PARAMETRIC STUDY OF A PLASTIC WASTE PYROLYZER USING THE TAGUCHI METHOD

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ABSTRACT

This study aims to parameterize a prototype pyrolyzer for the treatment of plastic waste, in order to optimize its yield. The experimental set-up is based on a batch reactor operating in slow pyrolysis. The tests were carried out according to a Taguchi L8 design of experiments, evaluating three key parameters: the type of plastic, the filling rate of the reactor and the type of fuel used. Analysis of the results, performed with Minitab software, revealed that high-density polyethylene (HDPE) offers a notable gross yield of 79.60%, with a fill rate of 35% and the use of cardboard as fuel. Regarding the pyrolysis oils produced, several properties were compared to conventional fuels: water content, viscosity, flash point and lower calorific value. It was found that oil made from polyethylene terephthalate (PET) has characteristics close to diesel, with a usable energy efficiency of 57.11%. However, its high viscosity requires additional refining before any practical use. Despite these limitations, the results highlight the promising potential of pyrolysis as a sustainable solution for plastic waste management and reducing dependence on fossil fuels in Madagascar.

Keywords: *Plastic waste recovery, Sustainable development, Biofuel production, Pyrolysis of plastics*

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1. INTRODUCTION

Plastics are among the most widely used materials worldwide. Its lightness, durability, low cost, and ease of transformation make it ubiquitous in everyday objects from office supplies to modern technologies. These properties have led to their mass adoption in key sectors such as engineering, construction, armaments, and medicine [1] [2]. The growing demand for plastic is driving continued production, with a projected annual increase of 3.8% [3]. In 2022, global production reached 460 million tons, doubling in 20 years and potentially tripling by 2060 [4]. However, this expansion is accompanied by an exponential accumulation of plastic waste, which persists in the environment because of its resistance to biodegradation. This poses a major challenge for the preservation of ecosystems, as chemicals released harm biodiversity and environmental health. In addition, this proliferation contributes to the pollution of the soil, air, and water.

Developing countries, which are significant producers of single-use plastics, play a central role in this accumulation [5] [6]. In Madagascar, more than 10% of the waste is plastic [7], with approximately 400 tons generated every day in the capital Antananarivo [8]. The effective management and recovery of this waste is a crucial challenge, both nationally and internationally. Many studies have focused on optimizing plastic waste management processes [9]. Of these processes, pyrolysis occupies a central position. This thermochemical technique converts plastic waste into value-added products such as fuels. It has two advantages: it reduces the volume of waste while reducing dependence on fossil fuels. As part of a circular economy approach, it offers environmental and socioeconomic benefits to Madagascar. Thus, pyrolysis could become a major lever for sustainable development in the country.

This study aims to contribute to the optimization of the plastic pyrolysis process to maximize the yield and quality of pyrolysis oil. The Taguchi method was used to identify the optimal combination of operational parameters and assess their impact on the process performance.

2. LITERATURE REVIEW

2.1 Recovery of plastic waste by pyrolysis

Pyrolysis is a thermochemical process that breaks down materials in the absence of oxygen. It can be thermal or thermo-catalytic, with or without catalysts, and occurs between 200°C and 1,000 °C, depending on the materials and objectives. The pyrolysis of plastic waste degrades polymers into smaller molecules, producing three fractions: gas (syngas), liquid (pyrolysis oil), and solid residue (coal). Each fraction has an industrial value [10] [11] [12]. As they are derived from petroleum, pyrolysis products have a high calorific value, which makes them suitable for energy recovery as an alternative to fossil fuels. In addition, their physicochemical characteristics are close to those of conventional petroleum products such as petrol and diesel [13] [14].

Studies, including that of *Papari and al*. [14], have explored various technologies for processing non-biodegradable waste, including plastics. They conclude that pyrolysis, particularly flash pyrolysis, is an efficient and sustainable thermal depollution method, capable of producing 0.50 to 0.75 kg of fuel from 1 kg of plastic waste, without significant emission of contaminants.

Given the benefits of pyrolysis and the current environmental challenges, its optimization is essential. Precise parameterization of the pyrolyzer increases yield, reduces pollutant emissions, and improves product quality, while reducing operational costs. Therefore, process optimization requires a thorough understanding and rigorous control of key parameters [9].

2.2 Pyrolysis: optimised energy recovery

Almost half of the plastics produced end up as waste [15], representing a substantial amount. The accumulation of this waste is a major source of pollution, seriously threatening human health, as well as terrestrial and marine ecosystems. In addition, the degradation of plastics is extremely slow, with some types requiring up to 500 years to fully decompose [16].

Therefore, it is imperative to develop sustainable methods for the management and treatment of plastic waste [17]. Three main approaches were envisaged: reextrusion, chemical recycling, and energy recovery [18]. Although reextrusion allows the reuse of plastics, it is not a sustainable solution, as the resulting products become waste again. Chemical recycling, while offering the potential for depolymerization of plastics, remains difficult to implement owing to its high cost and the need for rigorous sorting of materials; not all plastics are recyclable. However, energy recovery appears to be the most promising option, offering a viable solution for converting plastic waste into useful energy.

Extensive research has led to the development of three main processes for recovering energy from plastic waste: incineration, gasification, and pyrolysis. However, incineration has serious environmental disadvantages, generating significant emissions of NO_x, CO_x, SO_x, dioxins, furans, and a considerable amount of fumes [19]. Conversely, gasification and pyrolysis are more environmentally friendly alternatives, with pyrolysis being distinguished by its lower energy consumption [20]. Owing to these advantages, pyrolysis appears to be a promising solution for the management and recovery of plastic waste [5].

2.3 Influences of Operational Parameters on the Performance and Flexibility of Pyrolysis of Plastics

One of the main strengths of pyrolysis is the flexibility of its operational parameters, which can be adjusted according to the specifications of the final product [21].

To better understand and optimize this process, many experimental studies have been conducted to explore various aspects, such as operational parameters, type of reactor, and composition of raw materials. The presence of pollutants and their influence on the quality and composition of the obtained fuel have also been studied [22].

Operational parameters play a decisive role in optimizing the yield and composition of pyrolysis products. In the context of the pyrolysis of plastics, key variables such as temperature, type of reactor, pressure, residence time, use of catalysts, and nature of the plastic process directly influence the distribution of the final products, including pyrolysis oil, syngas, and solid residue (coal) [23].

- ***Influence of temperature and pressure***

Temperature is undoubtedly one of the most critical operating parameters in pyrolysis, as it directly controls the cracking process of polymer chains. As the temperature increased, the intensity of the molecular vibrations increased, thereby promoting the evaporation of compounds. This phenomenon occurs when the energy supplied exceeds the enthalpy of the C-C bonds, leading to the rupture of the carbon chains. The distribution of yields between different fractions (gaseous, liquid, solid) varies depending on the type of plastic and the temperature applied, with a low recovery of the condensable fraction at low temperatures [24] [25]. Temperature-induced thermal cracking also influences the quality of gaseous and liquid products; at low temperatures, long-chain hydrocarbons are mainly produced, whereas at high temperatures, short-chain hydrocarbons predominate. Therefore, it is crucial to operate at an optimal temperature to maximize yield and product quality. Miandad *and al.* (2016) demonstrated that this optimal temperature range varies depending on the type of polymer being processed [21].

Pressure plays a key role in the distribution of carbon chains within liquid products, promoting the formation of low molecular weight compounds under high pressures. The thermal degradation of plastics varies according to temperature range and is influenced by van der Waals forces between molecules, which can limit the cracking process. In addition, pressure has a significant impact on the rate of double-bond formation, thus changing the chemical composition of the final products [9].

- ***Effects of catalysts and additives***

Catalysts, as accelerators of chemical reactions, remain unchanged at the end of the process and are widely used in industry and research to optimize product distribution and improve reaction selectivity [23]. Their incorporation reduces energy consumption while accelerating the reaction kinetics. The use of catalysts can also lead to lower operational costs, improved process selectivity, and inhibition of the formation of undesirable products such as cyclic, aromatic, and branched hydrocarbons during the catalytic cracking of polyolefins. In addition, the reaction time in the catalytic pyrolysis of plastics decreases with increasing catalyst concentration [24] [26]. Machiraju *and al.* showed that catalytic pyrolysis can produce fuels with chemical properties comparable to those of conventional fuels [27].

Catalysts commonly used in the pyrolysis of plastics include FCC, HZSM-5, MCM-41, HY, Hβ, HUSY and mordenite. Among these, zeolite catalysts stand out for their remarkable efficiency in processes such as cracking, isomerization, and oligomerization/aromatization. This performance is attributed to their specific physicochemical properties, particularly their high acidity and microporous crystal structure, which promote increased reactivity in catalytic reactions [28].

2.4 Experimental studies on the optimization of the operating parameters of pyrolysis of plastics

Given the significant advantages offered by pyrolysis of plastic waste, this process has been the subject of numerous studies aimed at improving its efficiency. Table 1 presents a selection of examples of studies on the optimization of this process.

Table -1 : Examples of pyrolysis optimization studies

References	Methodologies	Results and Discussion
[29]	Determination of the optimum temperature for maximising the oil yield from polystyrene pyrolysis; Temperatures studied: 400°C, 450°C and 500°C	The yields obtained were 76% oil at 400°C, 80.8% oil at 450°C and 78.7% oil at 500°C. Optimum conditions for a maximum liquid oil yield of 81% were obtained at a temperature of 450°C.
[6]	Determination of the impact of using barium chloride as a catalyst by comparing the yields of pyrolyses carried out with and without a catalyst; Types of plastic studied: PP, HDPE and LDPE; Heating temperature: between 350°C and 400°C	Without a catalyst, yields are 47.5% for HDPE, 45% for PP and 75% for LDPE. In the presence of a catalyst, the yields are 92.5% for HDPE, 72.5% for PP and 92% for LDPE. Pyrolysis with a catalyst gives higher yields than without.
[30]	Study of slow pyrolysis in a batch reactor; Types of plastic studied: PP, HDPE and LDPE; Temperatures studied: ranging from 350 to 450°C, for a period of 4 to 6 hours; Tests carried out: - 100% PP, - 100% HDPE, - 100% LDPE, - And mixing of plastics	Liquid fuel yields for the various tests: - For PP, 80% ; - For HDPE, 70%. - For LDPE, 73%; - For the blend, 46%. The higher the temperature, the higher the yield of liquid products.
[31]	Determination of the optimum temperature for maximising PET pyrolysis yield; Reactor used: fixed-bed batch reactor equipped with a condensation system connected by a gas line; Temperatures studied: 300°C, 350°C and 400°C;	Test yields : - At 300°C: 08% ; - At 350°C: 23% ; - At 400°C: 49%; The higher the temperature, the higher the liquid yield.
[32]	Study of the behaviour of plastics at different temperatures; Types of plastic studied: PE, PP, PET, LDPE and PS; Temperatures studied: 300°C, 400°C, 500°C, 600°C and 700°C.	- The liquid yields of PP and PE decrease with increasing temperature; - The liquid yields of LDPE and PS increase with temperature; - PP gas yields are high. - The oils obtained from PET are considered to be zero, as their physical appearance was not in liquid form.

Table 1 illustrates that optimizing the performance of plastic pyrolysis relies on careful selection of operational parameters, such as temperature, reaction time, and the use of catalysts. These variables play key roles in improving the efficiency of the process.

2.5 Challenges of Industrial Scale-Up of Pyrolysis

The main limitation of pyrolysis is the difficulty of transposing the results obtained in the laboratory to an industrial scale. Indeed, the majority of studies have focused on small-scale experiments, which limits the understanding of the technical and economic challenges associated with large-scale implementation. Capital and operating costs for industrial facilities remain high, constituting a major obstacle to their adoption. In addition, pyrolysis requires a considerable source of energy, making it difficult to compete with fossil fuels, which are often cheaper and more widely available.

3. MATERIALS

This study aims to identify the optimal parameters for the pyrolysis of plastic waste. To this end, a pyrolyzer prototype was designed, and the operational parameters were optimized using the Taguchi method.

3.1 Raw materials

The plastic waste used in this study were made up of plastics belonging to the olefin family, selected because of their prevalence in waste streams in Madagascar. Figures 1- 4 illustrate the different types of plastics.

Fig -1: Polypropylene (PP)

Fig -2: Polyethylene Terephthalate (PET)

Fig -3: High-Density Polyethylene (HDPE)

Fig -4: Low-Density Polyethylene (LDPE)

3.2 Detailed description of the pyrolysis test device

The experimental pyrolysis device included a reactor dedicated to thermal decomposition, burner for heat generation, and chimney for the evacuation of flue gases. It is also equipped with a condensing system to liquefy the vapors produced, as well as a network of pipes for transporting the generated gases. To maximize the process efficiency, this package ensures the precise management of heat and mass flows. In addition, the system has temperature sensors positioned at strategic points on the pyrolyzer, allowing continuous monitoring and real-time recording of critical data throughout the process.

- ***Reactor***

The reactor used was a cylindrical fixed-bed batch model with an inner diameter of 5 cm and height of 100 cm (see Figure 5). It is hermetically sealed to prevent oxygen entry, owing to a seal between the lid and reactor wall, thus guaranteeing anaerobic conditions throughout the process. Heat transfer occurs by conduction through the walls of the reactor, whereas convection ensures the distribution of heat inside the reactor.

- ***Burner or fireplace***

This section of the device ensures the generation of the heat required for heating the reactor. Fuels were supplied continuously to ensure that the experiments ran smoothly. The heat transfer in this zone is mainly by convection. Figure 6 presents a detailed illustration of the burner.

- ***Condenser***

The condenser allows for the conversion of condensable gases from the reactor, changing them from a gaseous state to a liquid state. The system consisted of two receiving tanks, each immersed in a basin of water to facilitate cooling. The tanks were connected in series using a pipe. The first vessel receives the gases coming directly from the reactor, whereas the second vessel, via an outlet pipe, evacuates the residual non-condensable gases. Figure 7 illustrates the condenser used in the device.

- ***Temperature Logger***

The logger accurately tracked the temperature variations in real time using four thermocouples strategically placed in the pyrolysis machine. This configuration provides an overview of the thermal conditions, detects fluctuations that can affect performance, and allows data to be analyzed to optimize the prototype stability and efficiency. It was composed of the following equipment: an Arduino Mega microcontroller, four MAX 6675 thermocouples, an SD module, an RTC module, and an I2C module. The temperature recorder used is shown in Figure 8.

Fig -4: Pyrolyzer prototype reactor

Fig -4 : Burner of the pyrolyzer prototype

Fig -4 : Condenser of the pyrolyzer prototype

Fig -4 : Temperature recorder of the pyrolyzer prototype

4. METHODS

4.1 Applied Pyrolysis Process

The operating procedure of the pyrolysis system involves several essential steps:

- **Reactor cleaning**: Removal of residues from the previous operation to ensure precise loading and reliable results.
- **Raw material loading**: Weighing and introducing the materials into the reactor.
- **Startup phase**: The reactor is heated to a maximum temperature to initiate the pyrolysis reaction.
- **Transformation phase**: The gases released are condensed into pyrolytic liquid in two successive tanks, while non-condensable gases are evacuated.
- **Termination phase**: The operation concludes when the fluid output decreases, indicating that the system is primarily evacuating water.

These steps ensure an efficient process and optimal results. Figure 9 illustrates the followed process:

Fig -_9_ : Pyrolysis process

4.2 Design of the design of experiments - Taguchi's method

➢ ***Parametric study by the Taguchi method***

The Taguchi method incorporates the variability of materials and processes from the design phase, thus improving the quality while reducing costs [33]. It is based on rigorous experimental planning using orthogonal networks, which allows targeted experiments to be carried out to identify optimal performance conditions. By minimizing the number of trials required, this approach helps industries reduce development costs and time, while maximizing profits [34].

The Taguchi statistical approach also makes it possible to analyze the impact of various parameters on a process, thus facilitating the optimization of the settings. This method includes parameter screening, quantification of effects and synergies, and predictive modeling of the responses [35]. The results were evaluated using the signal-to-noise ratio, which helped identify the most influential parameters and their optimal levels. Regression techniques were used to build the predictive model. Statistical processing of the data was performed in the Minitab environment [34] [23].

➢ ***Taguchi's experimental parameters and L8 design of experiments***

The controllable parameters studied and their respective levels are as follows:

1. ***Plastic waste type:*** Polypropylene (PP), Polyethylene Terephthalate (PET), Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE),
2. ***Reactor fill rate:*** 35%, 100%,
3. ***Fuel type:*** Cardboard, polypropylene film.

Based on the analysis conducted using Minitab, the Taguchi L8 experimental design was the most appropriate for this study. Table 2 shows the L8 experimental design generated using this software.

Table -2 : Design of Experiments Generated by Minitab

	PLASTIC WASTE TYPE	FILL RATE	FUEL TYPE
Test 1	PP	35%	FILM
Test 2	PP	100%	CARDBOARD
Test 3	PET	35%	FILM
Test 4	PET	100%	CARDBOARD
Test 5	HDPE	35%	CARDBOARD
Test 6	HDPE	100%	FILM
Test 7	LDPE	35%	CARDBOARD
Test 8	LDPE	100%	FILM

- ***Design of Experiments System Responses***

The objective of this study was to determine the optimal parameter values to improve the pyrolysis yields. The answers analyzed during the experiments included gross yield, net yield, technological yield, and energy efficiency of the pyrolysis tests.

- Gross yield

Gross yield measures the primary efficiency of plastic waste-to-oil conversion, considering variations in plastic waste during the process. It provides an accurate assessment of the performance of the technology being used, allowing the identification of adjustments required to optimize performance.

- Net yield

The net yield provides an accurate assessment of the efficiency of the oil extraction process, incorporating plastic waste and fuel losses as well as the overall performance of the energy conversion system.

- Technological yield

Technology yield is a key indicator for evaluating the efficiency of oil production in reactors, considering the energy density of the treated plastic waste and the performance of the reaction system. This allows for an in-depth analysis of technological performance and highlights opportunities for improvement.

- Energy yield

Energy efficiency evaluates the efficiency of energy conversion by considering the lower calorific value (LCV) of each component as well as the necessary adjustments for potential losses and inefficiencies in the plastic waste-to-oil process.

4.3 Characterizations of the products obtained

To assess the suitability of the resulting oils for use as fuel, their characterization was carried out according to several criteria: density, flash point, viscosity, and water content. These analyses were conducted within the Office of the National Mines and Strategic Industries (OMNIS).

5. RESULTS AND DISCUSSIONS

5.1 Results of experimental pyrolysis tests

Eight pyrolysis tests on plastic waste were conducted using our experimental setup. Table 3 presents the yields obtained for each trial.

Table -3 : Yields of the different pyrolysis tests

Test	Plastic waste type	Fill rate (%)	Fuel type	Gross yield (%)	Net yield (%)	Technological yield (Kg/m^3)	Energy yield (%)
1	PP	35	FILM	3.08	0.53	2.04	1.65
2	PP	100	CARDBOARD	2.83	2.16	9.07	2.52
3	PET	35	FILM	40.00	5.41	6.11	57.11
4	PET	100	CARDBOARD	14.44	3.85	6.62	20.36
5	HDPE	35	CARDBOARD	79.60	1.07	0.61	7.93
6	HDPE	100	FILM	73.33	1.87	2.24	10.11
7	LDPE	35	CARDBOARD	30.00	8.59	5.96	27.19
8	LDPE	100	FILM	23.53	5.87	10.19	21.65

The graphical representations in Figure 10 illustrate the yields of the eight pyrolysis tests, depending on the type of fuel used (polypropylene film or cardboard) and the different types of plastic waste (PP, PET, HDPE, and LDPE).

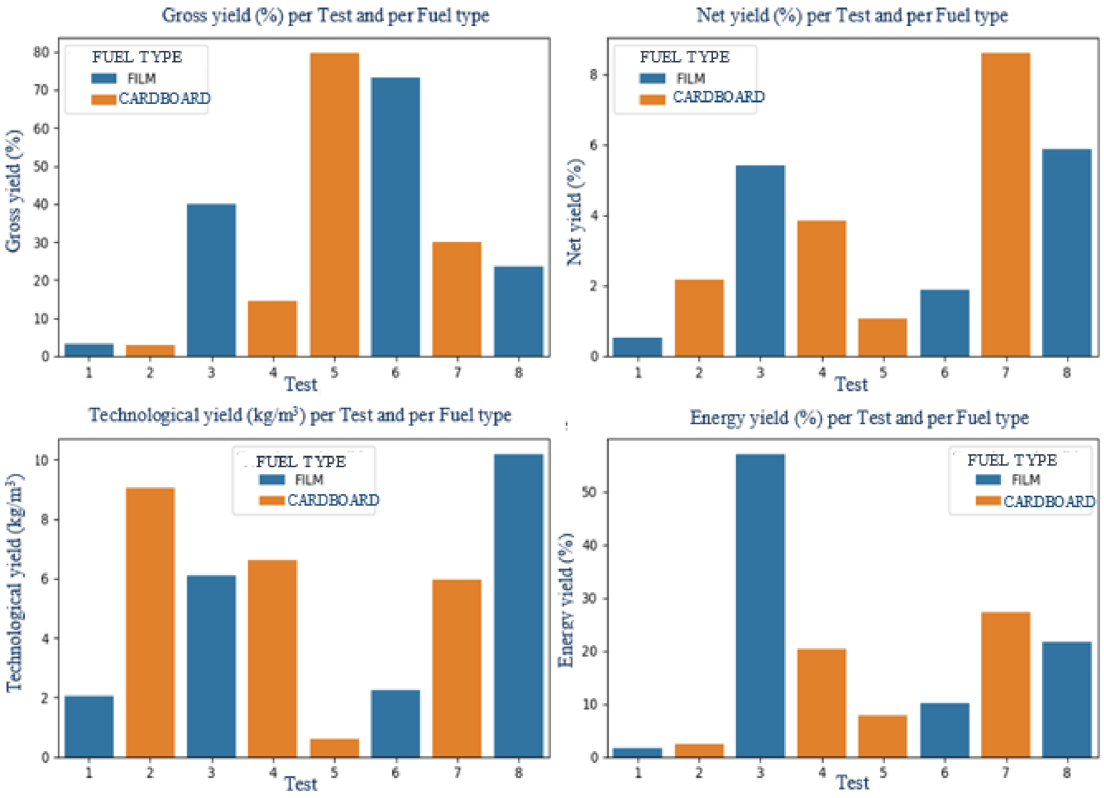

Fig -10: Yields obtained on the 8 trials

Figure 10 shows that:

- HDPE (tests 5 and 6) had the best gross yields of more than 70%, particularly with cardboard as a fuel. PET (Test 3) also showed a high gross yield (~40%) with a polypropylene film. Other plastic waste, particularly PP, had lower gross yields.
- LDPE (test 7) with cardboard as the fuel showed the highest net yield (~8.6%). PET (Test 3) followed a net return of 5.41%. The other trials show relatively low net returns.
- LDPE (test 8) with a polypropylene film achieved the highest technological yield (~10.19 Kg/m^3). The PP (test 2) with cardboard also showed a high technological yield (~9.07 Kg/m^3).
- PET (test 3) stood out for its very high energy efficiency (~57%), followed by LDPE (test 7) at ~27%. The other tests showed more modest energy yields.

5.2 Effects of the parameters on the pyrolysis yields of plastic waste

The results presented in Table 3 were subjected to an in-depth analysis using the Taguchi method with the aim of identifying the parameters having a significant impact on the yields obtained. The following section details the results of these analyses and highlights the key factors that influence process performance.

- ***Taguchi analysis: gross and net yield as a function of plastic waste type, fill rate and fuel type***

Figures 11, 12, 13, and 14 show graphs of the main effects for Averages and for S/N ratio of gross and net yields.

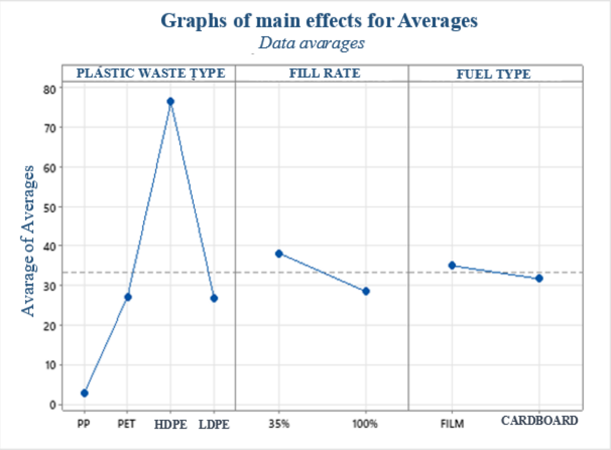

Fig-11: Graphs of main effects for Averages for gross yeild

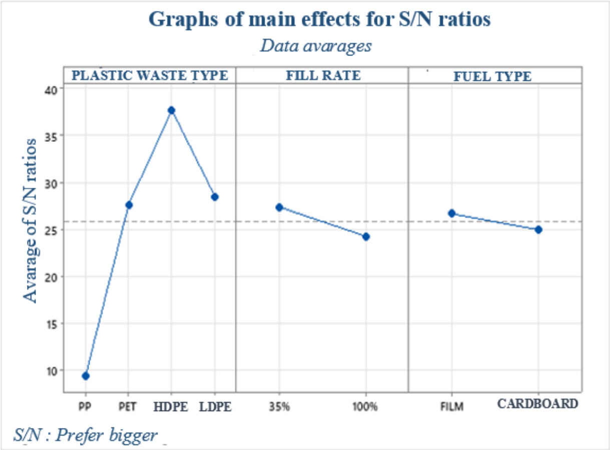

Fig-12: Graphs of main effects for S/N ratios for gross yeild

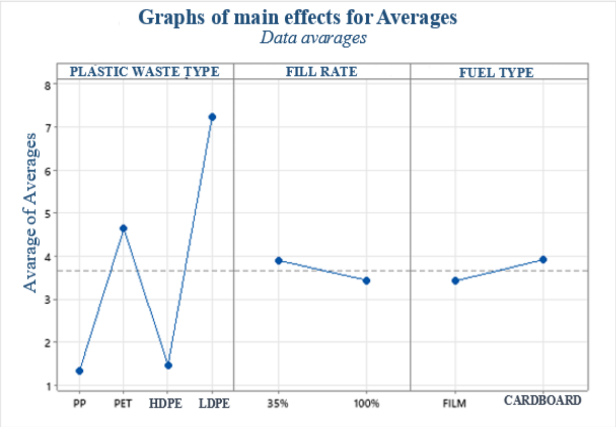

Fig-13: Graphs of main effects for Averages for net yeild

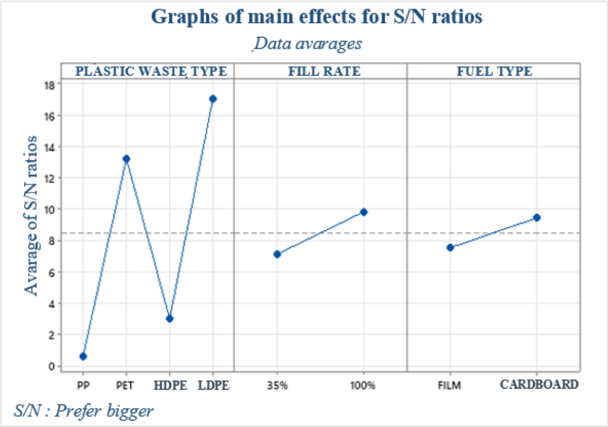

Fig-14: Graphs of main effects for S/N ratios for net yeild

HDPE and LDPE showed significantly higher gross yields than PP and PET. LDPE appears to offer the highest average yield (Fig-11). PP showed a very low yield, whereas PET was between these two extremes. The difference between the fill rates at 35% and 100% was minimal, but a fill rate of 35% was slightly more favorable for the gross yield. The type of fuel (polypropylene film or cardboard) did not have a significant effect on the gross yield, as the two were almost equivalent. LDPE had a significantly higher average net yield than that of the other plastic waste types (Fig-13). PP, although showing some variability, had a higher yield than PET but lower than that of HDPE. In contrast to the gross yield, a 100% fill rate seems slightly more favorable for maximizing the net yield. The fuel type had no significant impact on the net yield, with similar results for both types.

The signal-to-noise ratio also shows that LDPE and HDPE are the best-performing plastic waste in terms of gross yield stability, with an advantage for LDPE (Fig-12). PP had a very low S/N ratio, indicating poor performance and high variability in the results. A load factor of 35% seems slightly more favorable than 100%, although the difference is modest. As with the averages, the type of fuel does not have a significant impact on the signal-to-noise ratio, with similar performances for polypropylene film and cardboard. The signal-to-noise ratio showed that LDPE and HDPE were the most stable plastic waste in terms of net yield (Fig-14). PP, although showing some variability, had a higher S/N ratio than PET. A 100% fill rate seems to be slightly more favorable in terms of net yield stability than a 35% fill rate. As with the other graphs, the type of fuel did not have a significant effect on the stability of the net yield.

These results indicate that the optimization of the pyrolysis process should focus primarily on the use of HDPE or LDPE as the main plastic waste, owing to their superior performance in terms of gross and net yields. A finer optimization of other parameters, such as filling rate and fuel type, could be considered depending on the specific objectives of the study (maximization of gross or net yield).

Tables 4, 5, 6 and 7 analyse the effects of different parameters on gross and net pyrolysis yields, using both averages and signal-to-noise (S/N) ratios.

Table -4: Estimated model coefficients for averages for gross yield

TERM	Coeff	Coef ERT	T	P
Constante	33.35	3.16	10.54	0.01
PP TYPE	-30.40	5.48	-5.55	0.03
PET TYPE	-6.13	5.48	-1.12	0.38
HDPE TYPE	43.12	5.48	7.87	0.02
FILL RATE 35%	4.82	3.16	1.52	0.27
FUEL TYPE FILM	1.63	3.16	0.52	0.66

Table -5: Estimated model coefficients for S/N ratios for gross yield

TERM	Coeff	Coef ERT	T	P
Constante	25.79	1.03	25.08	0.00
PP TYPE	-16.40	1.78	-9.21	0.01
PET TYPE	1.83	1.78	1.03	0.41
HDPE TYPE	11.87	1.78	6.67	0.02
FILL RATE 35%	1.55	1.03	1.51	0.27
FUEL TYPE FILM	0.85	1.03	0.82	0.50

Table -6: Estimated model coefficients for net yield averages

TERM	Coeff	Coef ErT	T	P
Constante	3.67	0.60	6.18	0.03
PP TYPE	-2.32	1.03	-2.29	0.15
pet TYPE	0.96	1.03	0.94	0.49
hdpe TYPE	-2.20	1.03	-2.14	0.17
fill rate 35%	0.23	060	0.39	0.74
fuel TYPE FILM	-0.25	0.60	-0.42	0.72

Table -7: Estimated model coefficients for S/N ratios for net return

TERM	Coeff	Coef ERT	T	P
Constante	8.46	2.15	3.94	0.06
PP TYPE	-7.85	3.72	-2.11	0.17
PET TYPE	4.73	3.72	1.27	0.33
HDPE TYPE	-5.45	3.72	-1.47	0.28
FILL RATE 35%	-1.35	2.15	-0.63	0.60
FUEL TYPE FILM	-0.95	2.15	-0.44	0.70

Tables 4 and 5 show that for gross yield, PP has a significant negative effect on gross yield (P = 0.03 and P = 0.01), meaning that the use of PP significantly reduces gross yield. PET did not have a significant effect (P > 0.05) in either case, suggesting that its influence on gross yield was negligible. HDPE had a significant positive effect (P = 0.02, Table 5), indicating an increase in gross yield. The 35% fill rate was not significant in either tables (P > 0.05), indicating that this parameter did not have a major impact on gross yield. The fuel type (film or cardboard) did not have a significant effect.

As shown in Tables 6 and 7, PP and HDPE had a non-significant negative effect on net yield stability (P > 0.05). PET also did not have a significant effect (P > 0.05) on the stability of the net return. The same applies to the 35% fill rate, which has no significant effect on the stability of net yield. As with gross efficiency, the type of fuel does not have a significant effect on the stability of net efficiency.

Overall, plastic waste such as HDPE and LDPE are distinguished by their high yields and good stability in terms of the signal-to-noise ratio. The type of fuel (film or cardboard) had no significant influence on yield or stability. The fill rate has a moderate impact, with a slight preference for a 35% rate to maximize gross yield, whereas a 100% rate seems slightly more favorable for the net yield.

- ***Taguchi analysis: technological and energy efficiency as a function of plastic waste type, filling rate and fuel type***

The graphs presented in Figures 15, 16, 17, and 18 represent the main effects of the different factors on two types of yields: **technological efficiency** and **energy efficiency**. The graphs were divided into two categories: average and **signal-to-noise ratios (S/N)**.

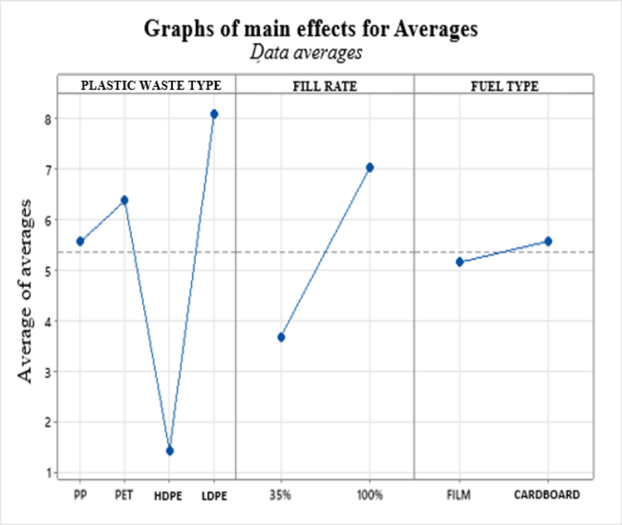

Fig -15 : Graphs of main effects for Averages for technological yeild

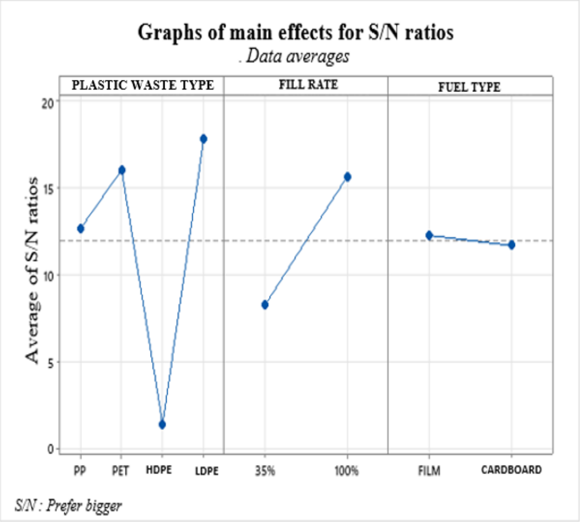

Fig -16 : Graphs of main effects for S/N ratios for technological yeild

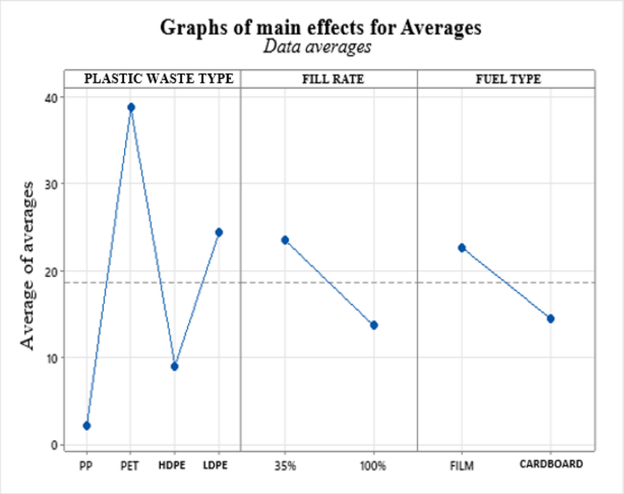

Fig -67 : Graphs of main effects for Averages for energy yield

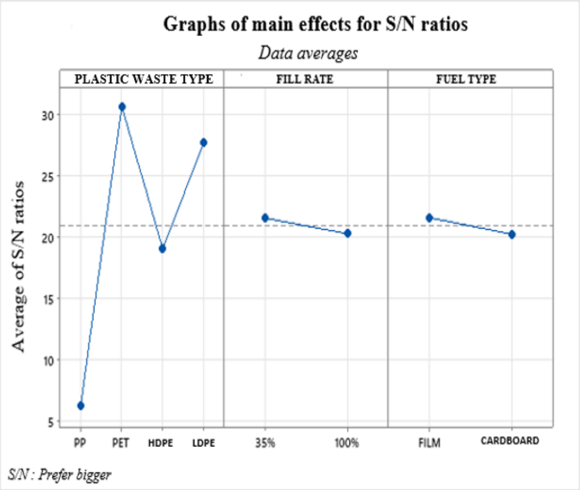

Fig -68 : Graphs of main effects for S/N ratios for energy yield

According to Figures 15 and 16, the type of plastic waste has a significant effect on technological yield: LDPE seems to give the highest average technological yield, while PET gives the lowest. The 100% fill rate was slightly higher than the 35% fill rate. The type of fuel has a moderate effect, with a slight preference for film over cardboard. The signal-to-noise ratio is higher for HDPE, indicating better robustness or stability of the technological performance with this material. A 100% load factor also appears to provide a better S/N ratio. The type of fuel does not have a major effect, but film is slightly preferred.

According to Figures 17 and 18, for energy efficiency, PET and LDPE yield much higher average energy yields than the other types of plastic waste. The 35% load factor appeared to be slightly better than the 100% occupancy rate. The type of fuel had no significant effect. PET offers a much higher signal-to-noise ratio, indicating better energy efficiency stability with this material. The filling rate and fuel type had relatively small effects on the S/N ratio.
To maximize the technological yield, it seems preferable to use LDPE with a 100% fill rate and fuel in film form. To maximize the energy efficiency, PET or LDPE with a fill rate of 35% seems to be the best option. The signal-to-noise ratios show that some materials (such as PET for energy and HDPE for technology) offer better performance robustness.

5.3 Summary of the results of the Taguchi analysis and discussions

Tables 8 and 9 summarize the results of the Taguchi analysis for the optimization of the yields of different types of plastic waste, filling rates, and fuels.

Tableau -4 : Taguchi Analysis Recap for Averages for All Yields

	Gross yield		Net yield		Technological yield		Energy yield	
Parameters	Rank	Level	Rank	Level	Rank	Level	Rank	Level
Plastic waste type	1	HDPE	1	LDPE	1	LDPE	1	PET
Fill rate	2	35%	3	35%	2	100%	2	35%
Fuel type	3	Film	2	Cardboard	3	Cardboard	3	Film

Tableau -5 : Taguchi Analysis Recap for signal-to-noise ratios (S/N) for All Yields

	Gross yield		Net yield		Technological yield		Energy yield	
Parameters	Rank	Level	Rank	Level	Rank	Level	Rank	Level
Plastic waste type	1	HDPE	1	LDPE	1	LDPE	1	PET
Fill rate	2	35%	2	100%	2	100%	2	35%
Fuel type	3	Film	3	Cardboard	3	Film	3	Film

The results show that the choice of plastic waste type has a significant impact on the different types of yield. HDPE and LDPE stand out as the best materials for gross and net yields, whereas PET is optimal for energy efficiency. These results are consistent with those of other studies that highlight the importance of material-specific characteristics in optimizing the energy processes. This corroborates the study by Hadhoum-Loubna (2021), which showed that the type of plastic waste strongly influenced the pyrolysis yield [36]. For this parameter, LDPE was the best, followed by HDPE. This is because the chemical structure of LDPE is simple, which facilitates its thermochemical decomposition. HDPE has a highly crystalline and rigid structure. Its thermochemical decomposition is more difficult, which reduces the yield of recoverable products. For the other types of plastic waste, PP and PET, their yields were lower because of their more complex structures and the difficulty of thermal decomposition.

The fill rate was the second factor that significantly influenced all the yields studied. The optimization of this parameter varies between 35% and 100%, highlighting the complexity of the interactions between the density of the material and the energy efficiency of the process. This variability reflects the inherent challenges in managing combustion conditions, where the density of the material plays a decisive role in energy performance. Indeed, a study of plastic waste yield modeling showed that density directly influences the quality of energy yield [37]. However, an excessive fill rate can lead to efficiency losses, mainly attributed to incomplete combustion or insufficient air circulation, thus compromising the process optimization. These observations underline the importance of precise adjustment of this parameter to maximize energy performance.

Among the parameters studied, the type of fuel appears to have the least influence on the pyrolysis yields. The plastic film appeared to be the best level. This is due to the fact that cardboard has a higher calorific value (between 40 and 46 MJ/kg) than cardboard (15 to 18 MJ/kg). However, the environmental impacts of burning these two types of fuels must also be considered. The choice between Film and Cardboard as the optimal fuel depends on the specific type of target yield. This is in line with other studies showing that the chemical composition of fuels influences their calorific value [38]. The combustion of plastic film is more harmful and toxic than that of cardboard.

The results were also statistically insignificant. This could be due to the high variability in the data or complex interactions between factors that were not captured by the simple linear model.

Taguchi analysis identified the optimal levels for maximizing different types of yields in a plastic waste process. These results are consistent with the current scientific literature, which highlights the importance of the choice of material, filling rate, and fuel type in energy optimization. These results can be used to improve the efficiency of plastic waste -based energy systems while considering local specificities such as material availability and environmental conditions.

5.4 Quality of pyrolysis oils obtained

To assess the properties of the oils from the pyrolysis process more precisely, their characteristics were compared with those of conventional fuels such as petrol and diesel. Table 10 presents a detailed comparative analysis of the oils obtained by pyrolysis with the fuels currently in use, thus highlighting the similarities and differences in terms of performance and physicochemical properties.

Tableau -6 : Comparison of the characteristics of pyrolysis oils obtained with those of petrol and diesel

	PP	PET	HDPE	LDPE	PETROL		DIESEL	
					Min	Max	Min	Max
Water content (%)	2.20	<0.20	0.20	0.25				0.05
Density at 15°C (kg/L)	0.78	0.94	0.80	0.79	0.71	0.79	0.81	0.89
Kinematic viscosity at 50°C (cSt)	1.89	9.94	2.86	9.94		1.17	1.60	5.70
Flash point (°C)	24.00	62.00	37.00	24.00	42.50		55.00	
Lower calorific value (kcal/kg)	9 457.50	9 097.50	9 426.00	9 384.50	10 154.10		10 273.60	

The water content of pyrolysis oils varies significantly depending on the type of plastic. PP had the highest content (2.20%), whereas PET had a value of less than 0.20%. HDPE and LDPE oils have similar values (0.20% and 0.25%, respectively), whereas commercial fuels (Gasoline and Diesel) have a very low water content (<0.05%). The high-water content of pyrolysis oils can affect combustion and reduce energy efficiency. In other studies, it is often recommended to reduce this content to improve the engine performance when these oils are used as alternative fuels [39].

The density at 15°C of pyrolysis oils varies between 0.78 kg/L (PP) and 0.94 kg/L (PET). HDPE and LDPE had densities close to those of gasoline (0.79 kg/L). Petrol has a density of between 0.71 and 0.79 kg/L, while diesel is denser (0.81 to 0.89 kg/L). Density directly influences the amount of energy contained in a given volume of fuel. Pyrolysis oils from PET are denser than those from petrol and are similar to diesel. Studies have shown that pyrolysis fuels can be used in diesel engines after adjusting the injection parameters to compensate for this difference in density [40] [41].

The viscosity varies widely depending on the type of plastic. PP has the lowest viscosity (1.89 cSt), which is close to that of gasoline (1.17 cSt), whereas PET and LDPE have a much higher viscosity (9.94 cSt). High viscosity can cause atomization problems in internal combustion engines. Pyrolysis oils from PET and LDPE would likely require modification of the injection system for their effective use in diesel engines. Studies have shown that viscosity can be reduced by distillation or blending with other fuels [42].

Petrol has a relatively low flash point (24 to 42.5°C), while diesel has a higher flash point (55°C). Comparatively, the flash point of pyrolysis oils varied between 24°C (PP and LDPE) and 62°C (PET). HDPE had an intermediate flash point at 37°C. A lower flash point indicates an increased risk of spontaneous ignition at room temperature. Pyrolysis oils from PP and LDPE have flash points similar to those of gasoline, which could pose safety challenges during storage and transport [42]. However, these oils can be adapted for applications that require volatile fuels [40].

The calorific value varies between 9,097.50 kcal/kg (PET) and 9,426 kcal/kg (LDPE), which is comparable to the values observed for petrol (10,154.10 kcal/kg) and slightly lower for diesel (10,273.60 kcal/kg). The calorific value of pyrolysis oils is high enough that they can be used as substitutes for fossil fuels in some industrial or automotive applications [39] [41]. However, their overall energy efficiency also depends on their behavior during combustion.

Pyrolysis oils from plastics have interesting characteristics that make them potentially usable as partial or complete substitutes for traditional fossil fuels, such as petrol or diesel. However, certain properties, such as high viscosity and water content, need to be improved to ensure optimal performance in modern engines. Other studies suggest that these oils can be blended with diesel or used after distillation to improve their performance in internal combustion engines. Adjustments to the fuel injection or combustion systems may also be necessary to optimize their use.

6. LIMITATIONS AND PERSPECTIVES

This study confirms the feasibility of pyrolysis of plastic waste using the developed prototype. However, the temperature of the process, often below 200°C, limits the production of oil and gas. It is recommended that the thermal insulation of the burner and reactor be improved to achieve higher temperatures, thus optimizing the conversion of plastics. Condensation and pipe clogging problems caused by the accumulation of paraffins and olefins were observed, which reduced the overall performance. Regular cleaning of pipes is recommended to avoid such blockages.

The oils obtained, although close to the specifications of diesel in Madagascar, have a high viscosity, requiring distillation to comply with the standards of use. Figures 19 and 20 illustrate the differences before and after distillation, respectively, showing a marked improvement in the physical properties. Finally, optimizing the operating parameters (temperature, residence time, and catalysts) is crucial for maximizing the liquid production while reducing unwanted by-products. Further studies on the integration of pyrolysis oils into fuel blends are recommended to assess their compatibility with modern diesel engines and their environmental impact.

Fig -19 : Crude pyrolytic oils

Fig -20 : Distilled pyrolytic oils

It is important to note the limitations of this study. Due to technical constraints, some key points could not be analyzed:

- Study of the catalyst type parameter;
- Detailed characterization of the physico-chemical properties of the pyrolytic oils obtained, such as pH, density, corrosiveness, etc.;
- Determination of the chemical compositions of distilled pyrolytic oils for each type of treated plastic;
- Financial analysis of the implementation of the optimized pyrolysis process;
- Comparison of the optimized pyrolysis process with direct combustion in terms of energy recovery.

However, as this article serves as a starting point for more in-depth research on pyrolysis, subsequent papers will focus more extensively on all these aspects.

7. CONCLUSION

This study demonstrates the potential of pyrolysis as a promising technology for the recovery of plastic waste in the specific context of Madagascar, where sustainable waste management is crucial. The application of the Taguchi method identified optimal conditions, revealing that high-density polyethylene (HDPE) with a fill rate of 35% offers the highest gross yield, while polyethylene terephthalate (PET) generates oil with energy characteristics close to that of diesel. These results highlight the decisive influence of the type of plastic and the filling rate on the efficiency of the process.

However, several challenges remain for industrial implementation. Improving the thermal insulation of the reactor and managing obstructions caused by paraffin deposits are key to optimizing this process. Although pyrolysis oil from PET has potential as an alternative fuel, its high viscosity requires further refining to meet the standards for use in engines. These findings open up future research perspectives focused on optimizing the condensation and distillation steps as well as adapting the process to an industrial scale. This study provides a solid basis for the development of sustainable solutions for the recovery of plastic waste through pyrolysis, with significant environmental and economic benefits in regions facing similar challenges, such as southern Madagascar.

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