Economic Analysis of Pyrolysis of Wood Waste to Produce Bio-Oil

SAMUEL AKPAN[1], JOSEPH ESANG[2], PROF. INNOCENT OBOH[3], DR. UWEM INYANG[4], DR. KINGSLEY EGEMBA[5]

[1, 3, 4, 5]Department of Chemical Engineering, Faculty of Engineering, University of Uyo, Uyo L.G.A, Akwa Ibom State, Nigeria.

[2]Department of Chemical Engineering, Faculty of Engineering, Akwa Ibom State University, Mkpat Enin L.G.A, Akwa Ibom State, Nigeria.

Abstract- Waste management remains a critical global challenge, exacerbated by rapid urbanization, population growth, and industrial activities. Among the innovative solutions, pyrolysis has emerged as a transformative technology for converting waste into valuable resssources such as bio-oil, biochar, and syngas. This seminar explores the economic analysis of pyrolysis technology, emphasizing its viability for addressing both waste management and energy demands. The study evaluates the financial implications, from capital investment and operational costs to revenue generation through by-products, demonstrating pyrolysis as an economically competitive option and introducing Fluid catalytic cracking for further processing and production of bio-oil. Comparative analysis highlights its advantages over traditional waste treatment methods, such as landfilling and incineration, in terms of resource recovery and environmental impact mitigation. Furthermore, the presentation delves into real-world applications and case studies, underscoring its scalability across urban and rural contexts. Through this comprehensive analysis, the presentation seeks to provide policymakers, investors, and stakeholders with actionable insights into adopting pyrolysis technology. By aligning with global sustainability goals and leveraging economic incentives, pyrolysis, can catalyze a shift towards a circular economy, where waste is viewed not as a liability but as an asset.

Indexed Terms- Pyrolysis, Waste management, Bio-oil, Economic viability.

I. INTRODUCTION

1.1Background of Study

Waste management has become a global challenge in the 21st century, with increasing waste volumes attributed to urbanization, population growth, and industrial development. According to the World Bank, global waste generation is projected to rise from 2.01 billion tons in 2016 to 3.4 billion tons by 2050. Traditional methods of waste disposal, such as landfilling and incineration, are fraught with environmental and economic drawbacks, including methane emissions, groundwater contamination, and rising operational costs.

In response to these challenges, pyrolysis technology has emerged as a promising solution, offering the potential to convert waste into valuable products such as bio-oil, syngas, and biochar. Pyrolysis operates by thermally decomposing organic materials at high temperatures in the absence of oxygen, resulting in minimal emissions and high resource recovery rates. It is particularly suited to managing non-recyclable waste streams such as plastics, tires, and agricultural residues, making it an essential component of the circular economy (Vigouroux, 2001).

The importance of pyrolysis extends beyond waste management. Countries like Germany, Japan, and the Netherlands have implemented pyrolysis to reduce waste accumulation while simultaneously generating energy and industrial raw materials. These nations have demonstrated that pyrolysis can reduce dependency on fossil fuels and contribute to achieving sustainability goals. Developing nations like Nigeria, which face severe waste management challenges, stand to gain significantly from adopting this technology, especially in urban areas with growing populations and waste burdens.

In Akwa Ibom State, Nigeria, urban waste generation has escalated due to economic and population growth. With inadequate infrastructure for waste processing and high demand for energy, pyrolysis technology presents an opportunity to address these dual challenges. By converting waste into energy and other commercially viable by-products, pyrolysis can foster economic development, create jobs, and reduce environmental degradation.

To contextualize the relevance of pyrolysis, a comparison of waste management methods is provided below:

Table 1: Different types of waste management methods (Abnisa, *et al.,* (2011)

Parameter	Landfilling	Incineration	Pyrolysis
Capital Cost	Low	Moderate	High
Operational Cost	Low	Moderate	Moderate
Revenue Potential	None	Low (Heat Energy)	High (Multiple Streams)
Environmental Impact	High (Methane emission)	High (Air Pollution)	Low (Net Carbonnegative)

Despite its promise, pyrolysis adoption in developing countries is hindered by high initial costs and limited technical expertise. However, as technologies advance and become more affordable, this barrier is gradually being reduced. This study focuses on the economic feasibility of pyrolysis, analyzing its costs and potential revenues while proposing strategies for effective implementation in Akwa Ibom State.

By addressing the nexus of waste management and renewable energy, the seminar explores how pyrolysis can redefine waste as a resource, contributing to both local economic development and broader sustainability goals. This work aims to inspire actionable policies and investments, ensuring the practical deployment of pyrolysis technology in Nigeria and beyond.

II. OVERVIEW OF PYROLYSIS TECHNOLOGY

Pyrolysis is a thermal decomposition process that occurs in the absence of oxygen, breaking down organic materials into smaller molecules to produce bio-oil, biochar, and syngas. The process operates at temperatures typically between 300°C and 900°C, with variations depending on the type of material and the desired product composition. Pyrolysis is widely recognized for its versatility in treating diverse waste streams, including municipal solid waste, agricultural residues, plastics, and petroleum-based wastes (Vigouroux, 2001; Bridgwater, 2012).

This technology plays a central role in the circular economy by enabling the conversion of waste into energy and raw materials, reducing reliance on virgin fossil fuels while addressing waste management challenges. Bio-oil from pyrolysis can be used as a substitute for diesel or as a chemical feedstock, while syngas serves as a clean energy source. Biochar, a solid residue, has significant applications in soil improvement and carbon sequestration (Sharma *et al.,* 2021).

2.1 Capital Costs

The capital cost of a pyrolysis system is one of the most critical factors influencing its adoption. The initial investment varies based on scale, technology type, and feedstock handling capabilities.

I. Small-Scale Systems: These systems are typically designed for localized waste treatment and cost between $50,000 and $200,000. These are ideal for small communities or agricultural applications.

II. Medium-Scale Plants: These cater to municipal waste management and range between $500,000 and $1 million. They include additional features like automated sorting and higher energy efficiency.
III. Large-Scale Industrial Systems: Costs can exceed $10 million and often include advanced features such as catalytic upgrading of bio-oil and carbon capture systems (Laird *et al.,* 2009; Bridgwater, 2012).

While capital costs can be a barrier, financing mechanisms like government subsidies, green bonds, and international climate funds can mitigate the upfront expense.

2.2 Operational Costs

Conducting a cost-benefit analysis (CBA) and calculating the payback period are critical components in assessing the economic feasibility of a pyrolysis project. The CBA compares the costs of investment and operation with the potential revenue from by-products over a set time period (often 10–20 years). According to studies by Li *et al,*. (2017), the payback period for pyrolysis plants can vary between 4 and 7 years, depending on the scale and efficiency of the plant. This is a relatively short time frame compared to other renewable energy technologies, which makes pyrolysis an attractive option for investors.

Operational costs encompass feedstock acquisition, energy usage, labor, maintenance, and distribution of by-products.

i Energy Consumption: Pyrolysis plants are self-sustaining once operational due to the syngas produced during the process, which powers the system. This reduces external energy reliance, cutting costs significantly.
ii Labor Costs: Skilled labor is essential for the operation and maintenance of pyrolysis systems. Training programs can reduce long-term expenses by increasing operational efficiency.
iii Maintenance: Regular maintenance, including cleaning and replacing parts, constitutes about 10–15% of the annual operating budget.

For example, studies from countries like India and Japan report operational costs as low as $20–$50 per ton of processed waste, depending on feedstock type and plant efficiency (Vigouroux, 2001).

III. REVENUE GENERATION AND PRODUCT MARKET DEMAND

The revenue potential from pyrolysis arises primarily from the sale of bio-oil, biochar, and syngas. Bio-oil, which can be refined into liquid fuels or chemicals, has a growing market, especially in industries seeking sustainable fuel alternatives. Biochar, a carbon-rich by-product, is used in agriculture for soil conditioning and in carbon sequestration projects (Singh *et al.,* 2018).

Syngas, which can be utilized for electricity generation or as a feedstock for chemical production, further enhances the revenue stream. The market demand for these products can be influenced by factors such as the price of crude oil, government policies on renewable energy, and shifts in consumer preferences toward sustainable products (Verma *et al.,* 2021).

3.1 Revenue Streams

The economic viability of pyrolysis is enhanced by the diverse revenue streams generated from its by-products:

1. Bio-Oil: As a renewable fuel, bio-oil commands a global price of $0.50–$1 per liter. It is used in industrial boilers, power plants, and as a chemical feedstock. For example, Japan's waste-to-energy sector heavily relies on bio-oil, contributing to energy security and reducing import dependency (Venderbosch& Prins, 2010).
2. Biochar: The global biochar market is expanding rapidly, driven by its use in agriculture and carbon sequestration. Prices range between $300–$1,200 per ton, depending on quality and application. A pyrolysis plant processing 50 tons of waste per day could generate up to $1.5 million annually from biochar alone.
3. Syngas: This clean-burning gas is used for electricity generation and industrial heating. Its economic contribution depends on the scale of production and local energy prices.

4. Carbon Credits: Pyrolysis plants that produce biochar qualify for carbon credits, providing additional financial incentives under global carbon markets.

IV. ECONOMIC ANALYSIS OF PYROLYSIS OF MAHOGANY WOOD

Economic analysis plays a pivotal role in evaluating the feasibility, financial sustainability, and environmental impact of pyrolysis technologies, as well as management of waste products particularly when considering their implementation at scale. The importance of such an analysis is most evident in the process of determining the financial viability of a pyrolysis project. This includes assessing capital investment, operational expenses, and revenue generation potential from by-products such as bio-oil, biochar, and syngas. A thorough cost-benefit analysis provides investors, entrepreneurs, and policymakers with a clear understanding of the financial risks and rewards involved, ultimately enabling data-driven decisions about project initiation (Zwart *et al.,* 2019). Furthermore, economic analysis aids in optimizing operational efficiency by identifying cost-reduction opportunities and improving overall resource use. For example, the analysis might point out areas where energy consumption can be reduced or where process adjustments can increase throughput, thereby improving the overall cost-effectiveness of the pyrolysis operation (Devi *et al.,* 2014).

In addition to direct financial considerations, economic analysis also helps in understanding market demand and product profitability. This is particularly relevant for pyrolysis products whose market prices can be highly volatile, such as bio-oil and biochar. By conducting a market analysis, stakeholders can assess demand trends and make informed decisions about the types and quantities of products to prioritize, thus ensuring that operations are aligned with consumer demand (Verma *et al.,* 2021). Economic analysis also supports policymakers by highlighting the environmental and social advantages of pyrolysis, such as reduced landfill waste, energy recovery, and job creation. By quantifying these broader benefits, the economic argument for adopting pyrolysis technologies becomes stronger, thus facilitating the creation of policies and incentives that promote its adoption (Shah *et al.,* 2020). The economic analysis, when performed comprehensively, thus not only supports individual projects but also contributes to the broader societal transition towards sustainable waste management solutions.

Furthermore, Gproms was used to simulate the thermochemical conversion of mahogany wood waste into renewable chemicals like bio-oil, below is a simulated conceptual design or the PFD of bio oil production.

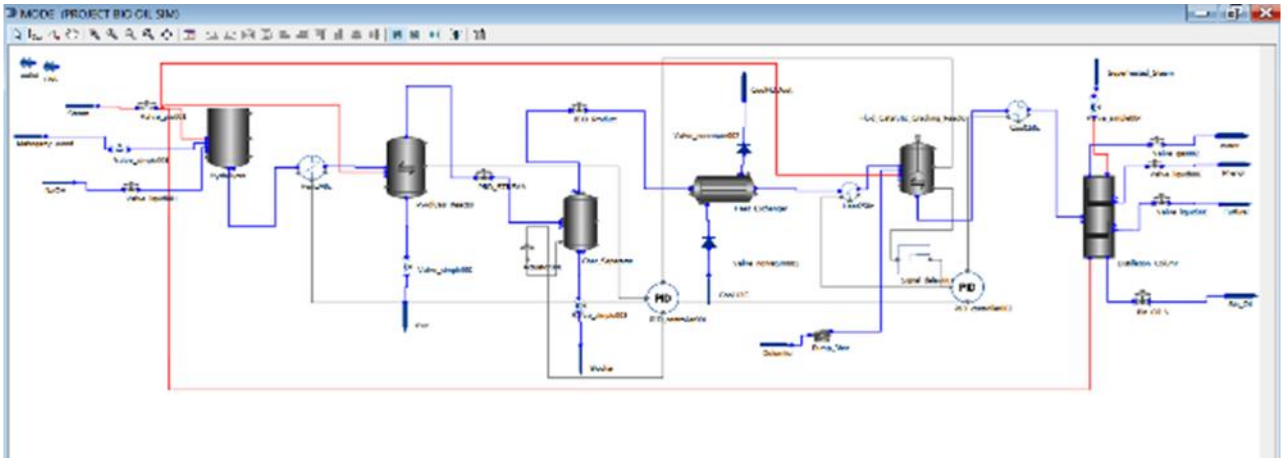

Figure 1: Process Flow Diagram for the Production of Bio-Oil from waste wood using Gproms Model Builder

From Figure 1.0, the simulated data showing the total capital cost, total utility cost, total operating cost, equipment cost and total installed cost obtained for the economic analysis is shown in Table 2.0.

The design of each piece of equipment, capital cost estimation, production cost estimation, taxation, cash flow, and profitability are the basis for the thorough estimation. The primary machinery in this chemical plant is used to calculate the profit margin and profitability of the manufacturing of bio-oil annually from Mahogany wood ("Pricing & Tariffs - Tenaga Nasional Berhad," 2023). The selected apparatus is as follows:

i. Hydrolyzer
ii. Pyrolysis Reactor
iii. Char Separator
iv. Heat Exchanger
v. Fluid Catalytic Cracking Reactor
vi. Distillation Column

In order to assess the facility's economics and make future planning decisions, the expected cost of the equipment is used to calculate the overall cost of the equipment employed in the plant. The first stage in creating a financial evaluation should be to estimate the taken-a-cost-of-capital, which is the total amount of money needed to create a contemporary capital expansion, and the generation costs, which is the total amount of money needed to operate a chemical plant. A number of broad assumptions must be made in order to evaluate the planned facility's financial viability. These are as follows:

1. The plant life span is 15 years.
2. The price of raw materials and products is fixed for the whole period of operation.
3. All the data for the purchased cost of equipment in Turton et al., (2018) were obtained from a survey of equipment manufacturers during the period April of 2025, so an average value of the CEPCI of 397 was used when accounting for inflation.
4. The purchased cost for non-major equipment is taken from where the prices are from the purchased cost of major equipment.

4.1 Purchase Equipment Cost

Capital cost is calculated by estimating the purchased cost of the specified equipment using the bare module cost. The cost of current equipment is determined using the following equation,

$$C_2 = C_1(\frac{l_2}{l_1})$$

Where,

C_2 = Purchase cost in the year 2001

C = Purchase cost in the year 2025

I_1 = CEPCI value 2001

I_2 = CEPCI value 2025

Table 4.1 Total Bare Module cost of equipment in Naira

Equipment	Non-Base (USD)	Base (USD)
Hydrolyzer	384,137.46	194,804.53
Pyrolysis Reactor	486,410.89	555,109.66
Char Separator	161,496.71	44,060.13
Heat Exchanger	837,902.70	432,116.57
FCC Reactor	3,750,253.11	646,595.36
Distillation Column	48,052.35	26,253.85
TOTAL	5,668,253.23	1,898,939.10

4.2 Estimation of Total physical plant cost

Total physical plant cost, PPC $= PCE(1 + f_1 + f_2 + f_3 + \_\_\_\_ + f_n)$

Where

$f_1 - Equipment\ erection = 0.40$

$f_2 - piping = 0.70$

$f_3 - Instrumentation = 0.20$

$f_4 - Electrical = 0.10$

$f_5 - Building = 0.15$

$f_6 - Utilities = 0.50$

$f_7 - storages\ provided\ in\ PCE = 0.15$

$f_8 - site\ development = 0.05$

$f_1 - anciliary\ buildings = 0.15$

Hence, Total physical plant cost,

$$\text{PPC} = 3{,}642{,}590(1 + 0.40 + 0.70 + 0.20 + 0.10 + 0.15 + 0.5 + 0.15 + 0.05 + 0.15)$$

= \$12,384,806

Table 4.2 Estimation of Indirect cost

I	Item	f_i
10	Design and Engineering	0.30
11	Contractor's fee	0.05
12	Contingencies	0.1

Fixed capital Investment $= PPC(1 + f_{10} + f_{11} + f_{12})$

$= 12{,}384{,}806(1 + 0.30 + 0.05 + 0.1)$

$= \$17{,}957{,}969$

Table 4.3 Estimation of Direct cost

S/N	Item	%	Cost = % of PCE in \$1000 units
1	Purchase Equipment cost	100	3642.59
2	Purchased Equipment Installation cost	40	1457.04
3	Instrumentation and control cost	15	546.39
4	Piping cost	60	2185.55
5	Electrical installation cost	12	437.11
6	Building cost	18	655.67
7	Yard improvement cost	10	364.26
8	Service facilities cost	70	2549.81
9	Land Purchase cost	10	364.26

4.3 Total Direct cost

$$= 3642.59 + 1457.04 + 546.39 + 2185.55 + 437.11 + 655.67 + 364.26 + 2549.81 + 364.26$$

$= \$12{,}202{,}680$

4.4 Working capital Investment

Working capital Investment

$= 20\%\ of\ fixed\ capital$

$$= \frac{20}{100} x\ \$17{,}957{,}969$$

$= \$3{,}591{,}593.80$

Total capital Investment= $Fixed\ capital\ investment + working\ capital\ Investment$

$\$17{,}957{,}969 + \$3{,}591{,}593.80$

$= \$21{,}549{,}562.80$

4.5 Estimation of Fixed Cost

1. Depreciation = $10\%\ of\ fixed\ capital\ Investment$

$$= \frac{10}{100} * \$17{,}957{,}969$$

$$= \$1{,}795{,}796.90$$

2. Local Taxes $= 2\%\ of\ Fixed\ capital\ Investment$

$$= \frac{2}{100} * \$17{,}957{,}969$$

$$= \$359{,}159$$

3. Insurance Cost $= 3\%\ of\ fixed\ capital\ investment$

$$= \frac{3}{100} * \$17{,}957{,}969$$

$$= \$538{,}739.07$$

Royalties $= 1\%\ of\ Fixed\ capital\ investment$

$$= 0.01 * \$17{,}957{,}969$$

$$= \$179{,}579.69$$

Total Fixed Cost $= Depreciation + Local\ Taxes + Insurance\ cost +$ Royalties

$$= \$1{,}795{,}796.90 + \$359{,}159 + \$538{,}739.07 + \$179{,}579.69$$

$$= \$2{,}873{,}274.66$$

4.6 Estimation of annual operating Costs

Since annual operating cost is a function of the operating time of plant. Also, taking a 95% plant attainment, we have

$$= \frac{345\ days}{year} * \frac{0.95}{1} * \frac{24hours}{1day} = 7866hr/day$$

But starting amount of wood = 323.1Kmol/hr

Hence amount in tonnes required to produce 15,000 tonnes per year of bio-oil

$$= \frac{323.1Kmol}{hr} * \frac{24hr}{day} * \frac{345days}{yr} * \frac{106.2kg}{1Kmol\ mahogany\ wood} * \frac{1ton}{1000kg}$$

$$= 284{,}113.46tons/yr$$

But the cost of mahogany wood at present $= \$1000/ton$

For 36108.67 tonnes per year taking a basis of one year we have,

$Annual\ Raw\ material\ cost$

$$= \frac{\$1000}{ton} * \frac{284113.46tons}{1}$$

$$= \$284{,}113{,}460$$

4.7 Estimation of Production cost

4.7.1 Direct production cost

Annual Raw material Cost = $284,113,460

Working days = 345 days per year

Utilities cost$= 20\%\ of\ raw\ material\ cost$

$$= 0.2 * \$284{,}113{,}460$$

$$= \$56{,}822692$$

Maintenance and repair cost $= 10\%\ of\ Fixed\ capital\ investment$

$$= 0.1 * \$284{,}113{,}460$$

$$= \$28{,}411{,}346$$

Operating labour and supervision cost

$$= 5\%\ of\ raw\ material\ cost$$

$$= 0.05 * \$284{,}113{,}460$$

= $14,205,673 Per year

Laboratory and other services cost $= 1\%\ of\ raw\ material\ cost$

$$= 0.01 * \$284{,}113{,}460$$

$= \$2{,}841{,}134.60$

Direct production cost

$$= \text{Raw material Cost} + \text{Utilities cost} + \text{Maintenance and repair cost} + \text{operating labour and supervision cost} + \text{Laboratory and other services cost}$$

$$= \$284{,}113{,}460 + \$56{,}822{,}692 + \$28{,}411{,}346 + \$14{,}205{,}673 + \$2{,}841{,}134.60$$

$$= \$386{,}394{,}305.60$$

4.8 Plant overhead cost

These costs are 100% of labour cost.

Hence, plant overhead cost is $14,205,673

Total manufacturing Cost $= Direct\ Production\ cost + Total\ fixed\ cost + Plant\ overhead\ cost$

$$= \$386{,}394{,}305.60 + \$2{,}873{,}274.66 + \$14{,}205{,}673$$

$$= \$403{,}473{,}253.30$$

4.8.1 General Expenses

General Expenses:

Administrative Cost $= 1\%\ of\ manufacturing\ cost$

$$= 0.01 * \$403{,}473{,}253.30$$

$$= \$4{,}034{,}732.53$$

Distribution and Marketing cost $= 2\%\ of\ manufacturing\ cost$

$$= 0.02 * \$403{,}473{,}253.30$$

$$= \$8{,}069{,}465.07$$

Hence Total General expenses $= \text{Administrative Cost} + \text{Distribution and Marketing cost}$

$$= \$4{,}034{,}732.53 + \$8{,}069{,}465.07$$

$$= \$12{,}104{,}197.60$$

4.9 Annual Production Cost

Annual Production Cost $= \text{Total manufacturing Cost} + \text{Total General expenses}$

$$\$403{,}473{,}253.30 + \$12{,}104{,}197.60$$

$$= \$415{,}577{,}450.90$$

Therefore, the Annual production Cost

$$= \$415{,}577{,}450.90$$

4.10 Annual depreciation cost

Annual depreciation, $A_D = \frac{Fixed\ capital - salvage\ value}{Plant\ life}$

Where salvage value $= 10\%\ of\ fixed\ capital\ investment$

$$= 0.1 * \$17{,}957{,}969$$

$$= \$1{,}795{,}796.90$$

Assuming a plant life of 15 years

$$A_D = \frac{\$17{,}957{,}969 - \$1{,}795{,}796.90}{15} = \$1{,}077{,}478.14$$

This implies that the plant depreciates by 6% of its initial fixed capital investment annually.

Production cost per ton $= \frac{Annual\ production\ cost}{annual\ raw\ material\ cost}$

$$= \frac{\$415{,}577{,}450.90}{\$284{,}113{,}460}$$

$$= \$1.46/kg$$

4.11 Profitability Analysis

Each investment seeks to make a profit; as such, it must be evaluated in relation to certain profitability benchmarks. A quantifiable measure of profit in relation to the investment necessary to produce that profit is known as a profitability standard. Prior to making any investment, it is crucial to understand how much can be made and whether it would be better to put the money into another kind of business. The following criteria will form the basis of the profitability analysis:

i. Turnover Ratio (TOR)
ii. Rate of Return on investment (ROR)
iii. Payback period

4.11.1 Total Annual sales

The entire revenue made from product sales over the course of a year is shown by annual cash flow. The following table summarizes the overall yearly sales:

Table 4.4 Estimation of Annual sales

Product	Daily quantity(tonne)	Cost,$ per tonne	Annual sales,$
Bio-Oil	5	1000	15,000,000
		Total annual sales (TAS)	15,000,000

Gross profit $= Total\ annual\ sales - Total\ production\ cost$

Gross profit $= \$15,000,000 - \$4,155,774.50$

Gross profit $= \$10,844,225.50$

Gross profit before tax $= Gross\ profit - Depreciation$

$= \$10,844,225.50 - \$1,795,796.90$

$= \$9,048,428.60$

Corporate income tax is 25% of Gross profit before tax

$= 0.25 * \$9,048,428.60$

$= \$2,262,107.15$

Actual annual net income after tax $=$ $\text{Gross profit before tax} - \text{Corporate income tax}$

$= \$9,048,428.60 - \$2,262,107.15$

$= \$6,786,321.45$

Actual net cash flow $=$ $\text{Actual annual net income after tax} + \text{Depreciation}$

$= \$6,786,321.45 + \$1,795,796.90$

$= \$8,582,118.35$

Table 4.5 Summary of annual cash flow

Gross annual profit		$10,844,225.50
Life of project		15
Plant attainment		95%
Depreciation		$1,795,796.90
Gross profit before tax		$9,048,428.60
Corporate income tax		$2,262,107.15
Net annual profit after tax		$6,786,321.45
Annual net cash flow		$8,582,118.35

4.11.2 Turnover Ratio (TOR)

The turnover ratio measures the relationship between the yearly gross product sales and the fixed capital investment. It is a gauge of how well a plant is using its resources to generate income. The turnover ratio ranges from 0.25-5.0. A greater turnover ratio translates into improved overall plant performance.

Mathematically, TOR $= \frac{Gross\ annual\ sales}{Fixed\ capital\ investment}$

$= \frac{\$15,000,000}{\$17,957,969}$

$= 0.84$

4.11.2 Rate of Return on investment (ROR)

The performance of capital invested may be measured in the simplest way possible, especially when two projects with very differing capital costs are being compared. The project must have a rate of return more than 15% to be successful. It is determined as:

Rate of Return on investment (ROI), $= \frac{Cummulative\ net\ cash\ flow\ at\ the\ end\ of\ the\ project}{project\ life * Total\ capital\ Investment}$

$$= \frac{107{,}182{,}212.45}{15 * 21{,}549{,}562.80}$$

$$= 33.2\%$$

Net Cash Flow (NCF) and Cumulative Net Cash Flow (CNCF) Projection for plant life (2023-2038)

Plant life	year	NCF	CNCF
0	2023	-21,549,562.80	-21,549,562.80
1	2024	8,582,118.35	-12,967,444.45
2	2025	8,582,118.35	-4,385,326.10
3	2026	8,582,118.35	4,196,792.25
4	2027	8,582,118.35	12,778,910.60
5	2028	8,582,118.35	21,361,028.95
6	2029	8,582,118.35	29,943,147.30
7	2030	8,582,118.35	38,525,265.65
8	2031	8,582,118.35	47,107,384.00
9	2032	8,582,118.35	55,689,502.35
10	2033	8,582,118.35	64,271,620.70
11	2034	8,582,118.35	72,853,739.05
12	2035	8,582,118.35	81,435,857.40
13	2036	8,582,118.35	90,017,975.75
14	2037	8,582,118.35	98,600,094.10
15	2038	8,582,118.35	107,182,212.45

4.11.3 Payback period

The payback period is the amount of time needed after the project's launch for the initial expenditure to be recovered through revenue. A project should typically have a payback period of 2 to 5 years to be considered commercially viable (Sinnott, 2008). It is predicted that the payback period will last about two (2) years. This is seen in the figure below:

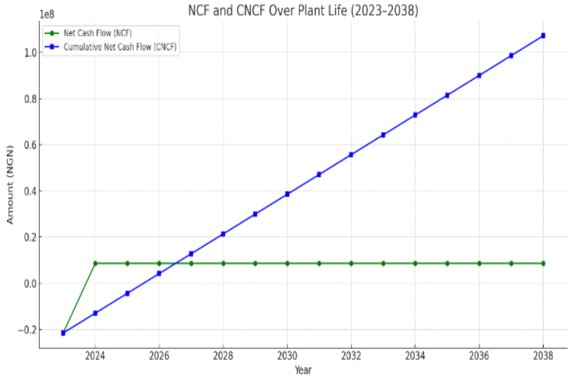

Fig 4.2 Graph of cumulative cash flow against Plant life

4.1 Challenges and Mitigation Strategies

Despite its potential, pyrolysis faces several significant challenges that could hinder its widespread adoption. These obstacles are primarily categorized into technical, economic, and regulatory barriers, each of which requires specific mitigation strategies. One of the foremost challenges is the high initial capital cost required to set up a pyrolysis facility. These costs include the purchase of pyrolysis reactors, feedstock preparation systems, and other necessary infrastructure, which can total several million dollars, depending on the scale of the operation (Bui *et al.,* 2020). This can be particularly burdensome for small- and medium-sized enterprises (SMEs) or in developing countries, where access to capital may be limited. To address this, governments and financial institutions can step in to offer subsidies, low-interest loans, or grants to lower the financial barriers to entry for these businesses. Public-private partnerships (PPPs) could also help distribute financial risk, making it more attractive for private investors to fund pyrolysis projects.

Feedstock variability is another significant challenge in pyrolysis. The performance and profitability of pyrolysis are closely linked to the consistency and quality of the raw materials, which are often waste products like plastics, agricultural residues, and municipal waste. These materials can vary widely in terms of moisture content, chemical composition, and contamination, leading to inefficiencies in the pyrolysis process (Kwon *et al.,* 2018). For example, high moisture content can lead to higher energy consumption and reduced product yields, making it less cost-effective. To mitigate this issue, feedstock pre-treatment processes, such as shredding, drying, and sorting, can help ensure that the input materials meet the required specifications for efficient pyrolysis. Technological advancements in sensors and automation can also allow for real-time monitoring and control of feedstock quality, helping to optimize the process (Liu *et al.,* 2018).

Market uncertainty is another challenge that affects the adoption of pyrolysis technologies. The market for pyrolysis by-products, such as bio-oil and biochar, can fluctuate significantly depending on external factors like crude oil prices or shifts in consumer demand for renewable products (Verma *et al.,* 2021). To mitigate market volatility, governments and industry stakeholders can work to develop stable markets for these by-products through incentives, targeted marketing, and public procurement policies. By fostering demand for these products, policymakers can ensure a consistent revenue stream for pyrolysis operators, thereby enhancing the financial sustainability of these projects. Furthermore, regulatory barriers and environmental concerns often present hurdles, particularly around emissions and waste management. Many regions lack clear regulations for pyrolysis operations, leading to delays in permits or unexpected costs due to the need for environmental compliance (Niazi *et al.,* 2020). Governments can mitigate these challenges by establishing clear and consistent regulations that balance environmental protection with the promotion of innovative waste-to-energy technologies. Ensuring a predictable regulatory environment will not only accelerate the development of pyrolysis but also reduce the uncertainty faced by investors.

Finally, public perception can sometimes hinder the widespread acceptance of pyrolysis projects, particularly when communities are concerned about environmental pollution or safety risks. Public resistance often arises from misconceptions about the technology's environmental impact. Addressing this challenge requires comprehensive public engagement strategies, including awareness campaigns and community consultations. Transparent communication about the safety, environmental, and economic benefits of pyrolysis is essential to gaining public support and facilitating smoother project approvals (Berenji *et al.,* 2019). By addressing these technical, economic, and societal challenges, the adoption of pyrolysis technologies can be accelerated, allowing for broader integration of this waste-to-energy solution.

V. POLICY RECOMMENDATIONS

To overcome the challenges facing pyrolysis and foster the widespread adoption of this technology, several policy recommendations can be proposed. These recommendations focus on providing the necessary financial support, ensuring clear regulatory frameworks, and promoting collaboration between various stakeholders to create an enabling environment for pyrolysis technologies.

One critical policy intervention is the provision of financial incentives for businesses investing in pyrolysis projects. High capital costs remain one of the most significant barriers to the adoption of pyrolysis, and policies that reduce these costs could accelerate the development of pyrolysis plants. These incentives could include tax breaks, grants, low-interest loans, or even direct subsidies for the construction of pyrolysis facilities. Additionally, governments could offer incentives for the purchase of feedstock pre-treatment equipment, which would help ensure that feedstocks meet the necessary quality standards for efficient pyrolysis. Such financial support would make pyrolysis more financially viable, especially for small and medium-sized enterprises (SMEs) that may lack the resources to invest in the technology on their own (Devi *et al.,* 2014).

Another important policy recommendation is the development of clear, consistent, and transparent regulatory frameworks that guide the operation of pyrolysis plants. The regulatory environment must be predictable and balanced to ensure that businesses can operate without the fear of frequent changes in regulations or unanticipated costs. Clear emissions standards, waste management guidelines, and operational protocols would help businesses navigate the regulatory landscape with confidence. Importantly, these regulations should be designed to encourage innovation and investment, without stifling the development of new technologies (Niazi *et al.,* 2020). By creating a favorable regulatory environment, governments can encourage the adoption of pyrolysis while maintaining high environmental standards.

Furthermore, promoting collaboration between public and private sectors is essential to the growth of the pyrolysis industry. Governments should facilitate public-private partnerships (PPPs) that share the risks and rewards of investing in pyrolysis. Such partnerships can help mitigate the financial burden on both parties and ensure the success of pyrolysis projects. Additionally, industry stakeholders, including businesses, research institutions, and environmental organizations, should collaborate to create markets for pyrolysis products. Policies that incentivize the use of sustainable products like biochar and bio-oil in agriculture, energy production, and other industries will help stabilize the market for these products and provide a reliable revenue stream for pyrolysis operators (Yuan *et al.,* 2021). By working together, stakeholders can ensure that the economic, environmental, and social benefits of pyrolysis are fully realized.

Finally, promoting public awareness and community engagement is essential for the successful adoption of pyrolysis technologies. Governments and businesses should engage with local communities early in the project planning process to address any concerns and ensure that the benefits of pyrolysis are understood. Public awareness campaigns that highlight the environmental, economic, and social benefits of pyrolysis can help dispel myths and build public support for these projects. Engaging local communities in the decision-making process also fosters a sense of ownership and involvement, which can lead to smoother project approvals and better long-term outcomes (Berenji et al., 2019). In summary, the successful implementation of pyrolysis technologies requires a combination of supportive policies, strategic investments, and active stakeholder collaboration to overcome challenges and realize the full potential of this innovative waste-to-energy solution.

CONCLUSION

The economic analysis of pyrolysis of waste highlights its immense potential as an innovative solution for waste management, energy recovery, and environmental sustainability and most importantly revenue generation. Through rigorous financial assessments, it is clear that while the initial capital investments and operational costs are significant, the long-term benefits of pyrolysis, such as waste reduction, energy production, and the creation of valuable by-products make it a promising technology for both developed and developing economies. A comprehensive understanding of the economic aspects of pyrolysis, including cost-benefit analysis and market demand for its products, is crucial for attracting investment and ensuring the technology's successful implementation on a large scale.

However, the widespread adoption of pyrolysis faces significant challenges, such as high capital costs, feedstock variability, and regulatory uncertainties. To address these obstacles, targeted policy interventions are needed, including financial incentives, clear regulatory frameworks, and policies that foster innovation. Stakeholder engagement is also essential to ensure the successful integration of pyrolysis into waste management systems. Governments, private companies, environmental organizations, and local communities must collaborate to create an enabling environment for pyrolysis technologies to thrive.

In conclusion, the economic analysis of pyrolysis provides valuable insights into its potential as a sustainable waste-to-energy technology. With the right policies, financial support, and stakeholder collaboration, pyrolysis can play a key role in addressing the growing challenges of waste management and environmental conservation, making it an essential part of the global transition toward a circular economy.

REFERENCES

[1] Abatzoglou, N., and Boivin, S.(2009). A Review of Biogas Purification Processes. *Journal of Biofuels, Bioproducts and Biorefining*, 3:42 – 71.

[2] Agar, D.A. and Schneider, S.L. (2004). Pyrolysis of municipal solid waste: Environmental considerations. *Journal of Environmental Engineering,* 130:(10) 1189-1197.

[3] Abnisa, F. and Daud, W.M.A.W. (2011). Pyrolysis of solid waste for biofuel production: A review. Renewable and Sustainable Energy Reviews, 15:(5) 2969-2976.

[4] Bernstein, S. and Yaw, M. (2017). Pyrolysis technology for waste oil and petroleum recovery. Energy and Fuels, 31:(5) 5472-5481.

[5] Briassoulis, D. and Hiskakis, M. (2009). Recent advances in the pyrolysis of organic waste for energy recovery. Energy Conversion and Management, 50:(5) 1340-1346.

[6] Bridgwater, A.V. (2012). Review of fast pyrolysis of biomass. Renewable and Sustainable Energy Reviews, 16: 2126-2143.

[7] Bridgwater, A.V., and Peacocke, G.V.C. (2000). Fast pyrolysis of biomass: A handbook. CPL Press.

[8] Cao, X., and Li, Z. (2011). Pyrolysis of petroleum sludge and waste plastics: Product distribution and properties. Environmental Science & Technology, 45:(7) 3150-3156.

[9] Carmo, M., and Santoro, D. (2019). Catalytic pyrolysis of biomass and waste: Current status and perspectives. Springer.

[10] Challender, F. (1943). Biochemistry of pyrolysis. Academic Press.

[11] Chiaramonti, D., and Prussi, M. (2014). Biomass pyrolysis for biofuel production. Springer.

[12] Czernik, S., and Bridgwater, A.V. (2004). Overview of applications of biomass fast pyrolysis oils. Energy & Fuels, 18:(2) 539-558.

[13] Dufour, J., & Henna, L. (2018). Thermochemical conversion of biomass into biofuels. Wiley-VCH.

[14] Fahim, M.A. (2013). Handbook of petroleum refining processes. McGraw-Hill Professional.

[15] Figueiredo, J., and Junqueira, T. (2016). Pyrolysis of agricultural waste for biofuels. Renewable and Sustainable Energy Reviews, 60: 808-819.

[16] Fukui, Y., and Kikuchi, M. (2007). Conversion of waste plastic to valuable products via pyrolysis. Polymer Degradation and Stability, 92:(7) 1304-1309.

[17] Ghanem, H.M., and Badr, M. (2015). Pyrolysis and combustion of plastic waste for energy recovery. Energy Conversion and Management, 89: 132-139.

[18] García-Pérez, M., and Pérez, M. (2015). Biomass pyrolysis in fluidized bed reactors: Recent advances. *Journal of Analytical and Applied Pyrolysis*. 113: 58-73.

[19] Huang, Y., and Zhu, S. (2009). Chemical transformations during the pyrolysis of biomass. Fuel Processing Technology, 90:(1) 19-28.

[20] Huang, Z., and Wang, S. (2007). Pyrolysis of waste oils and fats for biodiesel production. Bioresource Technology, 98:(8) 1641-1648.

[21] Jung, S., Lee, K., and Lee, Y. (2016). Pyrolysis of petroleum waste: Potential energy applications. Energy Reports. 2: 50-59.

[22] Kalogiannis, K., & Lappas, A. (2015). Pyrolysis of plastic waste: Comparative study of different reactors. Waste Management, 35, 32-39.

[23] Khandelwal, S.K., & Tiwari, G.B. (2015). Handbook of biofuels production. Elsevier.

[24] Khor, C.P., and Sopi, M. (2013). Green energy from waste: Biomass, pyrolysis and biorefining processes. Springer.

[25] Lappas, A., and Stournas, S. (2008). Pyrolysis of waste polymers and oils: Characterization of products and applications. *Journal of Analytical and Applied Pyrolysis*, 82:(1) 3-17.

[26] Lal, M., and Baral, K. (2018). Waste-to-energy technologies and global policy: Analysis of environmental impact. Elsevier.

[27] Li, X., and Zeng, J. (2012). Pyrolysis of waste plastics and their applications. *Journal of Hazardous Materials,* 239: 298-307.

[28] Meyer, E., and Caslin, J.R. (2001). Pyrolysis of organic materials for waste-to-energy. Energy Reviews, 16: 41-57.

[29] Muñoz, L., and Bojczuk, L. (2012). Advances in pyrolysis technologies for waste recycling. Waste and Biomass Valorization, 3: 491-502.

[30] Oasmaa, A., and Czernik, S. (1999). Fuel oil quality of biomass pyrolysis oils – State of the art for the year 2000. Energy and Fuels, 13:(3) 567-576.

[31] Olsson, L., and Nilsson, A. (2010). Pyrolysis of waste oils in fluidized bed reactors: Process optimization and product quality. Fuel Processing Technology, 91:(11) 1473-1481.

[32] Padhye, L. and Schmidt, C. (2017). Pyrolysis of rubber waste: A review of thermochemical processes. Energy & Fuels, 31:(9) 9910-9923.

[33] Purschke, B. and Hecht, A. (2009). Waste-to-energy technology: Principles and applications. Elsevier.

[34] Ragauskas, A.J. and Williams, C.K. (2014). Biomass to biofuels: Strategies for global warming and sustainability. Wiley-Blackwell.

[35] Ravindranath, N.H. and Hall, D.O. (1995). Biomass, energy and environment: A developing country perspective from India. Oxford University Press.

[36] Shafizadeh, F. and Bradbury, G.W. (1979). Thermal degradation of cellulose in air and nitrogen at low temperatures, *Journal of Applied Polymer Science.* 23: 1431-144.

[37] Shafizadeh, F. and -Z Lai, Y. (1975). Thermal degradation of 2-deoxy-Darabino-hexonic acid and 3-deoxy-D-ribo-hexono-1,4-lactone, Carbohydrate Research 42: 39-53.

[38] Silva, S. and Malkow, T. (2009). Pyrolysis of municipal solid waste: Energy recovery and environmental protection. Journal of Hazardous Materials, 167:(3) 97-103.

[39] Soto, R.,and Chavarria, J. (2016). Biomass and waste pyrolysis: Key processes and technology. Wiley.

[40] Sun, Y. and Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: A review, Bioresource Technology, 83: 1-11.

[41] Tomas-Pejo, E., Hassan, M. and Mohammed, Q. (2008). Realistic approach for full-scale bioethanol production from lignocellulose: a review. *Journal of Science Industry Research*, 67: 874-884.

[42] Van der Drift, A., and Kijko, E. (2008). Pyrolysis of waste plastics and its future applications. *Journal of Chemical Technology and Biotechnology*, 83:(3) 479-493.

[43] Vasileiou, M. and Karakoulia, S. (2018). Energy recovery from plastic waste via pyrolysis. Renewable and Sustainable Energy Reviews, 82: 473-485.

[44] Wijekoon, P., Wickramasinghe, C., Athapattu, B.C.L., Narayana, M., de Alwis, A. and Vithanage, M. (2021). Biomass valorization and phytoremediation as integrated technology for municipal solid waste management for developing economic context. Biomass Conversion Biorefinery, 11(2): 363-382.

[45] Williams, P.T. (2005). Waste treatment and disposal. Wiley-Blackwell.

[46] Yacob, T., Donald, W. and Manny, F. (2018). Pyrolysis of human feces: Gas yield analysis and kinetic modelling, Waste Management, 79: 214 - 222.

[47] Younus, S., Tu, M. and Roessler, M. (2013). Performance and emissions characteristics of diesel engine fueled with tyre pyrolysis oil and diesel blends with additives, *International Journal of Engineering Science Invention.* 2(5): 32-37.

[48] Ziwei, Y., Max, W. and Lai, Y. (2018). Improvement of pyrolysis oil obtained from co-pyrolysis of WPCBs and compound additive during two-stage pyrolysis.