Economic Analysis of Recycling of Plastic Waste Through Pyrolysis Process

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Abstract

Persistent plastic has emerged as a major global environmental challenge as plastic production volume continues to surge. Though efforts towards recycling have been rising, most plastic waste winds up in landfills, which pose major ecological dangers. As the amount of this waste increases, urgent development of effective and sustainable recycling methods is required. The objective of this study is to quantify plastic waste generated in Peshawar, Pakistan, to classify their types and to evaluate the economic feasibility of the use of pyrolysis (as a recycling technique) in plastic waste management. Samples of plastic waste are collected from different transfer stations and landfills situated in Peshawar. These samples are then sorted into major categories of the most common types: Polyethylene (PE), Polystyrene (PS) and Polypropylene (PP). An economic evaluation of a pyrolysis plant is performed to assess the feasibility of the plant, including capital cost, operational cost, and profit potential. Real-time data is taken from local waste streams for the analysis. Polyethylene (50.8%), then PET (13.7%), and Wrappers (12.8%) are the most abundant plastic types found. To achieve the same level of processing, a pyrolysis plant would require an investment of $267,365, which would yield a net profit of $57,767 annually. The payback time of investment is calculated to be 4.6 years. It is proved that pyrolysis is a promising, economically viable option for plastic waste management in Peshawar. The approach provides a sustainable method for recycling plastic waste and for producing useful energy resources with significant environmental benefits.

Keywords*:* Pyrolysis; Plastic Recycling; Energy Recovery; Capital Investment; Economic Feasibility; Sustainable Waste Management.

Introduction

One of the biggest global environmental challenges has become plastic waste. Whilst production of plastic has grown rapidly, recycling rates are low. Only 15 percent of the world's plastic, about 400 million tons globally per year, is being recycled (Eze et al., 2021). A larger portion of

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that is discarded in landfills, oceans, and out into the environment, leading to extensive ecological damage. Despite efforts to increase recycling rates over the past 30 years, the rate of plastic production continues to outpace recycling, leading to a growing accumulation of plastic waste (Eze et al., 2021).

To combat plastic waste pollution, many countries have resorted to banning certain plastic products, such as straws, as a short-term solution. However, in the long term, plastics will remain indispensable in various applications. Thus, in addition to product bans, other avenues must be explored to manage plastic waste sustainably (Jeswani et al., 2021). A key approach is the transition to a circular economy, which promotes waste prevention, reuse, recycling, and recovery, as opposed to the traditional linear model of "take, make, dispose" (Payne et al., 2019). The circular economy offers a promising framework for sustainable plastic waste management. However, the reuse of plastic in the same form or function is often limited due to technical, economic, and legislative challenges (Coelho et al., 2020; Harussani et al., 2022). Therefore, recycling, especially chemical recycling, is regarded as the most viable solution to prevent the disposal of plastic waste, displacing the need for virgin materials (Lee et al., 2021; Uğuz et al., 2017; Zeller et al., 2021).

Plastics can be recycled through two main methods: mechanical recycling and chemical recycling. Mechanical recycling involves sorting, cleaning, and shredding plastic to create secondary raw materials or products without significantly altering the material's chemical structure. However, the process tends to be cost-ineffective due to the high costs of collection, sorting, and processing, leading many companies to favor virgin materials (Bezergianni et al., 2017; Commission, 2018; Quadri et al., 2020).

Method and Materials

Mechanical Recycling of Plastic Waste

For recycling of plastic waste, mechanical Recycling is the most common method, which typically involves collection, sorting, washing, and grinding of plastic waste. These steps may vary in order and frequency depending upon certain factors, such as the composition and origin of waste (Al–Salem et al., 2017; Ragaert et al., 2017). This type of recycling is best suitable for hard plastic, plastic bottles, and HDPE, because of the high material cost. Also, the recycling of this material into energy is not technically possible. In plastic recycling, granulation is the process of shredding plastic objects to be recycled into flakes or pellets, suitable for later reuse in plastic extrusion as shown in Figure 1. In the first stage, plastic objects to be recycled are fed to an electric motor-powered cutting chamber, which continually cuts the material using one of several types of cutting systems. The material is ground into all the smaller flakes until they become fine enough to fall through a mesh screen. In wet-granulation lines, water is continually sprayed in the cutting chamber to remove the debris and impurities and acts as a lubricant for the steel blades. In many cases, granulation may be the only step required before the plastics can be reused for manufacturing new products. In other, the new or recycled plastic material must be remade into pellets. The material is molten and extruded into thin rods, which are then cooled in a water tank and finely chopped into small cylindrical pellets (Belden et al., 2022; Grigore, 2017).

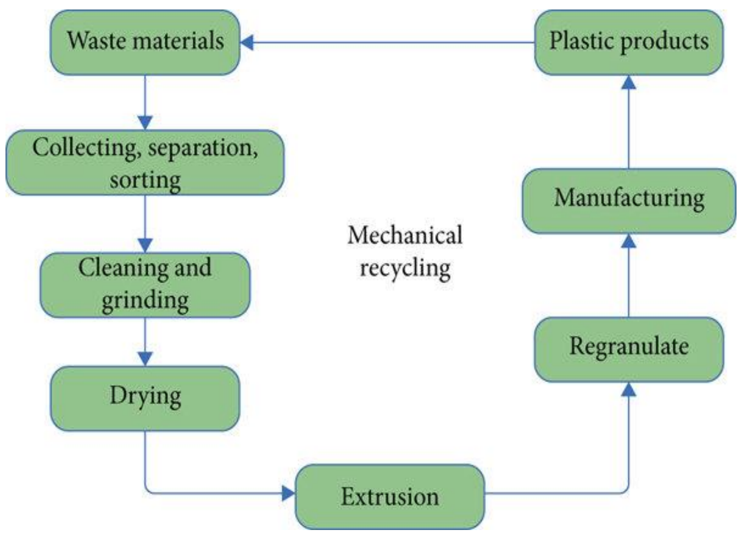

Figure 1: Presents a typical schematic diagram of mechanical recycling unit.

Chemical Recycling of Plastic Waste

Chemical recycling converts plastic packaging waste into chemical products, avoiding their production from fossil feedstock. Therefore, chemical recycling is expected to decrease the demand for finite fossil resources as well as the emissions of greenhouse (Meys et al., 2020). Chemical recycling is an accepted recycling method that follows the principles of sustainable development. Chemical recycling methods are opening newer pathways for using plastic waste as feed in generating pure value-added products for various industrial and commercial applications (Ali et al., 2023; Chaiphet et al., 2021; Quesada et al., 2020). Among other recycling techniques such as Methanolysis, Hydrolysis, and Glycolysis, Pyrolysis is an interesting technology that depolymerizes the complex plastic waste feeds such as the mixture of PE, PS, and PP, multilayered packaging (Ragaert et al., 2017; Zolghadr et al., 2021).

In pyrolysis, plastic decomposes into a light and heavy hydrocarbon (fuel oil) and in non-condensable gases at 300- 900^{o}C in the absence of oxygen. There are two types of pyrolysis: thermal pyrolysis and catalytic pyrolysis. Thermal pyrolysis occurs at high temperatures and requires high energy. As there is no catalyst involved in thermal pyrolysis, production of low molecular weight hydrocarbon is high, and the product has a low quality, which makes the process unfeasible. Catalytic pyrolysis occurs at low temperatures and requires less energy which makes this process cost-effective. The catalyst plays a very important role in increasing the efficiency of pyrolysis. The catalyst that is most widely used catalyst is ZSM-5. Zeolite, Y-Zeolite, Ti-Al-Beta, FCC, and MCM-41 (Hamid et al., 2021; Ziad et al., 2021).

The current study is carried out in Peshawar Khyber Pakhtunkhwa. A comprehensive study is undertaken to quantify plastic waste, with municipal waste samples collected from various transfer stations located across different areas as well as from the landfill site as mentioned in the GIS map as shown in Figure 2. The collected waste samples are systematically segregated into distinct components, with plastic waste further categorized into major types as outlined in Table 1.

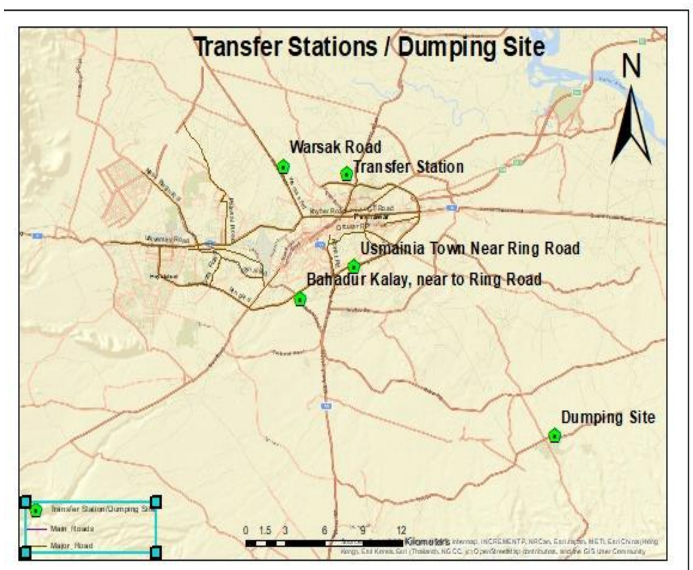

Figure 1: Showing sample collection map.

The composition of each plastic waste type generated in the study area is quantified and its daily generation in tonnage is analyzed. For the pyrolysis process feasibility analysis, specific plastic waste types are selected, including Polyethylene (PE), Polystyrene (PS), and Polypropylene (PP), due to their suitability for thermal degradation. Conversely, Polyethylene terephthalate (PET) and High-Density Polyethylene (HDPE) are excluded from the pyrolysis process, as their market value makes them more viable for mechanical recycling. This recommendation aligns with previous findings by Ziad et al. (2021).

Subsequently, an Economic analysis of the pyrolysis plant is carried out while keeping in view the specific feedstock or plastic waste type. During this process, specific plastic types are included, such as PP, PE, and PS, while the PET HDPE and PVC types of plastic are not considered due to their high value in the market. Furthermore, these types of plastic are diverted from the main waste stream even at the source. Therefore, they are not considered for the pyrolysis process. This assessment provided insights into the financial feasibility and resource optimization potential of using specific plastic waste streams for energy recovery through pyrolysis.

Results

Plastic Waste Quantification

Study findings show that plastic waste occupies a major share of the municipal waste stream with an average generation rate of 0.077 kg/capita/day, equivalent to about 16% of the total waste stream. Plastic waste samples collected from various transfer stations and the landfill site are classified into eight major categories: PE, PS, HDPE, PET, PP, wrappers, tetra packs, and diapers. A detailed quantification of these plastic-type wastes generated in the study area is given in Table 2. Also, in the results, Polyethylene (50.8%) is the most prevalent type of plastic waste, followed by Polyethylene Terephthalate (PET) (13.7%) and Wrappers (12.8%). Packaging and non-packaging applications, which are consumed rapidly and discarded, make the predominance of Polyethylene possible. The high generation rates of waste plastics for some of the plastics types, as highlighted in Table 1, illustrates the urgent need for targeted waste management strategies that will significantly reduce these wastes in the waste streams.

Fixed Expenditure (Direct Expenditure)

Fixed expenditure is the first capital which is required for acquisition, installation and setup of a pyrolysis plant. All direct and indirect costs are included. Direct costs are those relating to the cost of the construction of the plant and the acquisition of necessary equipment (process machinery, installation, instruments, piping, plant building setup and grounds, etc.). Else, direct cost includes $119,760 for process machinery like crusher, processing line and LPG fueling station, and piping cost of $23,952 for good, leakproof and high temperature operation. Aside from construction of the building in which the plant will sit, electricity is to be paid for. While indirect costs are not explicitly itemized in this table, indirect costs generally involve the design consultant fee, safety test, and certification cost. Fixed expenditure is divided into total fixed expenditure where the latter represents the investment required to initiate a pyrolysis plant as shown in Table 2.

Table 1: Plastic waste quantification.

Plastic Type	Percentage
Polypropylene (PP)	7.6%
Wrappers	12.8%
Polystyrene (PS)	3.4%
High Density Polyethylene (HDPE)	1.4%
Polyethylene (PE)	50.8%
Polyethylene terephthalate (PET)	13.7%
Tetra packs	6.2%
Pampers	4.2%

Table 2: Fixed expenditure for pyrolysis plant.

Description	Justification	Cost $
Process Machinery	Crusher, Processing line and LPG fueling station	119,760
Installation	Transportation & Installation of Machinery	23,952
Instrument	Controller, sensors and actuators	17,964
Piping	Leakproof, high temp piping	23,952
Electricity	Provision of safe and stable electricity	5,988
Building	Plant Erection, facility for recycling setup	11,976
Land/Site Renovation	Ensuring Safety features	5,988
Service facility	Selling point & customer care service	17,964
Total		227,545

Fixed Expenditure (Indirect Cost)

The services necessary to ensure that the pyrolysis plant is installed in a safe and complaint manner comprise of the indirect costs. Most of the cost is for deploying payroll for design consultation, safety certification and such third party services as are required for proper operation to be set up. For the engineering costs, representing the design consultation and fabrication, is $11,377. Safety testing, certification and MEP (Mechanical, Electrical and Plumbing) works are third party services, that add up to $17,066. Furthermore, we've budgeted an extra amount $11,377 for the things we will encounter to be covered should costs surge during the installation process. The total expenditure in indirect is $39,820 and the plant installation complies to safety and operating standards. The indirect costs represent the services necessary to the safe and compliant installation of the pyrolysis plant. The installation is also allocated a contingency cost of $11,377 to cover unforeseen costs. The indirect costs for the installation of the pyrolysis plant are $39,820 total. The plant's total capital expenditure (Capex) of $267,365, when added to the direct costs of $227,545, are shown in Table 3.

Table 3: Indirect expenditure for pyrolysis plant installation.

Description	Justification	Cost $
Engineering	Design consultation and fabrication	11,377
Third party Services	Safety testing, certification and MEP works	17,066
Contingences		11,377
Total		39,820

Operational Expenditure: Variable Cost

Operational expenditure is the cost of running the day to day operations of the pyrolysis plant. These are Variable costs, Fixed costs and Overhead charges. These are the raw material costs of the waste collection, segregation, and transportation of $36,527; electricity costs of $61,639; and ZSM-5 catalyst costs of $76,707, which is critical to convert the waste pyrolytically. These fixed costs are site rent ($7,186), salaries ($43,114), and utilities ($3,234) or a total of $53,533. The overhead charges are based at 15% of the direct Capital expenditure which results to $34,132 as shown in Table 4. This leads to total operational expenditures being a central factor in the functioning of the plant after its installation.

Table 4: Operational expenditure breakdown.

Description	Justification	Cost $
Raw Material cost	Collection, segregation and transportation of waste	36,527
Fuel Cost	Electricity cost	61,639
Catalyst Cost	ZSM-5 catalyst for efficient conversion	76,707
Total		174,873

Operational Expenditure: Fixed Cost

The financial performance of the pyrolysis plant is provided by means of profitability analysis. Total sales of the plant are $405,449. Now deduct cost of goods sold ($174,873) and gross profit now comes out $230,576. Finally, fixed costs ($53,533) and overhead charges ($34,132) are taken off to get Earnings Before Interest and Tax (EBIT), $142,911. When you subtract taxes totaling $85,144 from the operative income, you get $57,767. Using the costs and sales shown in Table 5, this analysis shows a potential for the plant's profitability.

Table 5: Profitability analysis and return calculation.

`	Justification	Cost $
Site Rent	This cost covers the rental of office or operational space necessary for carrying out project activities. The site provides essential infrastructure, meeting space, and storage for equipment and materials.	7,186
Salaries		43,114
Utilities		3,234
Total		53,533

Overhead Charges

The additional expenses beyond the direct and variable costs to operate the pyrolysis plant are overhead charges. Overhead is estimated as 15% of direct capital expenditure (Capex). Indirect expenses needed for running the plant, for example, administration costs, management fees and other general operational overheads, amount to $34,132 of overhead. These charges are fundamental to account for the running costs of the plant and to support the uninterrupted operation of the plant. The overhead is also included in the financial analysis to give a complete view of all the cost involved in the operation of the plant as in Table 6.

Table 6: Overhead charges breakdown.

Description	Justification	Cost $
Overhead	15% of the Direct Capex	34,132

Profitability Analysis

Profit/loss statement, rate of return and payback period analysis are given here for the pyrolysis plant, and all of these include a comprehensive profitability analysis. By tracking down the sales of the plant we know that it generates a total sale of $405,449 and after deducting cost of goods sold ($174,873) the gross profit stands at $230,576. This leaves fixed costs of $53,533 and overhead charges of $34,132 to be subtracted to give Earnings Before Interest and Taxes (EBIT) of $142,911. Once taxes of $85,144 are taken out of that number, it comes to $57,767 in profit.

The return is a staggering 21.6% (that is the Net Profit divided by Total Capital Investment). Which shows a strong Rate of Return on the investment. With a rate of return that is the reciprocal of payback period, the initial capital investment is recovered in 4.6 years and the plant proceeds to generate profit thereafter in Table 7.

Table 7: Profitability analysis, rate of return, and payback period.

Sales	$405,449
Cost of goods sold	(174,873)
Gross Profit	$230,576
Fixed Cost	(53,533)
Overhead charges	(34,132)
EBIT	$142,911
Tax	(85,144)
Net Profit	$57,767

Discussion

Results of this study indicate that plastic waste forms an important portion of municipal waste stream in Peshawar, the most dominant plastic type being Polyethylene (PE) followed by Polyethylene Terephthalate (PET) and Wrappers. Its extensive use for both packaging and non-packaging applications and its fast consumed and discarded nature contributes to PE's high percentage (50.8%) of PE consumed. PE, a dominant component of the waste stream, is shown here to need targeted waste management strategies for this specific plastic type's disposal (Eze et al., 2021).

This study demonstrated that the pyrolysis process is economically possible for controlling the plastic waste. Pyrolysis plant costs are estimated at $267,365 to build and return $57,767 per year in Net profit over a Payback period of 4.6 years. This corresponds to previous studies of pyrolysis, which found pyrolysis to be economically viable as long as the long term benefits of sustainable resource recovery are factored in (Ziad et al., 2021). Despite the large capital investment, the relatively short payback period indicates that pyrolysis is an opportunity for both environmental and economic returns. Furthermore, the estimated profitability provides evidence that pyrolysis can act as an important part in relieving the economic load associated with plastic waste management (Meys et al., 2020).

While mechanical recycling is suitable for some plastic types, for other types such as PE and PP, economic and technical difficulties arise, including high energy consumption and the inefficiency at attempting to process contaminated plastics (Quadri et al., 2020). In contrast, pyrolysis enables the conversion of such mixed and contaminated plastics into usable products, such as fuel oil and gas, that can be a more versatile, sustainable approach to large scale waste management (Zolghadr et al., 2021).

In addition, the catalytic pyrolysis method, where catalysts like ZSM-5 are used, also seems to improve the efficiency of pyrolysis. Catalytic pyrolysis is cheaper in terms of energy input and yields better quality hydrocarbon products than thermal pyrolysis making the whole process more economically viable (Hamid et al., 2021). Catalysts also enable higher product quality and the environmental footprint of the process to be reduced by minimizing harmful emissions (Hamid et al., 2021; Kartika, 2023).

The results of this research are in line with the already expanding body of literature on pyrolysis in management of plastic waste. Increasingly, chemical recycling, particularly pyrolysis, is seen as an important technology to help deal with the global plastic waste crisis. Waste plastics will only increase, so the need for efficient, sustainable recycling technologies will become more and more urgent. This work is an economic evaluation of pyrolysis as this knowledge gap not only contributes to literature, but also provides insights into the potential of pyrolysis for large scale adoption in emerging countries like Pakistan, where the plastic waste management is a critical problem (Ali et al., 2023; Kantarli et al., 2018; Khair, 2023).

However, the economic viability of pyrolysis depends on several factors, including the local cost of feedstock, energy prices, and the market demand for the products generated through pyrolysis. While this study demonstrated promising results in Peshawar, the feasibility of scaling this technology will need to be evaluated in different geographical contexts, particularly in areas with lower waste management infrastructure. Moreover, additional research is needed to optimize the pyrolysis process for different types of plastic waste, especially those with higher contamination levels, to enhance the overall efficiency and reduce operational costs.

Techno Chemical Analysis of Pyrolysis with other Recycling Technologies

Below is the tabulated comparison of pyrolysis and other recycling technologies. Table 8 highlights the strengths and limitations of each method, emphasizing the need for integrated approaches to manage diverse plastic waste streams effectively. Based on the above comparison Pyrolysis is best suited for managing mixed or non-recyclable plastic waste with potential for high-value products, requiring policy and technological support to optimize cost-effectiveness. The same has been endorsed and reported by the (Saxena, 2025).

Table 8: Techno Chemical Analysis of Pyrolysis with other Recycling Technologies.

Aspect	Pyrolysis	Mechanical Recycling	Landfill/Incineration
Process	Converts plastic waste into fuels and chemicals through high-temperature, oxygen-free processes	Physically reprocesses plastics into new products without altering their structure	Disposal through land burial or incineration, sometimes with energy recovery
Capital Cost	High initial investment due to advanced technology	Low to moderate; dependent on sorting and cleaning infrastructure	Low for landfills; moderate to high for incineration
Operational Cost	Moderate; offset by revenue from valuable by-products	Moderate; influenced by feedstock quality and sorting requirements	Moderate to high; includes costs of land management and emissions control
Revenue Potential	High; generates fuels, monomers, and chemicals	Moderate; limited to low-value recycled plastics	Minimal; some revenue from energy recovery in incineration
Feedstock Suitability	Effective for mixed and non-recyclable plastics	Suitable for clean, homogenous plastic streams	Processes all waste types but without resource recovery benefits
GHG Emissions	Moderate; emissions from energy-intensive processing	Low; environmentally preferable for suitable plastics	High; significant emissions from methane (landfills) and CO_2 (incineration)
Environmental Impact	Addresses complex plastic waste streams; can reduce landfill dependency	Lowest environmental impact among the three	High environmental burden due to emissions and resource depletion
Waste Diversion	Diverts non-recyclable plastics; maximizes material recovery	Limited to specific, recyclable plastic types	Low; minimal resource recovery
Scalability	Highly scalable; adaptable to various waste compositions	Limited scalability for mixed or contaminated plastics	Scalable but faces increasing regulatory restrictions
Cost-Effectiveness	High for mixed and non-recyclable plastics; improves with policy incentives	High for clean, segregated plastic waste	Low; regulatory and environmental costs outweigh benefits

Challenges Of Scaling The Pyrolysis Plant

There are many challenges when scaling pyrolysis plants in real world applications that must be carefully addressed to ensure these plants will be implemented and become sustainable. A major challenge of pyrolysis is feedstock variability because the feedstock quality and composition must be consistent to maximize operational efficiency and maximize product yield. Due to the absence of effective waste segregation practices, heterogeneous feedstocks are present in many regions, especially in developing economies; heterogeneous feedstocks affect the efficiency of the pyrolysis process, as well as bio oil, syngas, and char outputs (Hasan et al., 2025).

There is also another big challenge, regulatory compliance. The setup and running of the pyrolysis plants demand concurring multitudinous stringent environmental regulations relating to emission treatment, waste management, and the safe disposal of the by-products. These regulations can add complexity, delays, and costs if being navigated in countries where the policy context is in evolution or unclear. Besides, the regulatory frameworks failed to have specific guidelines for pyrolysis, which created ambiguities and cumbersome hurdles for the permit and approval (Kibria et al., 2023).

The supply chain logistics are also a significant barrier, as pyrolysis plants require a constant and predictable supply of appropriate waste materials. A lack of consistent collection systems, inadequate infrastructure, and the high cost of transportation cause feedstock unavailability, thus raising operational inefficiencies. However, scaling these operations can need the coordination of multiple stakeholders—waste generators, local governments, and private sector partners, to name a few—that may be logistically complex (Lui et al., 2020).

To address these challenges, a collaborative effort needs to be undertaken that includes investment in waste segregation systems, robust regulatory frameworks that are made specific to pyrolysis, and the building of robust supply chain networks. Other innovative solutions may include large-scale adoption of public-private partnerships, community engagement, and technology advancements that may help to ease these barriers and enable large-scale adoption of pyrolysis plants.

Policy Implications And Incentives Needed To Promote Pyrolysis Adoption In Developing Regions

For pyrolysis adoption in developing regions, a multidimensional approach consisting of policy support, financial incentives, and capacity building is promoted. Thus, in order to integrate pyrolysis into national waste management policies compatible with circular economy goals, governments should set up clear regulatory frameworks that define hydrogenation emissions control standards and product quality standards (Lui et al., 2020). Streamlining implementation would include enforcing source separation of waste, implementing Extended Producer Responsibility (EPR) programs, and offering fast-track approvals of environmentally safe pyrolysis projects to enhance feedstock availability.

Offsets for high initial system costs and market demand can be facilitated through financial incentives such as subsidies, tax breaks, feed-in tariffs, and carbon credit schemes for pyrolysis products, including bio-oil and syngas (Malinauskaite et al., 2017). Improvement of technology efficiency and scalability can be further achieved by public private partnerships (PPPs) and investments in research and development and by training programs and technology transfer initiatives aimed at building local expertise. Awareness campaigns and including the community in the waste collection process will help to create employment and to build their public participation. These measures uptake facilitates waste management in developing regions utilizing pyrolysis technology, minimizing the environmental impacts, and providing a sound basis for sustainable economic growth.

Conclusion and Future Work

This study demonstrates that plastic waste, particularly Polyethylene (PE), PS, and PP, is one of the significant environmental challenges in Peshawar, Pakistan. For this purpose, a chemical recycling technique, i.e., the Pyrolysis process, is employed to manage this plastic waste in an environmentally friendly. To assess the economic feasibility, an economic analysis is carried out, which revealed a promising solution for managing plastic waste. The establishment of the Pyrolysis plant requires an annual capital investment of $267,365; the payback period of the capital investment is 4.6 years, along with other associated benefits such as job creation, etc. Pyrolysis offers a viable alternative to mechanical recycling, especially for mixed and contaminated plastics, by converting them into valuable products like fuel oil and gas. The use of catalytic pyrolysis enhances process efficiency and reduces energy costs. This study supports the potential of pyrolysis as a sustainable and economically feasible method for plastic waste management, contributing to environmental sustainability and energy recovery. Further research and optimization are needed to fully harness its benefits, particularly in developing regions.

Future research should focus on optimizing the pyrolysis process, particularly for plastics with higher contamination levels or complex compositions, to enhance its efficiency and reduce operational costs. Investigating the use of alternative, more cost-effective catalysts could further improve the economic feasibility of catalytic pyrolysis. Additionally, large-scale pilot projects should be conducted to evaluate the real-world performance of pyrolysis plants in different geographic regions, especially in areas with limited waste management infrastructure. Further studies should also explore the integration of pyrolysis with other recycling methods, such as mechanical recycling, to develop a comprehensive waste management strategy. Finally, assessing the environmental impact of pyrolysis, including emissions and by-products, will be crucial in ensuring that the process remains a sustainable and eco-friendly solution for plastic waste management.

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