrolysis include pyrolysis oil, a gas rich in hydro-carbons with a heating value ranging from 25 to 45 MJ/kg, a density ranging from 0.77 to 0.86 g/cm^3, and a cetane number between 40 and 60, making it an ideal source for process energy recovery, as well as char [45,46]. Consequently, the pyrolysis gas can be reintroduced into the process to extract energy for process heating, significantly reducing reliance on external heat sources.

The utilization of pyrolysis oil extends to serving as a viable transport fuel, with applications spanning gas turbine fuels, diesel generators, the aviation industry, and jet propulsion. When adequately mixed with diesel at appropriate proportions, pyrolysis oil can be applied in a variety of scenarios, including as fuel for boiler furnaces, in the production of lubrication oil, waxes, and as a feedstock for plastic production. The process of pyrolyzing waste plastic offers a more sustainable solution to the issue of plastic waste pollution, reducing dependence on fresh oil resources. Increased investment in and the adoption of waste plastic pyrolysis oil will alleviate the demand for newly extracted fossil fuels. Moreover, blending it with renewable fuels for power generation positions plastic waste pyrolysis as a notable contributor to the ongoing energy transition toward low-carbon power generation and consumption. [47].

Policymakers and healthcare facilities should prioritize waste management strategies that prioritize the reduction of GHG emissions, environmental protection, and public health.

Overall, the choice of waste disposal method should consider a broader range of factors, including GHG emissions, resource recovery, energy production, and long-term environmental impact. Pyrolysis holds promise for converting plastic waste into valuable products, but further research and technological advancements are needed to minimize its GHG emissions and maximize its efficiency. Additionally, a comprehensive waste management strategy may involve a combination of methods to achieve both environmental and resource recovery goals effectively.

1.3 Life cycle assessment (LCA) studies

Life cycle assessment (LCA) serves as a valuable tool for evaluating the environmental impacts associated with waste management scenarios. It encompasses various emission-related factors, including energy and material flows, the effects of inputs and outputs, and aids in result interpretation to make well-informed decisions [69].

The ISO 14040 standard defines Life Cycle Assessment (LCA) as a technique for assessing the environmental aspects and potential impacts associated with a product. LCA involves four main steps Initial step involves defining the specific goals and boundaries of the LCA study. It outlines what is being assessed and what environmental aspects and impacts are of interest. Life Cycle Inventory (LCI) stage encompasses data collection and the development of a calculation procedure to quantify the inputs and outputs of the system under investigation. It involves identifying and quantifying all relevant materials, energy, and emissions associated with the product or process. The results from the LCI are related to environmental impact indicators and categories. This step is where the raw data collected in the LCI are transformed into meaningful environmental impact assessments. The interpretation phase is essential for evaluating the results of the LCA. It involves checking for completeness, consistency, sensitivity, accuracy, and uncertainty of the results obtained. It ensures that the findings are reliable and can be used to inform decision-making [70].

LCA is a versatile approach that can be applied in various contexts, such as to com-pare the environmental performance of two different systems, products, or processes. This might include assessing their energy usage, total life cycle cost, and greenhouse gas (GHG) emissions [71].

LCA provides a systematic framework for assessing and comparing the environmental impacts of different options, allowing stakeholders to make informed decisions that consider the environmental aspects of their choices. In this study, LCA processes related to incineration, pyrolysis, and landfill methods, which are among the disposal methods of medical waste, are examined and compared.

The evaluation of environmental consequences associated with the management of mixed plastic waste reveals significant disparities depending on the chosen disposal method. Pyrolysis process yields a relatively modest release of 0.739 kilograms of carbon dioxide equivalent (CO_2e) for every kilogram of mixed plastic waste processed. In stark contrast, the incineration of mixed plastic waste leads to a much larger carbon footprint, emitting 1.777 kilograms of CO_2e per kilogram of waste. On the other hand, the disposal of mixed plastic waste in landfills results in a notably lower environmental impact, contributing just 0.154 kilograms of CO_2e to the overall environmental balance [22,61].

1.4 Medical waste management in Türkiye and Adana city

According to data from the Ministry of Environment, Urbanization, and Climate Change in Türkiye for the year 2019, approximately 3.7 million tons of plastic waste, which is 12% of the annual 31 million tons of municipal waste produced in Türkiye, are generated each year. Türkiye's per capita plastic consumption has increased by approximately 10% in the last three years, surpassing 90 kilograms [48].

In the context of the 11th Development Plan of the Republic of Türkiye, the following key approaches are recommended for environmental and natural resource management:

- Emphasizing a holistic approach that considers social inclusivity and sustainable environmental practices within the framework of economic development.
- Contributing to the sustainable management of resources through innovation and technological advancements.
- Adopting comprehensive and ecosystem-based approaches in sectoral and project-level planning.
- Transitioning to a new environmental management approach at the macro level, prioritizing sensitive areas.
- Promoting the principles of a circular economy throughout all aspects of life, efficient waste management, and a zero-waste approach [49].

Türkiye recycles approximately 1.1 million tons of plastic waste annually. Türkiye's plastic raw material sector, which results in a significant trade deficit, relies heavily on imports, accounting for 80%. The plastic recycling sector has the potential to reduce the plastic raw material trade deficit by 36% by 2030. It is expected that the global market size for the plastic recycling sector will reach $900 billion in 2050 at current prices. If Türkiye continues its current growth trajectory, it will have a $3.2 billion industry by 2025 and a $63 billion industry by 2050 [50].

The increasing problem of plastic waste in recent years has created various environmental issues worldwide and in Türkiye. In 2020, it was found that waste services were provided in 1,387 out of 1,389 municipalities in Türkiye. Of the waste collected in municipalities with waste services, 69.4% goes to sanitary landfills, 17% to municipal dumps, and 13.2% to recycling facilities. Only 0.4% is disposed of by burning in the open, burying, or dumping in rivers or land. The average daily waste generated per person in municipalities with waste services is calculated as 1.13 kilograms. Additionally, 110,000 tons of medical waste were collected from healthcare facilities.

Of the total medical waste, 23.7% was collected from healthcare facilities in Istanbul, 7.8% from Ankara, and 5.8% from Izmir. Of the collected medical waste, 90.6% was sterilized and sent to storage areas, while 9.4% was sent to incineration facilities for disposal [51].

The management of medical waste in Türkiye, as outlined in Law No. 5216 on Metropolitan Municipality and the Regulation on the Control of Medical Waste, entails clear responsibilities and procedures. These responsibilities are divided between metropolitan municipalities in metropolitan areas and municipalities in areas without metropolitan municipalities. The Regulation on the Control of Medical

Waste, effective since January 25, 2017, and published in the Official Gazette No. 29959, establishes the fundamental principles for the handling of medical waste generated by healthcare institutions [52].

According to this regulation, medical waste is subject to rigorous control measures throughout its lifecycle. Adana Metropolitan Municipality, as an example, adheres to these guidelines by periodically inspecting waste collection from healthcare institutions within the province. The inspections ensure that medical wastes from hospitals and other healthcare facilities are collected and temporarily stored in compliance with the regulation, utilizing appropriate waste bags. The collected medical wastes are then transported and managed using non-compacting vehicles that conform to the regulation's specifications. Notably, certain items, such as serum bottles and glass items, are collected separately [53].

To render the collected medical waste harmless, a medical waste sterilization unit is employed, with the capacity to process 8-10 tons of medical waste daily in Adana. The sterilization process utilizes pre-shredding autoclave technology and employs steam at a temperature of 135°C. This rigorous sterilization procedure ensures the safe management of medical waste, mitigating potential health and environmental risks [30].

In alignment with the "polluter pays" principle, a financial system has been established under the regulation to manage the expenses associated with medical waste collection, transportation, and disposal. Healthcare institutions, as the generators of waste, bear the responsibility for these costs and make payments to the municipalities accordingly. The determination of fees related to medical waste management is carried out by Provincial Local Environmental Boards.

The collected medical wastes are documented with a receipt at the end of the month, summaries are prepared, and after preparing the summary for all healthcare institutions, the municipality invoices them through the municipal software system. The same procedures for medical waste are also applied to pathological wastes. Pathological waste refers to tissues, organs, body parts, body fluids, and fetuses resulting from surgical procedures, autopsies, anatomy, or pathological studies. Detailed medical waste data of Adana province between 2014 and 2021, are shown in Table 1.

Table 1. Adana province medical waste amount (2014-2021) [30]

Year	Medical waste amount (kg/year)	Amount of Pathological Waste (kg/year)	Total (kg/year)
2014	2,795,975	-	2,795,975
2015	3,018,300	-	3,018,300
2016	3,145,240	12,632	3,157,872
2017	3,190,990	12,133	3,203,123
2018	3,296,083	14,436	3,310,519
2019	3,084,679	14,741	3,099,420
2020	3,730,256	22,017	3,752,273
2021	3,759,115	18,546	3,777,661

The primary objective of this research endeavor was to conduct a comprehensive assessment of the various disposal methodologies for medical waste, which possess the potential for substantial environmental detriment. This evaluation encompassed a detailed analysis of Adana city's medical waste values and sought to provide a forward-looking projection in the context of future environmental impact mitigation. As seen in Figure 1, obtaining a product resulting in a vehicle fuel instead of a disposal method resulting in landfill is the method of approach of this study. The precise research objectives of this investigation encompass; (a) the quantification of the anticipated quantities of medical waste in Adana City and (b) Comprehensive assessment of environmental aspects associated with various approaches to the management of medical waste plastics using LCA.

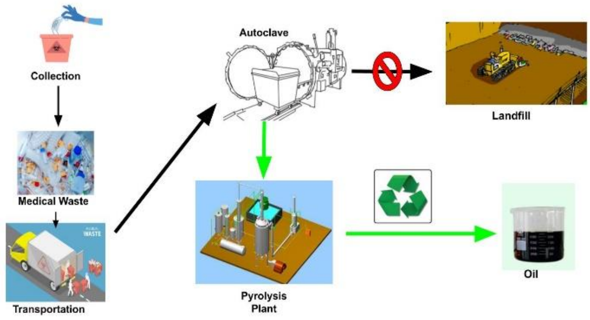

Figure 1. Method of approach

2 Material and method

The estimation of future quantities of medical waste is a critical concern for public health and environmental planning in urban areas like Adana city. Linear regression, a widely employed statistical method, is chosen for this study due to its suitability in modeling the relationship between a dependent variable (medical waste) and an independent variable (population). The selection of this method is rooted in its appropriateness in the context of population growth and its concomitant impact on the generation of medical waste.

In this specific case, linear regression is applied to project medical waste quantities (the dependent variable) based on the temporal variable representing the years from 2014 to 2021. The linear regression equation employed is represented at Equation (1).

$$\text{Medical Waste Amount (kg/year)} = \beta 0+\beta 1.Xi \quad (1)$$

Medical waste amount is the predicted medical waste amount in kilograms per year.

- β0 denotes the intercept, representing the estimated waste amount when the population is zero.
- β1 signifies the slope of the regression line, indicating how the waste amount changes for a unit change in population (Xi).

To conduct this analysis, data is meticulously collected from two primary sources:

- Population Data: Historical population data for Adana city, Türkiye, spanning from the years 2014 to 2021, is obtained. The population data for the city of Adana was sourced from the Turkish Statistical Institute. Additionally, projected population estimates for the years 2022 to 2030 are considered. Population data serves as the independent variable in the linear regression model, illustrating the effect of the changing population on medical waste generation.

- Medical Waste Data: Historical data on medical waste amounts for Adana city is collected, covering the years 2014 to 2021. This data serves as the dependent variable in the analysis and is crucial for estimating future medical waste quantities.

To estimate the population growth over time, also the simple exponential growth model was used (Equation 2).

$$\text{Population (t)} = \text{Population (2014)} * e \wedge (r * (t - 2014)) \quad (2)$$

where:

- Population (t) is the population in the year 't.'
- Population (2014) is the population in the base year 2014.
- 'r' represents the assumed annual population growth rate.
- 'e' is the base of the natural logarithm (approximately 2.71828).

A simple linear regression model is applied to predict medical waste amounts based on population. The simplicity of this model is suitable for this study as it allows us to discern the direct linear relationship between the population and the generation of medical waste. Using the linear regression equation, the projected population estimates for the years 2022 to 2030 are incorporated. Through this, it is possible to calculate the estimated medical waste amounts for each year. This forecasting of medical waste quantities plays a pivotal role in developing policies and infrastructure for waste management and disposal in Adana city, taking into account the expected population growth and its associated implications for healthcare waste. The utilization of linear regression in estimating future medical waste quantities in Adana city is a scientifically sound approach, grounded in statistical principles. By examining the linear relationship between population and medical waste, this study contributes to informed decision-making for the sustainable management of medical waste in the region.

When examining the examples from around the world, healthcare facilities within the United States produce an approximate daily waste volume of 14,000 tons. It is approximated that within this daily waste output, plastic packaging and plastic items contribute to roughly 20-25 percent. Furthermore, a substantial 85 percent of the generated waste is classified as non-infectious [54].

Medical waste primarily comprises various components, including paper, plastics, cotton, metals, and other materials [55]. The table presented below (Table 2) displays the results obtained from the global content analysis of medical wastes. Among the plastics commonly encountered in medical waste (constituting 33% by weight), one can identify polyethylene terephthalate, polyolefins (such as high density polyethylene, low density polyethylene, and polypropylene), polyurethanes, polystyrene, and polyvinyl chloride (making up 60% of the total plastic content in medical waste). These plastics hold significant potential as hydrocarbon sources for the chemical industry. Medical waste stems from disposable items like syringes, gloves, tubes, bags, trays, prosthetics, medication containers, diapers, and more [56].

Table 2. Global analysis of medical waste content [57]

Material Constituents	Global Composition Range (weight %)	Türkiye Constituent (weight %)
Paper/Carton	15 - 40	21
Plastics	10 - 60	40
Glass	5 - 15	7
Metal	1 - 10	2
Cloth/Cotton/Gauze	10 - 25	10
Other	5 - 25	20

For this study, medical waste generated during an ordinary day in a health facility in Adana was examined. The data obtained from the examination carried out under safety conditions on medical wastes placed in red bags revealed that the composite plastic composition constitutes 35% of the total medical waste. This medical waste consists of various plastic components such as face masks, syringes, infusion sets, medical gloves, blood and infusion bags. All of which are key components of the medical waste plastic spectrum. Upon analyzing medical waste from hospital, the predominant presence of polypropylene and polyvinyl chloride was observed, leading to the consideration of employing a pyrolysis method tailored to these specific materials.

Polypropylene (PP) is widely utilized in various medical applications, primarily within the packaging sector, due to its exceptional chemical resistance, high transparency, toughness, and resistance to bacterial contamination. Medical-grade PP also exhibits excellent performance under steam sterilization conditions. PP is the material of choice for manufacturing disposable syringes, offering numerous advantages over traditional glass syringes, including its lightweight nature, crack resistance, leak-proof design, easy disposability, environmental friendliness, sterilizability, and exceptional clarity. Additionally, PP is employed in the production of non-absorbable surgical sutures, particularly in vascular anastomosis procedures [56].

The findings elucidate the successful chemical conversion of mixed waste plastic samples into volatile fractions with notable yields ranging from 36.9% to 59.6% [58]. Rasul et al. resulted a viscous, brownish liquid oil to be 52% by weight, and the liquid's gross calorific content was measured at 41.32 megajoules per kilogram, a value similar to that of conventional diesel [59]. The extent of this conversion was intricately tied to the composition of the feed polymers present in the samples. This outcome underscores the promise of an efficacious transformation of waste plastics, wherein the inherent polymers play a pivotal role in dictating the outcome of the process. The resulting products manifested a complex composition predominantly characterized by paraffinic, olefinic, and aromatic compounds. These compounds exhibited distinct carbon number distributions, encompassing C_1-C_4 for fuel gases, C_5-C_{17} for gasoline, and C_{11}-C_{28} for light oils. Such variability in carbon numbers reflects the diverse nature of the polymeric constituents within the medical waste plastics, particularly the intertwined presence of PVC and PP. Based on the insights gleaned from the reviewed literature, it has been established that the oil production through pyrolysis is anticipated to reach 55% owing to the presence of PVC in medical waste plastics.

This study is documented in Supplementary-S.1., which was compiled with a specific focus on non-hazardous medical waste, constituting 85% of the total medical waste stream. It's important to note that the remaining 15% falls under the category of entirely hazardous waste, necessitating distinct disposal techniques. Within the non-hazardous segment, encompassing 85% of the waste, the approach involves the post-sterilization separation of plastics, followed by their transformation into oil through the pyrolysis process.

An initial approximation of the volume of plastics amenable to recycling within a hospital can be derived through the subsequent calculation at Equation 3 [60].

Total Estimated Quantity of Plastics Available for Recycling Annually (in tons) = Total Annual Hospital Waste Amount (in tons) × 35% (Adana City's plastic content od medical waste) × 85% (non-hazardous waste content of total medical waste) (3)

2.1 LCA methods

Establishing a system boundary is a crucial initial stage in the LCA analysis, and it has a direct impact on the data inventory and final results. In this study, it was defined the scope as "cradle-to-gate," which means that the evaluation of a product's environmental impact from raw material extraction to the point of factory gate departure. It focuses on the production stages leading up to manufacturing and packaging, offering insights into how to reduce a product's environmental footprint through process optimization, sustainable material choices, and resource efficiency enhancements. The data inventory includes information related to emissions, energy usage, and materials at this particular stage. These data are then translated into specific effects on human health and the environment through the use of a developed LCA model [72]. Figure 2 shows the system boundary of this LCA study.

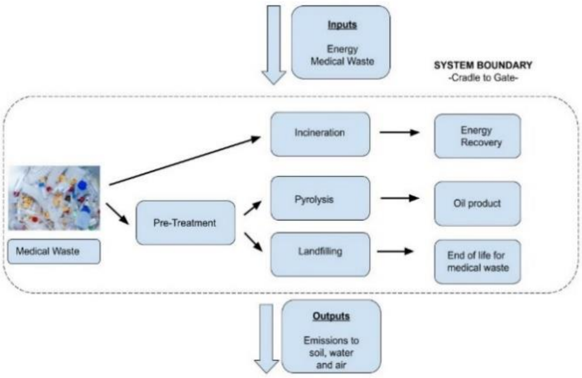

Figure 2. System boundary of medical waste treatment methods of LCA study

For this study openLCA 1.10.3 was used. This application, which outlines the material and energy flows involved throughout the product life cycle, is typically employed to optimize the LCA methodology. By inputting unit process values as the input and output parameters for each process within the production system, the LCA software computes the environmental impacts based on the provided data and the information stored in its database [73]. For this study the life cycle inventories were constructed using the Ecoinvent-3 database, supplemented by energy/mass stoichiometry and balance. Furthermore, for the presentation of LCA results in user-friendly formats and easily comprehensible units, the The Tool for the Reduction and Assessment of Chemical and other Environmental Impacts (TRACI) methodology, focusing on midpoint impacts, was employed for impact assessment. TRACI 2.1 is an enhanced version that provides an expanded quantification of various stressors capable of causing potential environmental effects [74].

These discerning findings accentuate the pivotal significance of adopting sustainable waste management practices, with particular emphasis on pyrolysis or environmentally conscientious disposal methods. These eco-friendly approaches serve as formidable allies in significantly curbing the carbon footprint entailed in the disposal of plastic waste. The selection of such environmentally responsible methods emerges as a critical imperative in the endeavor to ameliorate the ecological consequences stemming from the generation and subsequent treatment of plastic waste, as underscored by relevant research.

3 Results

Through the application of linear regression analysis, projections for population and medical waste amounts for Adana City until the year 2030 were calculated and are presented in Table 3.

Table 3. Projected data of Adana city

Year	Projected Population of Adana City	Projected Medical Waste Quantity (kg/year)
2022	2,274,106	3,884,115
2023	2,294,903	4,009,115
2024	2,305,981	4,134,115
2025	2,316,131	4,259,115
2026	2,325,701	4,384,115
2027	2,334,761	4,509,115
2028	2,343,337	4,634,115
2029	2,351,452	4,759,115
2030	2,359,131	4,884,115

Table 4 shows the projected quantity of medical waste plastics for recycling (kg/year) with using Equation 2 and 3.

Table 4. Projected quantity of medical waste plastics for recycling

Year	Projected Quantity of Medical Waste Plastics for Recycling (kg/year)
2022	1,155,524
2023	1,192,711
2024	1,229,899
2025	1,267,086
2026	1,304,274
2027	1,341,461
2028	1,378,649
2029	1,415,836
2030	1,453,024

Table 5 displays the environmental impact results of LCA for the various medical waste treatment methods per kilogram (kg), specifically in terms of greenhouse gas emissions (GHG).

The effective management of medical waste is a pivotal concern, transcending its implications for public health to reverberate significantly within the realm of environmental sustainability. For this study is dedicated to a rigorous exploration of the greenhouse gas emissions entwined with the application of three prevalent medical waste disposal methodologies; pyrolysis, incineration, and landfilling. Figure 3 depicts a graphical representation illustrating the potential utilization of various waste disposal strategies throughout the period leading up to 2030.

Table 5. Environmental impacts of medical waste treatment methods of LCA (per kg)

Unit	Pyrolysis GHG	Incineration GHG	Landfilling GHG
Kg CO_2e	0.906	2.114	0.248

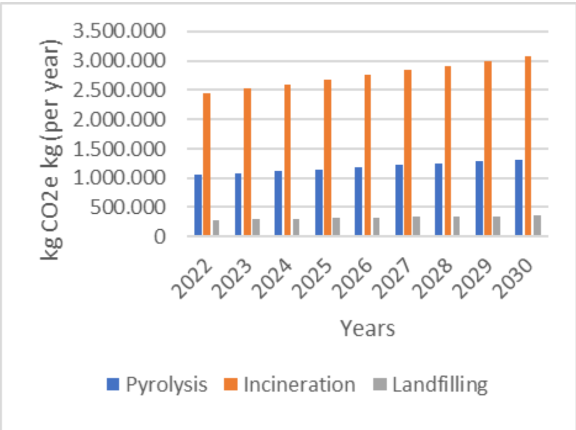

Figure 3. Projections of greenhouse gas emissions for medical waste plastic treatment methods

Pyrolysis, a thermal decomposition process, has gained attention as a production based technology for medical waste treatment. This study reveals that pyrolysis consistently results in lower GHG emissions compared to incineration. In 2022, pyrolysis generated approximately 1,046,904 kg CO_2e, and this value remained relatively stable over the study period. Incineration, a widely adopted method for medical waste disposal, shows higher GHG emissions when compared to pyrolysis.

In 2022, incineration emitted approximately 2,442,777 kg CO_2e, a significantly higher figure than that of pyrolysis. Strategies to mitigate its impact, such as improved technology and emissions control, should be explored to reduce its environmental burden.

The results emphasize the importance of considering the environmental consequences when choosing a medical waste disposal method. Pyrolysis emerges as a more sustainable option, with significantly lower GHG emissions compared to incineration. However, it is essential to acknowledge that pyrolysis may require further research and investment to scale up for widespread adoption. Landfilling, due to its long-lasting emissions and potential groundwater contamination risks, should be minimized in favor of more sustainable alternatives. Landfilling appears to have the lowest GHG emissions among the three methods throughout the years. However, it's essential to keep in mind that while landfilling produces fewer GHG emissions, it does not necessarily contribute to resource recovery or sustainability. The LCA results, particularly the Eutrophication Potential (EP) values indicating long-term impacts, were measured at 0.001487 (kg Neq), for landfill and 0.000227 (kg Neq) for incineration.

The composition and properties of pyrolysis products derived from plastic waste exhibit a remarkable spectrum of diversity, primarily contingent upon several critical factors. These influential determinants encompass the specific plastic type under consideration, the presence of catalysts, and, most notably, the operating temperature [62] Elevated temperature pyrolysis procedures, characterized by their higher thermal energy input, facilitate the breakdown of polyolefin compounds into smaller molecular constituents, resulting in the generation of greater gaseous byproducts. Conversely, pyrolysis executed at lower temperatures engenders augmented oil yields, wherein the resultant oil products manifest a progressively heavier molecular profile as the temperature diminishes. Such insights hold profound significance in the optimization of pyrolysis processes for the tailored production of desired products and the minimization of environmental impacts.

This process presents a chance to extract valuable products valued at up to $6,000 per metric ton from discarded plastics [63].

Table 6 outlines estimates for medical plastic quantities, oil production from waste plastic, and potential revenue. Using this oil in vehicles offers several advantages, including a reduction in plastic waste, resource efficiency, and energy recovery from waste materials.

It also aligns with the principles of a circular economy, diversifies fuel sources, and may lead to cost savings in waste management. Moreover, there are potential environmental benefits, such as reduced greenhouse gas emissions and particulate matter, depending on the source of plastics and emissions control systems in vehicles.

As sustainability awareness grows, market opportunities for products and services using recycled materials, including pyrolysis oil, may emerge. However, realizing these advantages requires attention to factors like the quality of the pyrolysis process, regulatory compliance, and infrastructure development.

Table 6. Potential of medical waste plastics to oil

Year	Medical Plastic Quantity (kg)	Oil Production from waste plastic (kg)	Potential Revenue Annualy ($)
2022	1,155,524	635,538	3,813,229
2023	1,192,711	655,991	3,935,946
2024	1,229,899	676,444	4,058,666
2025	1,267,086	696,897	4,181,383
2026	1,304,274	717,350	4,304,104
2027	1,341,461	737,803	4,426,821
2028	1,378,649	758,256	4,549,541
2029	1,415,836	778,709	4,672,258
2030	1,453,024	799,163	4,794,979

Over the course of a decade from 2022 to 2030, this table reveals a significant upward trend in the medical plastic waste generated, ranging from 1,155,524 kg in 2022 to 1,453,024 kg in 2030. In tandem with this, the column depicting oil production from these waste plastics showcases a consistent increase, beginning at 635,538 kg in 2022 and culminating at 799,163 kg in 2030. These figures represent a promising potential to not only manage healthcare-related waste efficiently but also generate substantial economic value, with potential revenues projected to rise from \$3,813,229 in 2022 to \$4,794,979 in 2030. From a scientific perspective, this data highlights the tangible benefits of exploring waste-to-oil conversion technologies in addressing both environmental concerns and economic opportunities within the medical waste sector.

3.1 The potential of medical waste plastics to oil process

In 2020, the worldwide pyrolysis oil market had a valuation of \$302.1 million. Projections indicate that it will experience a 4% Compound Annual Growth Rate (CAGR) from 2021 to 2031. By the conclusion of 2031, it is anticipated that the global pyrolysis oil market will achieve a value of \$459.3 million [64].

Research findings indicate that incorporating pyrolysis oil derived from medical waste plastics at a 5% rate into the production of new plastic products like HDPE and LDPE can lead to a notable reduction in greenhouse gas emissions, with a range of 18% to 23%. This highlights the potential for pyrolysis oil obtained from medical waste to play a significant role in achieving this reduction [65].

Pyrolysis oil derived from discarded plastic offers a cost-efficient alternative to traditional diesel fuel, which is notably more expensive to produce. According to statistics from the United States Environmental Protection Agency (EPA), an average passenger car releases around 46,000 kilograms of carbon dioxide into the atmosphere every year. Utilizing plastic pyrolysis oil technology, it becomes apparent that the decrease in carbon dioxide emissions is roughly akin to the annual emissions of 13 to 18 standard passenger vehicles [66].

In September 2023, pyrolysis-based chemical recycling plants, with a strong emphasis on mixed plastic waste, particularly polyolefins, constitute roughly 60% of the overall operational chemical recycling capacity in Europe. Forecasts indicate a substantial growth in this sector, with the combined capacity expected to surge nearly sevenfold, reaching approximately 600,000 tonnes per year by 2028 [67].

Pyrolysis oil derived from the conversion of medical waste plastics, presents a compelling opportunity as an eco-friendly vehicle fuel. According to the data provided in the study, pyrolysis can yield a significant volume of oil, with production figures reaching up to 799,163 kg annually by 2030. Notably, this oil, with a calorific value equivalent to traditional fossil fuels, has the potential to reduce greenhouse gas emissions and promote resource efficiency through waste recycling. To harness its benefits, the key step involves refining the pyrolysis oil to meet precise quality standards, ensuring compatibility with vehicle engines and emissions control systems. By incorporating pyrolysis oil into vehicle fleets, organizations and industries can not only mitigate their carbon footprint but also realize potential cost savings in waste management. However, successful adoption necessitates meticulous attention to the quality of the pyrolysis process, compliance with regulatory standards, and the development of a robust infrastructure for fuel distribution. Embracing pyrolysis oil as a vehicle fuel translates sustainability into tangible results, diversifies fuel sources, and actively contributes to a cleaner and more environmentally responsible transportation sector.

4 Conclusion

A comprehensive waste management strategy should address issues such as environmental sustainability, resource recovery and greenhouse gas (GHG) emissions for specialty medical waste plastics. As demonstrated by the data presented this study; pyrolysis emerges as a particularly promising and environmentally friendly option for both waste streams, producing substantial oil volumes, with figures climbing as high as 799,163 kg per year by 2030. An alternative to the landfill method, pyrolysis results in a lower greenhouse gas impact compared to incineration and turns waste into a valuable end product.

The pyrolysis process yields an array of valuable products, including diesel, gasoline, and fuel oil, offering a multifaceted solution to the pressing issue of waste landfills. Beyond its environmental benefits, pyrolysis can also lead to substantial cost savings by reducing the reliance on crude oil imports, thereby contributing to energy security. The global perspective underscores the anticipation of attractive prospects within the worldwide pyrolysis oil market, aligning with evolving energy and sustainability goals.

This comprehensive study illuminates the intricate web of environmental implications associated with various medical waste disposal methods. Pyrolysis, underscored by empirical data that highlights its efficiency in terms of resource recovery and GHG emissions reduction, stands out as the useful choice. The data, including the substantial numbers provided, underscores its potential. In stark contrast, incineration, as demonstrated by the significant GHG emissions figures, imposes a considerable environmental burden. Similarly, landfilling, while appearing to have lower GHG emissions, carries an array of distinct environmental challenges, including groundwater contamination and methane emissions. These findings underscore the paramount importance of transitioning to sustainable waste management practices within the healthcare sector, effectively curbing the carbon footprint associated with medical waste disposal. In an era marked by increasing environmental awareness and the imperative for sustainable solutions, embracing pyrolysis oil as a central pillar in waste management strategies holds the promise of a cleaner, greener, and more sustainable future for especially as vehicle fuel. In this context, future endeavors should prioritize conducting studies on the establishment of legal protocols governing the utilization of oil obtained through the pyrolysis process in vehicles.

The data from the study indicates that pyrolysis has the potential to yield a significant volume of oil, with production figures projected to reach up to 799,163 kg annually by 2030. This information, when considered from a scientific perspective, highlights the viability and potential benefits of pyrolysis as a waste-to-fuel technology.

Harnessing plastic waste through pyrolysis emerges as a more environmentally friendly solution to combat the issue of plastic waste pollution and diminish reliance on virgin oil consumption. The substantial increase in financial investments and the widespread application of pyrolysis oil derived from waste plastic will mitigate the demand for fresh fossil fuels. Furthermore, integrating this pyrolysis oil with renewable fuels for power generation purposes positions plastic waste pyrolysis as a noteworthy contributor to the shift toward low-carbon power generation and energy utilization. Remarkably, this pyrolysis oil, boasting a calorific value equivalent to traditional fossil fuels, holds the potential to curtail greenhouse gas emissions and enhance resource efficiency through effective waste recycling. This scientifically grounded approach offers a robust strategy for addressing environmental concerns by tapping into the energy content of discarded materials.

To fully realize the benefits, it is essential to focus on refining the pyrolysis oil to meet precise quality standards, ensuring compatibility with vehicle engines and emissions control systems. This quality control aspect is a fundamental scientific approach that must be addressed in adopting pyrolysis oil as a vehicle fuel.

The successful adoption of pyrolysis oil as a vehicle fuel not only assumes the meticulous attention to the quality of the pyrolysis process but also requires compliance with regulatory standards. These standards are based on scientific research and environmental considerations.

Moreover, the development of a robust infrastructure for fuel distribution is an essential component of this eco-friendly fuel approach. The creation of this infrastructure should be based on a thorough understanding of scientific and logistical principles, including transportation, storage, and distribution.

Embracing pyrolysis oil as a vehicle fuel assumes the integration of sustainability principles into tangible results. This involves diversifying fuel sources and actively contributing to a cleaner and more environmentally responsible transportation sector through the scientific application of waste-to-fuel technologies.

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Conflict of interest

The author declares that there is no conflict of interest.

Similarity rate (iThenticate): %18

References

[1] Recycling Magazine, Purdue Innovation Converts Plastic Waste into High-Value Fuels. https://www.recycling-magazine.com/2021/06/16/purdue-innovation-converts-plastic-waste-into-high-value-fuels/ , Accessed 26 September 2023.

[2] M. Mittal, D. Mittal and N. K. Aggarwal, Plastic accumulation during COVID-19: call for another pandemic; bioplastic a step towards this challenge?. Environmental Science and Pollution Research, 29 (8), 11039-11053, 2022. https://doi.org/10.1007/s11356-021-17792-w.

[3] T. T. Onay, M. A. Küçüker, S. Vardar ve T. Yücel, Türkiye'de Plastik Atik Sorunu ve Politika Önerileri, WWF-Türkiye (Doğal Hayatı Koruma Vakfı), Boğaziçi Üniversitesi Çevre Bilimleri Enstitüsü (BÜ-ÇEVRE), 2022.

[4] United Nations Environment Programme (UNEP), What You Need to Know About the Plastic Pollution Resolution. https://www.unep.org/news-and-stories/story/what-you-need-know-about-plastic-pollution-resolution/ , Accessed 26 September 2023.

[5] W.T. Chen, K. Jin and N.H.L. Wang, Use of Supercritical Water for the Liquefaction of Polypropylene into Oil. ACS Sustainable Chemistry & Engineering, 7, 3749–3758, 2019. https://doi.org/10.1021/acssuschemeng.8b03841.

[6] Plastics, the Circular Economy and Global Trade, World Economic Forum (WEF), 2020.

[7] E.A. Udofia, G. Gulis and J. Fobil, Solid Medical Waste: A Cross-Sectional Study of Household Disposal Practices and Reported Harm in Southern Ghana. BMC Public Health, 17 (464), 2017. https://doi.org/10.1186/s12889-017-4366-9.

[8] Y. Chartier, J. Emmanuel, U. Pieper, A. Prüss, P. Rushbrook, R. Stringer, W. Townend, S. Wilburn and R. Zghondi, Safe Management of Wastes from Health-Care Activities, 2nd ed., World Health Organization (WHO), Geneva, Switzerland, 2014.

[9] P. Kanchi, Knowledge, Attitude, Practice Regarding Hospital Waste Management among Interns & Nurses of Tertiary Care Hospitals of Navi Mumbai. Scholars Journal of Applied Medical Sciences, 5 (2), 526–530, 2017.https://doi.org/10.36347/sjams.2017.v05i02.044 .

[10] B. Sahiledengle, Self-Reported Healthcare Waste Segregation Practice and Its Correlates among Healthcare Workers in Hospitals of Southeast Ethiopia. BMC Health Services Research, 19 (5910), 2019. https://doi.org/10.1186/s12913-019-4439-9.

[11] K. Aydin and Ç. Ün, Usability of Municipal and Medical Waste Plastics as a Fuel in Diesel Engines. Recent Advances in Environmental and Biological Engineering: Proceedings of the 3rd International Conference on Sustainable Cities, Urban Sustainability and Transportation (SCUST '14), Istanbul, Turkiye, 15-17 December 2014. pp. 34-42, 2014.

[12] H. K. Shinn, Y. Hwang, B. G. Kim, C. Yang, W. Na, J. H. Song and H. K. Lim, Segregation for Reduction of Regulated Medical Waste in the Operating Room: A Case Report. Korean Journal of Anesthesiology, 70 (1),

100–104, 2017. https://doi.org/10.4097/kjae.2017.70.1.100.
[13] V. C. Sengodan, Segregation of biomedical waste in an South Indian tertiary care hospital. Journal of Natural Science, Biology and Medicine, 5 (2), 378–382, 2014. https://doi.org/10.4103/0976-9668.136194.
[14] Medical Waste and Climate Change – The Vicious Cycle We CAN Fix. https://envomed.com/medical-waste-and-climate-change-the-vicious-cycle-we-can-fix/ , Accessed 26 September 2023.
[15] A. D. Igalavithana, X. Yuan, C. P. Attanayake, S. Wang, S. You, D. C. W. Tsang, A. Nzihou, and Y. S. Ok, Sustainable management of plastic wastes in COVID-19 pandemic: The biochar solution. Environmental Research, 212, 113495, 2022. https://doi.org/10.1016/j.envres.2022.113495.
[16] Coronavirus: Disposable Face Masks Creating New Plastic Pollution Crisis, Experts Warn. https://news.sky.com/story/coronavirus-disposable-face-masks-creating-new-plastic-pollution-crisis-experts-warn-12045350 , Accessed 26 September 2023.
[17] A. L. Patrício Silva, J. C. Prata, T. R. Walker, A. C. Duarte, W. Ouyang, D. Barcelò and T. Rocha-Santos, Increased plastic pollution due to COVID-19 pandemic: Challenges and recommendations. Chemical Engineering Journal, 405, 126683, 2021. https://doi.org/10.1016/j.cej.2020.126683.
[18] A. Hanedar, D. I., Çifçi and N. Zafer, The impact of COVID-19 pandemic in medical waste amounts: a case study from a high-populated city of Turkey. Journal of Material Cycles and Waste Management, 24, 1760–1767, 2022. https://doi.org/10.1007/s10163-022-01428-3.
[19] S. Jung, S. Lee, X. Dou and E. E. Kwon, Valorization of disposable COVID-19 mask through the thermo-chemical process. Chemical Engineering Journal, 405, 126658, 2021. https://doi.org/10.1016/j.cej.2020.126658.
[20] Ö. Ak, COVID-19'un Başka Bir Sonucu: Plastik Salgını. TÜBİTAK Bilim ve Teknik Dergisi, 10, 26–35, 2020.
[21] M. Minoglou, S. Gerassimidou and D. Komilis, Healthcare Waste Generation Worldwide and Its Dependence on Socio-Economic and Environmental Factors. Sustainability, 9, 220, 2017. https://doi.org/10.3390/su9020220.
[22] C. Kenny and A. Priyadarshini, Review of Current Healthcare Waste Management Methods and Their Effect on Global Health. Healthcare, 9, 284, 2021. https://doi.org/10.3390/healthcare9030284.
[23] M. E. Boesch, C. Vadenbo, D. Saner, C. Huter and S. Hellweg, An LCA Model for Waste Incineration Enhanced with New Technologies for Metal Recovery and Application to the Case of Switzerland. Waste Management, 34, 378–389, 2014. https://doi.org/10.1016/j.wasman.2013.10.019.
[24] S. De and B. Debnath, Prevalence of Health Hazards Associated with Solid Waste Disposal: A Case Study of Kolkata, India. Procedia Environmental Sciences, 35, 201–208, 2016. https://doi.org/10.1016/j.proenv.2016.07.081.
[25] X. F. Lou and J. Nair, The impact of landfilling and composting on greenhouse gas emissions – A review. Bioresource Technology, 100 (16), 3792-3798, 2009. https://doi.org/10.1016/j.proenv.2016.07.081.
[26] A. Vlasopoulos, J. Malinauskaite, A. Żabnieńska-Góra and H. Jouhara, Life Cycle Assessment of Plastic Waste and Energy Recovery. Energy, 277, 127576, 2023. https://doi.org/10.1016/j.energy.2023.127576.
[27] B. Joseph, J. James, N. Kalarikkal and S. Thomas, Recycling of Medical Plastics. Advanced Industrial and Engineering Polymer Research, 4, 199–208, 2021. https://doi.org/10.1016/j.aiepr.2021.06.003.
[28] V. Krishnamurthi, R. Frota and B. Turna, Management of Vascular Complications. Section IV: Common Surgical Considerations, Chapter 21, Complications of Urologic Surgery Prevention and Management Book Fourth Edition, 2010. ISBN: 978-1-4160-4572-4.
[29] O. A. Alabi, K. I. Ologbonjaye, O. Awosolu and O. E. Alalade, Public and Environmental Health Effects of Plastic Wastes Disposal: A Review. Journal of Toxicology and Risk Assessment, 5 (21), 2019. https://doi.org/10.23937/2572-4061.1510021.
[30] M. O. Amankwa, E. K. Tetteh and G. T. Mohale, The Production of Valuable Products and Fuel from Plastic Waste in Africa. Discover Sustainability, 2 (31), 2021. https://doi.org/10.1007/s43621-021-00040-z.
[31] J. A. Onwudili, N. Insura and P. T. Williams, Composition of Products from the Pyrolysis of Polyethylene and Polystyrene in a Closed Batch Reactor: Effects of Temperature and Residence Time. Journal of Analytical and Applied Pyrolysis, 86 (2), 293–303, 2009. https://doi.org/10.1016/j.jaap.2009.07.008.
[32] U. Som, F. Rahman and S. Hossain, Recovery of Pyrolytic Oil from Thermal Pyrolysis of Medical Waste. Journal of Engineering Sciences, 5 (2), 5-8, 2018. https://doi.org/10.21272/jes.2018.5(2).h2.
[33] K. Aydin and Ç. Ün, Development of Solid Waste Management System for Adana Metropolitan Municipality. Exergy for A Better Environment and Improved Sustainability 2; Aloui, F., Dincer, I., Eds., 115–131, Springer: Cham, Switzerland, 2018. https://doi.org/10.1007/978-3-319-62575-1_8.
[34] H. K. Musale, Y. C. Bhattacharyulu and R. K. Bhoyar, Design Consideration of Pyrolysis Reactor for Production of Bio-Oil. International Journal of Engineering Trends and Technology (IJETT), 5 (2), 83-85, 2013. ISSN:2231-5381.
[35] M. I. Jahirul, M. G. Rasul, D. Schaller, M. M. K. Khan, M. M. Hasan and M. A. Hazrat, Transport fuel from waste plastics pyrolysis – A review on technologies, challenges and opportunities. Energy Conversion and Management, 258, 115451, 2022. https://doi.org/10.1016/j.enconman.2022.11545.
[36] J. Wang, J. Shen, D. Ye, X. Yan, Y. Zhang, W. Yang, X. Li, J. Wang, L. Zhang and L. Pan, Disinfection

Technology of Hospital Wastes and Wastewater: Suggestions for Disinfection Strategy during Coronavirus Disease 2019 (COVID-19) Pandemic in China. Environmental Pollution, 262, 114665, 2020. https://doi.org/10.1016/j.envpol.2020.114665.

[37] N. Asim, M. Badiei and K. Sopian, Review of the Valorization Options for the Proper Disposal of Face Masks during the COVID-19 Pandemic. Environmental Technology & Innovation, 23, 101797, 2021. https://doi.org/10.1016/j.eti.2021.101797.

[38] O. A. Fakayode, E. A. A. Aboagarib, C. Zhou and H. Ma, Co-Pyrolysis of Lignocellulosic and Macroalgae Biomasses for the Production of Biochar—A Review. Bioresource Technology, 297, 122408, 2020. https://doi.org/10.1016/j.biortech.2019.122408.

[39] G. Su, H. C. Ong, S. Ibrahim, I. M. R. Fattah, M. Mofijur and C. T. Chong, Valorisation of Medical Waste through Pyrolysis for a Cleaner Environment: Progress and Challenges. Environmental Pollution, 279, 116934, 2021. https://doi.org/10.1016/j.envpol.2021.116934.

[40] T. A. Aragaw and B. A. Mekonnen, Current Plastics Pollution Threats Due to COVID-19 and Its Possible Mitigation Techniques: A Waste-to-Energy Conversion via Pyrolysis. Environmental Systems Research, 10 (8), 2021. https://doi.org/10.1186/s40068-020-00217-x.

[41] R. K. Singh and B. Ruj, Time and Temperature Depended Fuel Gas Generation from Pyrolysis of Real World Municipal Plastic Waste. Fuel, 174, 164–171, 2016. https://doi.org/10.1016/j.fuel.2016.01.049.

[42] N. A. Antoniou and A. A. Zorpas, Quality protocol and procedure development to define end-of-waste criteria for tire pyrolysis oil in the framework of circular economy strategy. Waste Management, 15 (95), 161–170, 2019. https://doi.org/10.1016/j.wasman.2019.05.035.

[43] W. U. Eze, R. Umunakwe, H. C. Obasi, M. I. Ugbaja, C. C. Uche and I. C. Madufor, Plastics waste management: a review of pyrolysis technology. Clean Technologies and Recycling, 1 (1), 50–69, 2021. https://doi.org/10.3934/ctr.2021003.

[44] M. J. B. Kabeyi and A. O. Olanrewaju, Performance analysis and evaluation of Muhoroni 60MW gas turbine power plant. International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME), Mauritius, 7-8 October 2021, pp. 1–8, 2021.

[45] L. Fulgencio-Medrano, S. García-Fernández, A. Asueta, A. Lopez-Urionabarrenechea, B. B. Perez-Martinez and J. M. Arandes, Oil Production by Pyrolysis of Real Plastic Waste. Polymers, 14, 553, 2022. https://doi.org/10.3390/polym14030553.

[46] M. J. B. Kabeyi and A. O. Olanrewaju, Review and Design Overview of Plastic Waste-to-Pyrolysis Oil Conversion with Implications on the Energy Transition. Journal of Energy, 1821129, 2023. https://doi.org/10.1155/2023/1821129.

[47] M. J. B. Kabeyi and A. O. Olanrewaju, Sustainability Assessment for Non-Combustible Renewable Power Generation. 12th Annual Istanbul International Conference on Industrial Engineering and Operations Management, Istanbul, Turkiye, 7-10 March 2022, pp. 2232–2244, 2022.

[48] TMMOB Chamber of Chemical Engineers (KMO) Istanbul Branch Plastics and Rubber Commission. Plastic Recycling and Waste Import Report in Türkiye, 2021.

[49] T.R. Ministry of Development. Eleventh Development Plan (2019-2023) Sustainable Management of Environment and Natural Resources, Working Group Report, 2018.

[50] Anadolu Agency (AA), Türkiye Her Yıl 1,1 Milyon Ton Plastik Atığı Geri Dönüştürüyor. https://www.aa.com.tr/tr/cevre/turkiye-her-yil-1-1-milyon-ton-plastik-atigi-geri-donusturuyor/2427166 , Accessed 26 September 2023.

[51] Turkish Statistical Institute (TÜİK) Waste Statistics-2020. https://data.tuik.gov.tr/Bulten/Index?p=Atik-Istatistikleri-2020-37198 , Accessed 26 September 2023.

[52] Adana Governorship, Provincial Directorate of Environment, Urbanization and Climate Change, Adana Province Environmental Status Report, 2022.

[53] Adana Metropolitan Municipality Activity Report. https://www.adana.bel.tr/panel/uploads/yillikfaaliyetraporlari_v/files/2022yili-faaliyetraporu-small.pdf , Accessed 26 September 2023.

[54] How Should US Health Care Lead Global Change in Plastic Waste Disposal?. https://journalofethics.ama-assn.org/article/how-should-us-health-care-lead-global-change-plastic-waste-disposal/2022-10 , Accessed 26 September 2023.

[55] K. V. Wong, R. Narasimhan, R. Kashyap and J. Fu, Medical waste characterization. Journal of Environment and Health, 57 (1), 19-24, 1994.

[56] A. Dash, S. Kumar and R. K. Singh, Thermolysis of Medical Waste (Waste Syringe) to Liquid Fuel Using Semi-Batch Reactor. Waste Biomass Valorization, 6 (4), 507–514, 2015. https://doi.org/10.1007/s12649-015-9382-3.

[57] UNEP, Compendium of Technologies for Treatment/Destruction of Healthcare Waste, United Nations Environment Programme Division of Technology, Industry and Economics International Environmental Technology Centre Osaka, Japan, 2012.

[58] N. Miskolczi, L. Bartha and A. Angyal, Pyrolysis of Polyvinyl Chloride (PVC)-Containing Mixed Plastic Wastes for Recovery of Hydrocarbons. Energy & Fuels, 23 (5), 2743-2749, 2009. https://doi.org/10.1021/ef8011245.

[59] S. B. Rasul, U. Som and M. S. Hossain, Liquid fuel oil produced from plastic based medical wastes by thermal cracking. Scientific Reports, 11, 17048, 2021. https://doi.org/10.1038/s41598-021-96424-2.

[60] Hospital Waste Characterization. https://www.hprc.org/resources/hospital-waste-characterization , Accessed 26 September 2023.
[61] LCA ChemCyclingTM: CO_2 Emissions of Pyrolyzed Mixed Plastic Waste and the Mass Balance Approach. https://www.basf.com/global/documents/en/sustainability/we-drive-sustainable-solutions/circular-economy/chemcycling/Intern_Christian%20Kr%C3%BCger_BASF%20Dialog%20Forum.pdf , Accessed 26 September 2023.
[62] G. Lopez, M. Artetxe, M. Amutio, J. Bilbao and M. Olazar, Thermochemical Routes for the Valorization of Waste Polyolefinic Plastics to Produce Fuels and Chemicals, A Review. Renewable and Sustainable Energy Reviews, 346–368, 2017. https://doi.org/10.1016/j.rser.2017.01.142.
[63] Recycling Breakthrough Makes Plastic Waste a High-Value Commodity. https://oilprice.com/Energy/Energy-General/Recycling-Breakthrough-Makes-Plastic-Waste-A-High-Value-Commodity.html , Accessed 26 September 2023.
[64] Plastic Pyrolysis Oil Market Research Report 2023. https://www.transparencymarketresearch.com/pyrolysis-oil-market.html , Accessed 26 September 2023.
[65] R. U. Gracida-Alvarez, P. T. Benavides, U. Lee and M. Wang, Life-cycle analysis of recycling of post-use plastic to plastic via pyrolysis. Journal of Cleaner Production, 425, 138867, 2023. https://doi.org/10.1016/j.jclepro.2023.138867.
[66] H. Park, K. Kim, M. Yu, Z. Yun and S. Lee, Economic analysis of the circular economy based on waste plastic pyrolysis oil: a case of the university campus. Environment, Development and Sustainability, 15, 1-21, 2023. https://doi.org/10.1007/s10668-023-02963-1.
[67] ICIS Launches Pyrolysis Oil Pricing Indexes for Chemical Recycling. https://www.icis.com/explore/press-releases/icis-launches-pyrolysis-oil-pricing-indexes-for-chemical-recycling/ , Accessed 26 September 2023.
[68] UNEP. https://www.who.int/news-room/fact-sheets/detail/health-care-waste , Accessed 26 September 2023.
[69] S. Burnley, S. Wagland and P. Longhurst, Using life cycle assessment in environmental engineering education. Higher Education Pedagogies, 4, 64–79, 2019. https://doi.org/10.1080/23752696.2019.1627672.
[70] European Commission, "Life Cycle Assessment (LCA)," European Platform on Life Cycle Assessment. https://eplca.jrc.ec.europa.eu/lifecycleassessment.html , Accessed 26 September 2023.
[71] S. M. A. Rahman, S. Issa, M. E. H. Assad, S. K. Shah, M. A. Abdelkareem, M. E. Hoque and A. G. Olabi, Performance enhancement and life cycle analysis of a novel solar HVAC system using underground water and energy recovery technique. Thermal Science and Engineering Progress, 36, 101515, 2022. https://doi.org/10.1016/j.tsep.2022.101515 .
[72] H. Alhazmi, F. H. Almansour and Z. Aldhafeeri, Plastic Waste Management: A Review of Existing Life Cycle Assessment Studies. Sustainability, 13, 5340, 2021. https://doi.org/10.3390/su13105340.
[73] M. H. Mushtaq, F. Noor, M. A. Mujtaba, S. Asghar, A. A. Yusuf, M. E. M. Soudagar, A. Hussain, M. F. Badran and K. Shahapurkar, Environmental Performance of Alternative Hospital Waste Management Strategies Using Life Cycle Assessment (LCA) Approach. Sustainability, 14, 14942, 2022. https://doi.org/10.3390/su142214942.
[74] Y. Dong, M. U. Hossain, H. Li and P. Liu, Developing Conversion Factors of LCIA Methods for Comparison of LCA Results in the Construction Sector. Sustainability, 13, 9016, 2021. https://doi.org/10.3390/su13169016.

Supplementary

S1. Medical Waste Definitions and Contents

Healthcare activities play a crucial role in safeguarding well-being, restoring health, and preserving lives. However, it is essential to address the waste and by-products they produce.

Out of the total volume of waste generated through healthcare activities, approximately 85% constitutes general, non-hazardous waste that is akin to household waste. The remaining 15% comprises materials classified as hazardous, which may encompass infectious, chemical, or radioactive substances.

Varieties of Waste: The array of waste and by-products encompasses a diverse range of materials, as exemplified below:

1. Biological Waste: This pertains to waste contaminated with blood, bodily fluids (e.g., discarded diagnostic samples), cultures, and infectious agents from laboratory work. It also includes waste from patients with infections, such as swabs, bandages, and disposable medical devices.
2. Pathological Waste: This category encompasses human tissues, organs, fluids, body parts, and contaminated animal carcasses.
3. Sharp Objects Waste: It comprises syringes, needles, disposable scalpels, and blades, among other items.
4. Chemical Waste: Examples include solvents and reagents used for laboratory preparations, disinfectants, sterilants, and heavy metals contained in medical devices (e.g., mercury in broken thermometers) and batteries.
5. Pharmaceutical Waste: This relates to expired, unused, and contaminated drugs and vaccines.
6. Cytotoxic Waste: It involves waste containing substances with genotoxic properties, such as cytotoxic drugs used in cancer treatment and their metabolites.
7. Radioactive Waste: This includes materials contaminated by radionuclides, encompassing radioactive diagnostic materials and radiotherapeutic substances.
8. General Waste: This category encompasses waste that does not pose specific biological, chemical, radioactive, or physical hazards.

Prominent Sources of Healthcare Waste Include:

- Hospitals and other healthcare facilities.
- Laboratories and research centers.
- Mortuary and autopsy centers.
- Animal research and testing laboratories.
- Blood banks and collection services.
- Nursing homes for the elderly.

On average, high-income countries generate up to 0.5 kg of hazardous waste per hospital bed per day, while low-income countries generate an average of 0.2 kg. However, in low-income countries, healthcare waste is frequently not segregated into hazardous or non-hazardous categories, resulting in a significantly higher quantity of hazardous waste in practice [68].

Supplementary-Table 1. Environmental impacts of medical waste treatment methods

Year	Pyrolysis GHG (kg CO_2e)	Incineration GHG (kg CO_2e)	Landfilling GHG (kg CO_2 eq)
2022	1,046,904	2,442,777	286,569
2023	1,080,596	2,521,391	295,792
2024	1,114,288	2,600,006	305,014
2025	1,147,979	2,678,619	314,237
2026	1,181,672	2,757,235	323,459
2027	1,215,363	2,835,848	332,682
2028	1,249,055	2,914,463	341,904
2029	1,282,747	2,993,077	351,127
2030	1,316,439	3,071,692	360,349