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Enhanced Carbonization of Sawdust and Leather Waste for Fuel Use in Pyrolysis Pilot Furnace: A Taguchi Experimental Design Approach

Tsiry Angelos Andriamanampisoa[1], Nivonirina Eva Andriamanampisoa[2], Harry Chaplin[3], Edouard ANDRIANARISON[4]

[1,2,4]University of Antananarivo, École Supérieure Polytechnique, 101 Antananarivo-Madagascar

[3]Tatirano Social Enterprise, Bazarikely, Fort-Dauphin, Madagascar

* Corresponding author: Tsiry Angelos Andriamanampisoa; andry.angelos@yahoo.com

Abstract: Pyrolysis furnaces are an efficient means of carbonizing biomass, yielding biochar, and facilitating organic waste recovery. This study aimed to refine the carbonization process of biomass waste by employing the Taguchi method to assess the influence of biomass type (sawdust and leather waste), furnace filling rate (33% and 100%), and fuel type (cardboard waste and plastic waste) on carbonization yields. Four trials were conducted, with each factor systematically varied, and the results were analyzed using an L4(2^3) design replicated thrice. The parameters evaluated included gross, net, and weighted mass yields; energy yield; technological yield; and the characteristics of the resultant coals. Taguchi analysis revealed that fuel type, notably cardboard waste, exhibited the most significant impact on all yields studied, followed by a filling rate of 100%, favoring most outcomes. In comparison, a 0.196 m^3 pilot pyrolysis furnace carbonizing sawdust and leather waste demonstrated superior average mass yields of 47.8% and weighted mass yields of 44.4% compared with traditional charcoal pits, yielding 26% and 25.8%, respectively. Sawdust charcoal exhibited superior energy quality, boasting a higher percentage of fixed carbon and elevated Lower Calorific Value, with 85% of energy yield with a standard deviation of 3.5%, in contrast with 70.9% of energy yield and a higher standard deviation of 7.8% for leather waste. While the findings showcase promise, further exploration into alternative biomass types, comprehensive modeling of the entire process within the pyrolysis pilot furnace, and an assessment of large-scale profitability remain imperative.

Keywords: Biomass carbonization, Taguchi Method, Carbonization Yields, Biochar production

I. INTRODUCTION

In Madagascar, wood is extensively exploited in the form of firewood and charcoal, which constitute the primary sources of domestic energy [1] [2]. Owing to its availability and relatively low cost, wood energy accounts for over 80% of the domestic energy consumption, primarily for cooking purposes [3]. This practice is particularly prevalent on the island's most disadvantaged population. However, intensive exploitation of wood, coupled with insufficient reforestation efforts, poses a significant threat to biodiversity and leads to the rapid degradation of forest cover [4]. These pressures on forest resources have resulted in significant environmental problems including deforestation and pollution. Over the past few decades, Madagascar's forest area has significantly decreased, evolving from 24 to 28% of the national territory in 1950 to only 9–10 million hectares, or approximately 17% of the island. This decrease is estimated to be approximately 1.39% per year [5], with over 80% of the forest lost [6]. Faced with this environmental crisis, the quest for sustainable and accessible alternatives for low-income populations is crucial to preserve Madagascar's forest resources.

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Furthermore, the use of wood as an energy source has led to an increase in greenhouse gas emissions, significantly contributing to climate change, which is a global concern. Currently, global CO_2 emissions account for 75% of total greenhouse gas emissions [7]. In this context, it is imperative to develop environmentally friendly energy production techniques to reduce adverse climate impacts and promote long-term sustainability.

However, there is growing concern regarding the increasing accumulation of waste. In urban areas, waste production is estimated to be approximately 1890 tons per day, with a collection rate of approximately 48% per day [8]. Therefore, effective waste management is essential and it is imperative to develop methods for valorization. In Madagascar, waste consists mainly of agricultural residue, animal waste, forest waste, household waste, and urban and industrial organic waste [9]. This study specifically focused on the valorization of industrial waste, notably leather waste from shoe manufacturing companies and sawdust from wood-processing factories. These materials can be carbonized for transformation into fuels [10] [11], thus offering a dual opportunity to reduce waste while providing a more sustainable energy source. To achieve optimal results, it is crucial to improve the carbonization process by optimizing its parameters [12].

Carbonization is a process in which biomass is exposed to high temperatures, typically ranging between 300 and 700°C [13], in an inert atmosphere to produce solid carbonaceous materials and volatile compounds (liquids and gases) [14]. The traditional carbonization method (figure 1) exhibits a low mass yield, typically ranging between 10 and 15% [15]. This implies that a significant amount of wood (approximately 130 kg) is required to produce 10 kg of charcoal, contributing to large-scale deforestation. Conversely, enhanced carbonization is a continually evolving process. A primary improvement over the traditional method is pit carbonization (figure 2), which involves excavation directly into the soil to place the biomass for carbonization sheltered from wind [16]. Another variation of this method, known as subpit carbonization, was utilized by Fanalamanga [17]. The enhanced pit technique involves the installation of a telescopic metal cover to ensure furnace sealing, thereby representing an additional development of this method.

Figure 1: Traditional carbonization [18]

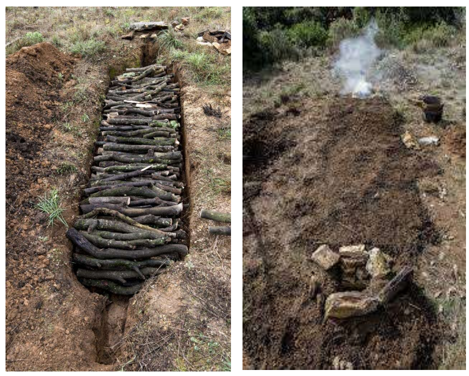

Figure 2: Pit carbonization [19]

Carbonization techniques are traditionally grouped into partial combustion batch kilns, retort kilns, and hot-gas contact. The first category can be further subdivided, based on whether the draft is direct or reversed. The yields of these different techniques have been documented in publications summarized in Table 1 [20]. The mass yield (RMba) was determined on an anhydrous basis, excluding charcoal (or tar), from both the initial wood charge and the product (charcoal and tar).

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Table 1: Summary of the advantages, disadvantages and mass yields of some carbonization techniques

Technique	Advantages	Disadvantages	RMba (%)	Sources
	Partial load combustion furnaces			
GRINDING WHEEL	Mobility (all terrain) No skidding Local materials No investment Carbonizes large logs without splitting Adjustable capacity Use of biomass residues	Demanding in terms of operator qualifications Labour-intensive (permanent) Sensitive to weather conditions Coal of variable quality and soiled by the blanket Low energy yield Significant pollution	***Traditional***	
			12-34	Schenkel et al., 1997 [21]
			26	Girard, 1992 [22]
			15-30	Sanogo et al., 2006 [23]
			15-35	Riuji Lohri et al., 2016 [24]
			10-22	Madon, 2017 [25]
			9-30	FAO, 2017 [26]
			8-12	Montagne et al., 2010 [27]
			Enhanced	
			19-42	Schenkel et al., 1997 [21]
			27	Mundhenk et al., 2010 [28]
			22-34	Sjolie, 2012 [29]
			Casamance	
			37	Mundhenk et al., 2010 [28]
			17-30	FAO, 2017 [26]
FOSSE	Mobility Local materials Investment: nil to very low Carbonizes large logs without splitting Adjustable capacity Use of biomass residues	Demanding in terms of operator qualifications Labour-intensive (permanent) Sensitive to weather conditions Requires deep, consistent soil Low energy yield Significant pollution	***Subri***	
			22-36	Schenkel et al., 1997 [21]
			30	Schenkel et al., 1999 [30]
			12-30	FAO, 2017 [26]
MASONRY FURNACES	Local materials Easy to operate Homogeneous, clean coal Good thermal insulation Unaffected by weather conditions	Construction requiring a skilled mason Large timber splitting Determined capacity Filling coefficient problem Labor-intensive	***Demi-orange***	
			20	Piketty et al., 2011 [31]
			13-32	Schenkel et al., 1997 [21]
			Mineirinho	
			25	Piketty et al., 2011 [31]
			28-36	Pennise, 2001 [32]

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	Long service life	Fixed installations Skidding costs Slow cooling Significant pollution (fumes)	***Missouri***	
			5-33	Riuji Lohri et al., 2016 [24]
			Adam retort	
			30	Sparrevik et al.,2015 [33]

Technique	Advantages	Disadvantages	RMba (%)	Sources
	Partial load combustion furnaces			
METAL FURNACES	Mobility Skidding in small areas Easy to drive Homogeneous, clean coal Short cycle thanks to rapid cooling	Large wood splitting Determined capacity Filling coefficient problem Short service life Sensitive to weathering (depending on operator and material quality) Average energy yield Significant pollution (fumes)	***Mark V***	
			12-32	Schenkel et al., 1997 [21]
			20-31	Riuji Lohri et al., 2016 [24]
			Magnien	
			25	Girard, 1992 [22]
	Retort furnaces			
METALLIC	Controlled, consistent quality High mass yield High energy efficiency Low to zero pollution Medium investment Average technicality	Wood transport (except for mobile horns) Wood splitting and preparation Determined capacity Filling coefficient problem Need for wood drying Deformation of enclosures	23-32	Schenkel et al., 1999 [30]
			22-40	FAO, 2017 [26]
CONTINUOUS INDUSTRIAL FURNACES WITH GAS RECIRCULA-TION	Controlled, consistent quality High mass yield High energy efficiency Low to zero pollution Automation	Considerable investment Highly technical Extensive supply perimeter Wood transport Wood splitting and preparation	26-35	Schenkel et al., 1999 [30]
			30-35	Riuji Lohri et al., 2016 [24]

The thermal conversion of biomass is dependent on parameters such as heating rate, pressure, temperature, and residence time. Pyrolysis is primarily a thermal decomposition process carried out in the absence or presence of oxidizing gases (such as oxygen or air), resulting in the production of solid (charcoal), liquid (pyrolysis oil consisting of a light aqueous solution and heavy organic phase), and gaseous (noncondensable gases) phases [34]. When the objective of pyrolysis is the production of charcoal, it is referred

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to as carbonization, a preconditioning technique that allows the concentration of energy contained in organic matter into a fixed carbon form. The carbonization of biomass in a pyrolysis furnace is an enhanced carbonization alternative for valorizing organic wastes in Madagascar. The objective of this study is to optimize a pilot pyrolysis furnace using the Taguchi method to identify the optimal combinations of factors for producing fuels from leather waste and sawdust with the highest yields (mass, weighted mass, energy, and technological yields).

The Taguchi method, or Taguchi approach, is an experimental design technique developed by the Japanese statistician Genichi Taguchi with the aim of simplifying statistical analysis techniques [35]. This method is widely used in the analysis of engineering and manufacturing systems to improve the quality of products and processes [36]. This involves designing an experimental plan to acquire data in a controlled manner to obtain information regarding the behavior of a given process [37]. To make the use of such a pyrolysis furnace practical and pragmatic in the context of Madagascar, the factors analyzed in this study included the type of biomass to be carbonized, filling rate, and type of fuel used, with the aim of gathering maximum information with a minimum number of trials, thus optimizing the experimental approach [38]. Various types of experimental designs exist, such as the Doelhert [39], Box-Behnken [40], Hadamard matrices [41], and Taguchi designs. In this study, the Taguchi plan was favored because it enables the attainment of robust products and processes that are insensitive to external disturbances [42], aligning with the research objectives.

II. MATERIALS AND METHODS

In this study, a pilot pyrolysis furnace with a water volume of 0.196 m^3 is constructed. Sawdust and leather waste were selected as the carbonization biomass. Plastic packaging waste and cardboard waste from the agro-food industry were utilized as fuels to maintain consistency with waste valorisation efforts. The Taguchi experimental design was used to interpret the results, and all physicochemical analyses were conducted at the OMNIS Laboratory in Madagascar.

2.1. Pilot Pyrolysis Furnace

A pilot pyrolysis furnace was used to carbonize the biomass (figure 3). The furnace, which was constructed of steel, included four main components:

- External combustion chamber.
- carbonization chamber
- A connection between the carbonization and combustion chambers facilitated the evacuation of the pyrolysis gases. The connection pipe was removed for ease of cleaning.
- A chimney containing a small opening for ignition of fire to initiate extraction.

A Smoke temperature measurement was performed at the chimney level using a MAX6675 thermocouple capable of operating within a temperature range of -200°C to +1350°C (figure 4).

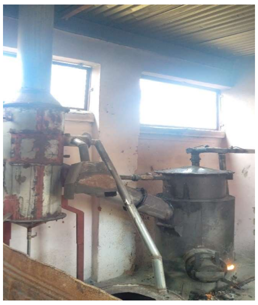

Figure 3: Pilot pyrolysis furnace

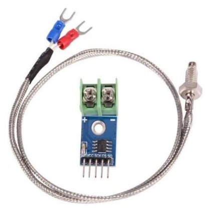

Figure 4: MAX6675 thermocouple

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2.2. Biomasses Utilized

Wood sawdust waste from a cutting factory (figure 5) and leather waste from a tannery (figure 6) were used as the biomass for the experiments. Table 2 summarizes the characteristics of the biomass analyzed at the OMNIS Laboratory.

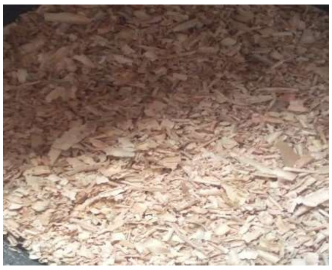

Figure 5: Wood sawdust waste

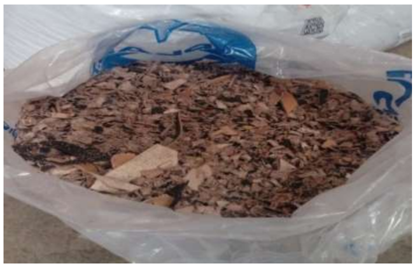

Figure 6 : Leather waste

Table 2: Characteristics summary of the used biomass

Biomass	Volatile Matter (%)	Ash Content (%)	Loss on Ignition (%)	Fixed Carbon Content (%)	Lower Heating Value (Kcal/Kg)
Wood Sawdust	92.72	0.59	99.41	6.59	7952.80
Leather Waste	88.08	2.37	97.63	9.55	7810.40

2.3. Fuels

To maintain a comprehensive approach to waste valorization, waste from an agro-food factory, such as cardboard waste (figure 7) and plastic packaging waste (figure 8), was used as fuel.

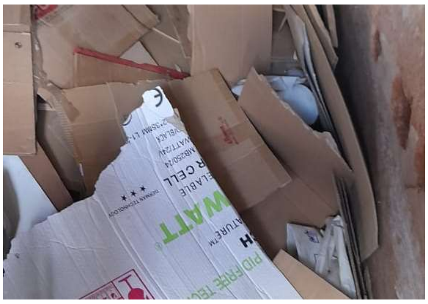

Figure 7: Cardbord waste

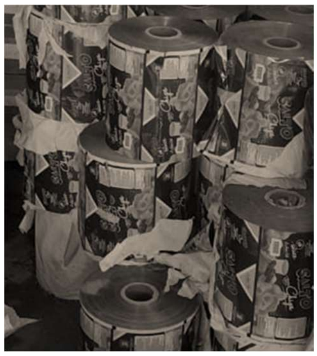

Figure 8: Plastic packaging waste

Plastic waste consists of laminated packaging, specifically oriented PolyPropylene (BOPP). This choice is due to the fact that the combustion of propylene primarily emits carbon dioxide, carbon monoxide, and aliphatic hydrocarbons (mainly methane and light unsaturated hydrocarbons) [43]. Operator exposure risks to these elements are managed by the presence of a chimney, increased room ventilation, and use of personal protective equipment. Smoke washing and the analysis of the combustion results of propylene as a fuel are currently under study. Table 3 summarizes the characteristics of these fuels as determined by the OMNIS laboratory.

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Table 3: Fuels characteristics

FUEL	Volatile Matter (%)	Ash Content (%)	Loss on Ignition (%)	Fixed Carbon Content (%)	Lower Heating Value (Kcal/Kg)
Cardboard Waste	86.85	8.64	91.36	4.51	7308.80
Plastic Waste	96.99	2.81	96.08	0.20	7686.40

2.4. Taguchi Experimental Design Plan

2.4.a. Factors

The parameters of the experimental design in this study were the type of biomass to be carbonized, filling rate of the furnace, and type of fuel used. In Minitab software, the factors were designated by labels for the graphs and analysis results. The three factors for this study, namely the type of biomass, filling rate, and type of fuel, were integrated into the "name" row. The levels of the factors "Type of Biomass" and "Type of Fuel" are defined with textual values: "sawdust" and "cardboard waste" for the respective minimum values, and "leather waste" and "plastic waste" for the respective maximum values. As for the "filling rate" factor, a minimum value of 33% (filling at 33%) and a maximum value of 100% are chosen for our reactor. We will adopt the experimental design plan recommended by Minitab, presented in Tables 4 and 5, which is of type L4(2^3), replicated thrice.

Table 4: Design Summary

Taguchi Array	L4(2^3)
Factors:	3
Runs:	4

Columns of L4(2^3) array: 1 2 3

Table 5: experimental design plan

	Type of biomass	Filling References	Fuel used
1	Sawdust	33%	Cardboardwaste
2	Sawdust	100%	Plasticwaste
3	Leatherwaste	33%	Plasticwaste
4	Leatherwaste	100%	Cardboardwaste

2.4.b. Outputs

We analyzed four types of responses to perform the carbonization process: gross and net mass yields, weighted mass yields, energetic yields, and technological yields. These indicators were selected to enable an objective comparison of the results obtained from the various carbonization processes. As observed in the literature review, there are several carbonization technologies, and their production performance varies depending on numerous parameters such as the pre-drying of wood and skill level of the experimenter [22].

- ***Mass Yield (R)***

The gross mass yield (R) is a measure of charcoal production from a material relative to the mass of the processed product. This represents the ratio of the mass of anhydrous charcoal produced to the mass of anhydrous carbonized wood. This relationship is defined by the following equation:

$$\boldsymbol{R = \frac{PC}{PO-I} \times 100} \quad (1)$$

- R: Mass yield on anhydrous basis.
- PC: Mass of charcoal immediately after unloading.

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- I: Mass of uncarbonised wood
- PO: Anhydrous wood mass.

$$PO = PH\left(1 - \frac{H}{100}\right) \tag{2}$$

- H: Moisture content of the wood
- PH: Total mass of charged wood

However, it is more reasonable to equate uncarbonized wood to anhydrous non-carbonized wood. Obtaining a significant amount of uncarbonized wood significantly skews the results and should, therefore, be excluded. Additionally, if supplementary fuel is used in carbonization, this energy should be accounted for in the yields. Considering these factors, the net mass yield was calculated using the following equation.

$$R_{net} = \frac{PC}{PO - I + BO} \times 100 \tag{3}$$

- BO: Quantity of anhydrous wood. If the fuel is not wood, Formula 4 allows for the calculation of its equivalent anhydrous wood.

$$BO = \frac{Anhydrous\ mass\ of\ the\ fuel \times Anhydrous\ PCI\ of\ the\ fuel}{Anhydrous\ PCI\ of\ the\ carbonized\ wood} \tag{4}$$

➢ ***Weighted Mass Yield (R80)***

The weighted mass yield (R80) enabled a comparison of charcoal produced by different carbonization technologies by normalizing them to the same fixed carbon content on an anhydrous basis of 80%. This was determined using the following formula:

$$R80 = R_x \times \frac{CF_x}{80} \times 100 \tag{5}$$

- Rx: Gross mass yield as a percentage controlled during the test and at index x of volatile matter.
- CFx: Fixed carbon content on an anhydrous basis of charcoal at index x of volatile matter.

➢ ***Technological Yield (Rt)***

The technological yield (Rt), expressed in kg/m³, was used to measure the quantity of charcoal produced per cycle, relative to the furnace volume. This value can be calculated using the following equation:

$$Rt = \frac{PC}{V} \tag{6}$$

V: Water volume in the furnace

➢ ***Energy Yield (Re)***

The energy yield (Re) represents the ratio of the potential calorific energy of charcoal produced to that of the initial raw wood. The calculation formula is as follows:.

$$Re = \frac{PC \times PCIc}{PH \times PCIb} \times 100 \tag{7}$$

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- PCIc: Lower calorific value of charcoal.
- PCIb: Lower calorific value of wood.

III. RESULTS AND DISCUSSIONS

3.1. Improved carbonization results

Four leather and sawdust carbonization trials were conducted by manipulating the levels of each factor and repeating the trials thrice. The experiments were carried out in a pilot pyrolysis furnace with a water volume of 0.196 m^3. Table 6 summarizes the parameters of these tests and the data obtained.

Table 6: Carbonization test data

No. of tests	Type of biomass	Filling rate	Fuel Type	Wet mass (kg)	Humidity (%)	Mass of the Uncook-ed	Mass of coal (kg)	Anhydrous mass of fuel (kg)	Average smoke tempera-ture (°C)	Process duration
1	**Sawdust**	33%	Cardboard	6.0	18.0	0	2.4	18.0	256	4
	Sawdust	100%	Plastic	17.0	16.0	0	6.5	46.1	370	8
	Leather	33%	Plastic	13.3	14.0	0	4.8	26.1	287	5
	Leather	100%	Cardboard	40.0	12.0	0	18.6	63.0	328	12
2	**Sawdust**	33%	Cardboard	6.0	17.5	0	2.3	17.0	251	4
	Sawdust	100%	Plastic	17.0	16.5	0	6.4	45.0	375	8
	Leather	33%	Plastic	13.3	13.5	0	4.9	27.0	275	5
	Leather	100%	Cardboard	40.0	12.5	3	17.8	60.0	335	12
3	**Sawdust**	33%	Cardboard	6.0	17.8	0	2.5	17.5	261	4
	Sawdust	100%	Plastic	17.0	16.8	0	6.7	46.5	377	8
	Leather	33%	Plastic	13.3	13.7	0	4.7	27.5	294	5
	Leather	100%	Cardboard	40.0	12.8	2	17.5	64.0	324	12

The smoke temperature and process duration were recorded to ensure comparability of the trials in future research and were not included in the analysis elements of this study.

3.2. Effects of Taguchi parameters on the valuation process

Following the analysis and determination of the parameters influencing the yields, the following results were obtained.

- **Taguchi analysis: gross mass yield as a function of biomass type, filling quantity and fuel type**

For further analysis to determine the factors influencing the raw mass yield, each test was repeated thrice. The mass yields (R) obtained for each test are presented in Table 7.

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Table 7: Gross mass yield values

TYPE OF BIOMASS	QUANTITY	FUEL TYPE	R1	R2	R3
SAWDUST	33%	CARDBOARD	47.8%	46.5%	50.7%
SAWDUST	100%	PLASTIC	45.5%	45.1%	47.4%
LEATHER	33%	PLASTIC	41.7%	42.6%	40.9%
LEATHER	100%	CARDBOARD	52.8%	55.6%	53.2%

These data were analyzed using the Taguchi method, and Tables 8–13 show the results.

Table 8: Model Summary

S	R-Sq	R-Sq(adj)
*	100,00%	*

Table 9: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of biomass	1	0,000043	0,000043	0,000043	*	*
Filling References	1	0,002407	0,002407	0,002407	*	*
Fuel used	1	0,005254	0,005254	0,005254	*	*
Residual Error	0	*	*	*		
Total	3	0,007704				

Table 10: Estimated Model Coefficients for Means

Term	Coef
Constant	0,474908
Type of Sawdust	-0,003285
Filling 33 %	-0,024532
Fuel use Cardboar	0,036241

Table 11: Response for Signal to Noise Ratios

Larger is better

Level	Type of biomass	Filling References	Fuel used
1	-6,542	-6,962	-5,854
2	-6,484	-6,064	-7,172
Delta	0,059	0,898	1,318
Rank	3	2	1

Table 12: Response for Means

Level	Type of biomass	Filling References	Fuel used
1	0,4716	0,4504	0,5111
2	0,4782	0,4994	0,4387
Delta	0,0066	0,0491	0,0725
Rank	3	2	1

Table 13: Response for Standard Deviations

Level	Type of biomass	Filling References	Fuel used
1	0,01684	0,01489	0,01832
2	0,01166	0,01361	0,01018
Delta	0,00517	0,00128	0,00813
Rank	2	3	1

The results of the linear regression analysis for the gross mass yield offer valuable insights into the factors influencing this essential parameter in the carbonization process. Tables 8, 9, and 10 provide detailed interpretations of the results.

According to Table 8, the model explains 100% of the variation in the data (R-Sq = 100%), which may indicate overfitting. The analysis of variance (Table 9) revealed that all three factors had significant effects on gross mass yield, with p-values below 0.05.

Table 10 lists the levels of each factor that maximizes the gross mass yield. For the type of biomass, the coefficient for the use of sawdust was negative (-0.003285), suggesting a decrease of the gross mass yield compared to the use of leather waste. Concerning the filling quantity, the coefficient for the 33% fill reference was negative (-0.024532), indicating a decrease of the gross mass yield compared to a higher fill amount. For fuel type, the coefficient for the use of cardboard is positive (0.036241), suggesting an increase of the gross mass yield mass compared to the other fuel type (plastic). This is confirmed in tables 11, 12, and 13. Moreover, they suggested that fuel type and filling quantity are crucial factors in maximizing the gross carbonization mass yield and that the effect of biomass type appears to be negligible compared to the other factors.

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- **Taguchi analysis: net mass yield as a function of biomass type, filling quantity and fuel type**

Each test was repeated three times to determine the factors that affected the net mass yield. The net weighted mass yields (Rnet) of the tests are presented in Table 14.

Table 14: Weighted mass yield values

TYPE OF BIOMASS	QUANTITY	FUEL TYPE	Rnet-1	Rnet-2	Rnet-3
SAWDUST	33%	CARDBOARD	11.5%	11.8%	12.5%
SAWDUST	100%	PLASTIC	9.1%	9.1%	9.3%
LEATHER	33%	PLASTIC	10.9%	10.9%	10.3%
LEATHER	100%	CARDBOARD	20.8%	21.3%	19.9%

These data were analyzed using the Taguchi method, and Tables 15–20 show the results.

Table 15: Model Summary

S	R-Sq	R-Sq(adj)
*	100,00%	*

Table 16: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of biomass	1	0,002622	0,002622	0,002622	*	*
Filling References	1	0,001307	0,001307	0,001307	*	*
Fuel used	1	0,004083	0,004083	0,004083	*	*
Residual Error	0	*	*	*		
Total	3	0,008012				

Table 17: Estimated Model Coefficients for Means

Term	Coef
Constant	0,131111
Type of Sawdust	-0,025602
Filling 33 %	-0,018078
Fuel use Cardboar	0,031949

Table 18: Response for Signal to Noise Ratios

Larger is better

Level	Type of biomass	Filling References	Fuel used
1	-19,62	-18,96	-16,09
2	-16,57	-17,23	-20,10
Delta	3,04	1,73	4,01
Rank	2	3	1

Table 19: Response for Means

Level	Type of biomass	Filling References	Fuel used
1	0,10551	0,11303	0,16306
2	0,15671	0,14919	0,09916
Delta	0,05120	0,03616	0,06390
Rank	2	3	1

Table 20: Response for Standard Deviations

Level	Type of biomass	Filling References	Fuel used
1	0,003182	0,004213	0,006078
2	0,005180	0,004150	0,002285
Delta	0,001998	0,000063	0,003793
Rank	2	3	1

The results of the linear regression analysis of the net mass yield provided important information on the factors influencing this crucial parameter in the carbonization process.

According to Table 15, the model explains 100% of the variation in the data (R-Sq = 100%), which may indicate overfitting. Therefore, these results should be cautiously interpreted. Next, the analysis of variance (Table 16) shows that all three factors have significant effects on net mass yield, with p-values below 0.05.

Table 17 lists the levels of each factor that maximizes the net mass yield. For biomass type, the coefficient associated with the use of sawdust was negative (-0.025602), suggesting a decrease of the net mass yield compared to the use of leather waste). For the fill amount, the coefficient for the 33% fill reference was negative (-0.018078), indicating a decrease of the net mass yield compared to a higher fill amount. Regarding the type of fuel, the coefficient for the use of cardboard is positive (0.031949), suggesting an

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increase of the net mass yield compared to the use of the other fuel (plastic). This is confirmed in tables 18, 19, and 20. Furthermore, they suggested that the type of fuel used and the amount of filling are important factors in maximizing the net mass yield of the carbonization and that the effect of biomass type appears to be negligible compared to the other factors.

- **Taguchi analysis: weighted mass yield as a function of biomass type, filling quantity and fuel type**

Each test was repeated thrice to determine the factors affecting the weighted mass yield. The weighted mass yields (R80) of the tests are presented in Table 21.

Table 21: Weighted mass yield values

TYPE OF BIOMASS	QUANTITY	FUEL TYPE	R80-1	R80-2	R80-3
SAWDUST	33%	CARDBOARD	48.4%	47.0%	51.3%
SAWDUST	100%	PLASTIC	45.7%	45.2%	47.5%
LEATHER	33%	PLASTIC	34.8%	35.5%	34.2%
LEATHER	100%	CARDBOARD	45.4%	47.7%	45.7%

These data were analyzed using the Taguchi method, and Tables 22–27 show the results.

Table 22: Model Summary

S	R-Sq	R-Sq(adj)
*	100,00%	*

Table 23: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of biomass	1	0,004879	0,004879	0,004879	*	*
Filling References	1	0,001868	0,001868	0,001868	*	*
Fuel used	1	0,005042	0,005042	0,005042	*	*
Residual Error	0	*	*	*		
Total	3	0,011789				

Table 24: Estimated Model Coefficients for Means

Term	Coef
Constant	0,440376
Type of Sawdust	0,034924
Filling 33 %	-0,021612
Fuel use Cardboar	0,035503

Table 25: Response for Signal to Noise Ratios

Larger is better

Level	Type of biomass	Filling References	Fuel used
1	-6,476	-7,695	-6,465
2	-7,933	-6,714	-7,944
Delta	1,457	0,982	1,479
Rank	2	3	1

Table 26: Response for Means

Level	Type of biomass	Filling References	Fuel used
1	0,4753	0,4188	0,4759
2	0,4055	0,4620	0,4049
Delta	0,0698	0,0432	0,0710
Rank	2	3	1

Table 27: Response for Standard Deviations

Level	Type of biomass	Filling References	Fuel used
1	0,016987	0,014337	0,017377
2	0,009911	0,012561	0,009521
Delta	0,007076	0,001776	0,007856
Rank	2	3	1

The results of the linear regression analysis of the weighted mass yield provided important information on the factors influencing this crucial parameter during the carbonization process.

According to Table 22, the model explains 100% of the variation in the data (R-Sq = 100%), which may indicate overfitting. The analysis of variance (Table 23) shows that all three factors have significant effects on net mass yield, with p-values below 0.05.

Table 24 lists the levels of each factor that maximizes the weighted mass yield. Concerning the biomass type, the coefficient associated with sawdust was positive (0.034924), suggesting an increase of the weighted mass yield compared to the use of the other biomass. For the fill amount, the coefficient for the 33% filling reference was negative (-0.021612), indicating a decrease of the weighted mass yield compared to a higher fill amount. The coefficient for using cardboard as fuel was positive (0.035503), suggesting an increase of the weighted mass yield compared to the use of the other type of fuel. This is confirmed in tables 25, 26,

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and 27. Furthermore, they suggested that the type of fuel used and the amount of filling are important factors for maximizing the weighted mass yield of carbonization.

- **Taguchi analysis: energy yield depending on biomass type, filling quantity and fuel type**

Each test was repeated thrice to determine the factors affecting energy efficiency. The energy yields (Re) of the tests are presented in Table 28.

Table 28: Energy efficiency values

TYPE OF BIOMASS	QUANTITY	FUEL TYPE	Re-1	Re-2	Re-3
SAWDUST	33%	CARDBOARD	86.6%	83.8%	91.3%
SAWDUST	100%	PLASTIC	82.4%	81.6%	85.2%
LEATHER	33%	PLASTIC	63.3%	65.1%	63.3%
LEATHER	100%	CARDBOARD	80.1%	77.5%	76.2%

These data were analyzed using the Taguchi method, and Tables 29–34 show the results.

Table 29: Model Summary

S	R-Sq	R-Sq(adj)
*	100,00%	*

Table 30: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of biomass	1	0,147755	0,147755	0,147755	*	*
Filling References	1	0,231628	0,231628	0,231628	*	*
Fuel used	1	0,062899	0,062899	0,062899	*	*
Residual Error	0	*	*	*		
Total	3	0,442282				

Table 31: Estimated Model Coefficients for Means

Term	Coef
Constant	0,439917
Type of Sawdust	-0,192194
Filling 33 %	-0,240639
Fuel use Cardboar	0,125398

Table 32: Response for Signal to Noise Ratios

Larger is better

Level	Type of biomass	Filling References	Fuel used
1	-13,190	-14,538	-8,799
2	-5,764	-4,416	-10,156
Delta	7,426	10,122	1,357
Rank	2	1	3

Table 33: Response for Means

Level	Type of biomass	Filling References	Fuel used
1	0,2477	0,1993	0,5653
2	0,6321	0,6806	0,3145
Delta	0,3844	0,4813	0,2508
Rank	2	1	3

Table 34: Response for Standard Deviations

Level	Type of biomass	Filling References	Fuel used
1	0,007117	0,005699	0,018669
2	0,018620	0,020038	0,007068
Delta	0,011503	0,014339	0,011601
Rank	3	1	2

Linear regression analysis of the energy yield offers crucial insights into the factors influencing the carbonization process.

As shown in Table 29, the model explained 100% of the variation in the data (R-Sq = 100%), potentially indicating overfitting. The analysis of variance (Table 30) confirms the significant impact of all three factors (biomass type, filling quantity, and fuel type) on energy yield, with p-values below 0.05.

As shown in Table 31, the coefficient associated with sawdust was negative (-0.192194), indicating a decrease in energy yield compared to the use of another type of biomass (leather waste). Similarly, the coefficient for the 33% filling reference is negative (-0.240639), indicating a decrease in technological yield compared to a higher fill amount. In contrast, the use of cardboard as fuel showed a positive coefficient (0.125398), suggesting an increase in the energy yield compared to the use of cardboard. This is

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supported by the results presented in Tables 32, 33, and 34. Also, according to the latter, biomass type and filling quantity appear to have a significant influence on technological performance. However, fuel utilization also plays a crucial role, with optimum performance observed at different levels.

This highlights the importance of the biomass type, filling reference, and fuel type in optimizing the energy yield during the carbonization process. It also highlights the complexity of the process and the need for a balanced approach to maximize energy efficiency. These observations can be valuable in guiding carbonization plant operators in adjusting the process parameters to improve the overall efficiency and reduce energy costs.

- **Taguchi analysis: technological yield depending on biomass type, filling quantity and fuel type**

Each test was repeated thrice to determine the factors that affected technological performance. The technological yields (Rt) of the tests are presented in Table 35.

Table 35: Technological efficiency values

TYPE OF BIOMASS	QUANTITY	FUEL TYPE	Rt-1	Rt-2	Rt-3
SAWDUST	33%	CARDBOARD	13.1%	12.8%	13.9%
SAWDUST	100%	PLASTIC	36.1%	35.6%	37.2%
LEATHER	33%	PLASTIC	26.5%	27.2%	26.1%
LEATHER	100%	CARDBOARD	103.3%	98.9%	97.2%

These data were analyzed using the Taguchi method, and Tables 36–41 show the results.

Table 36: Model Summary

S	R-Sq	R-Sq(adj)
*	100,00%	*

Table 37: Analysis of Variance for Means

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Type of biomass	1	0,020257	0,020257	0,020257	*	*
Filling References	1	0,002433	0,002433	0,002433	*	*
Fuel used	1	0,008275	0,008275	0,008275	*	*
Residual Error	0	*	*	*		
Total	3	0,030965				

Table 38: Estimated Model Coefficients for Means

Term	Coef
Constant	0,780323
Type of Sawdust	0,071164
Filling 33%	-0,024663
Fuel use Cardboar	0,045484

Table 39: Response for Signal to Noise Ratios

Larger is better

Level	Type of biomass	Filling References	Fuel used
1	-1,409	-2,547	-1,687
2	-3,032	-1,894	-2,754
Delta	1,622	0,654	1,067
Rank	1	3	2

Table 40: Response for Means

Level	Type of biomass	Filling References	Fuel used
1	0,8515	0,7557	0,8258
2	0,7092	0,8050	0,7348
Delta	0,1423	0,0493	0,0910
Rank	1	3	2

Table 41: Response for Standard Deviations

Level	Type of biomass	Filling References	Fuel used
1	0,02855	0,02415	0,02897
2	0,01515	0,01954	0,01473
Delta	0,01341	0,00461	0,01424
Rank	2	3	1

The results of the linear regression analysis for technological yield provide important insights into the factors influencing this crucial measure in the context of carbonization.

As shown in Table 36, the model explained 100% of the variation in the data (R-Sq = 100%), which may indicate a perfect model fit, although it is important to consider these results with caution. Analysis of variance (Table 37) confirmed that all three factors had significant effects on energy yield, with p-values below 0.05. These results underline the importance of carefully selecting the type of biomass and fuel, as well as the amount of fill, to maximize the energy yield in the carbonization process.

From Table 38, the estimated coefficients reveal that biomass type, fill quantity, and fuel type have distinct effects on energy yield. For fuel type, the coefficient for sawdust was positive (0.071164), suggesting an increase in technological yield compared to the use of sawdust. In contrast, the coefficient for the 33% fill reference was negative (-0.024663), indicating a decrease in technological yield compared with a higher fill amount. For fuel type, the coefficient is also positive (0.045484), suggesting an increase in technological yield compared with the use of cardboard. These results are supported by the response tables for energy efficiency (Tables 39, 40, and 41).

These observations underline the complexity of the carbonization process and the need for a holistic approach to optimize technological performance.

Table 42 summarizes the influence of each factor (type of biomass, quantity of filling, and type of fuel) on the S/N (signal-to-noise) ratios of the four types of yields.

Table 42: Summary of Taguchi analysis results

	Mass yield		Weighted mass yield		Yield Technological		Yield energy	
Postman	Rank	Important level	Rank	Important level	Rank	Important level	Rank	Important level
Type of biomass	3	Leather	2	Sawdust	2	Leather	1	Sawdust
Filling quantity	2	100%	3	100%	1	100%	3	100%
Fuel type	1	Cardboard	1	Cardboard	3	Cardboard	2	Cardboard

1: most important factor

2: second most important factor

3: third most important factor

Table 42 provides valuable information on the influence of each factor (type of biomass, quantity of filling, and type of fuel) on the five types of yields studied. Looking at the signal-to-noise (S/N) ratio, an indicator of performance quality, we see that fuel type appears to be the most crucial factor, with cardboard being the most favorable level for all four performance types. Next, the amount of filling emerged as the second most important factor, with 100% being the most favorable for three of the four yield types. Finally, the type of biomass was positioned as the third most important factor, with leather and sawdust being the most favorable levels for some of the yields studied. These results highlight the importance of selecting the fuel type and filling quantity to optimize the performance of the mass-, weighted-, technological-, and energy-efficient processes. However, they also indicated that the choice of biomass type could play a significant role in some cases. These observations guide process design and optimization decisions in carbonization, highlighting the most influential factors to consider for improving yield quality.

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Table 43 summarizes the descriptive statistics of returns.

Table 43: Descriptive statistics of improved carbonization yields

Variable	Type of biomass	Mean	StDev
Gross Mass Yield	Sawdust	0,47162	0,02022
	Leatherwaste	0,4782	0,0675
Net Mass Yield	Sawdust	0,10551	0,01556
	Leatherwaste	0,1567	0,0550
Weighted Mass Yield	Sawdust	0,47530	0,02193
	Leatherwaste	0,4055	0,0633
Technological Yield	Sawdust	0,2477	0,1264
	Leatherwaste	0,632	0,401
Energy Yield	Sawdust	0,8515	0,0353
	Leatherwaste	0,7092	0,0781

Descriptive statistics provided important information on different yield measures (gross mass, net mass, weighted mass, and technological and energy yields) for the two types of biomass (sawdust and leather waste). The following is an interpretation of the results.

Gross mass yield: For sawdust, the average gross mass yield was 0.47162 with a standard deviation of 0.02022. For leather waste, the average gross mass yield was slightly higher (0.4782) with a higher standard deviation of 0.0675. This suggests a greater variability in gross mass yields for leather waste than for sawdust.

Net mass yield: For sawdust, the average net mass yield was 0.10551 with a standard deviation of 0.01556. For leather waste, the average net mass yield was significantly higher (0.1567) with a higher standard deviation of 0.0550. This indicates an increase in the net mass yield when leather waste is used compared with sawdust.

Weighted return: For sawdust, the average weighted mass yield was 0.47530 with a standard deviation of 0.02193. For leather waste, the average weighted mass yield was slightly lower (0.4055) with a higher standard deviation of 0.0633. This suggests a greater variability in the weighted mass yields for leather waste than for sawdust.

Technological performance: For sawdust, the average technological yield was 0.2477 with a high standard deviation of 0.1264. For leather waste, the average technological yield was much higher at 0.632, with an equally high standard deviation of 0.401 (presence of uncooked waste). This suggests large variability in the technological yields of the two types of biomass. However, on average, leather waste has a much higher technological yield than sawdust.

Energy efficiency: For sawdust, the average energy yield was 0.8515 with a standard deviation of 0.0353. The average energy yield of the leather waste was slightly lower (0.7092), with a higher standard deviation of 0.0781. This suggests a greater variability in the energy yields for leather waste than for sawdust.

These results indicate that leather waste tends to have a higher average yield than sawdust across all the yield measures. However, it is important to note the greater variability in the yields of leather waste, as indicated by higher standard deviations. This raises questions regarding the consistency and reliability of yields for leather waste compared with sawdust. Furthermore, the significant difference in technological yield between the two biomass types deserves special attention, as this could have implications for the overall efficiency and profitability of the production process.

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3.3. Comparison of the mass yield of the carbonizer with those of other types of carbonizations

The production performance in carbonization varies depending on numerous parameters, over which the carbonizer often has great freedom of action, such as the prior drying of biomass. [22]. Table 44 compares the mass yields obtained with three types of carbonizations of eucalyptus tereticornis with those of our pyrolysis pilot furnace (0.196 m^3 cylindrical oven) using sawdust and leather waste as biomass for carbonization.

Table 44: Comparison of carbonizer mass yields (average results) with those of other types of carbonizations

Types of carbonizations	Humidity level (%)	Mass yields (%)	Weighted mass yields (%)	Fixe carbon (%)	PCS (kJ/kg)	ash amount (%)	Volatile substances (%)	PCI (kJ/kg)
Magnien metal furnace 4 m^3	28,5	24,7	24,3	78,7	31830	3,6	17,7	
Traditional grinding wheel	28,4	26	25,8	79,5	32200	2,7	17,8	
Meule casamançaise	29,0	25,3	24,5	77,6	31000	3,3	19,1	
Pyrolysis pilot furnace using sawdust	17,1	47,2	47,6	80,6		1,5	17,9	32992
Pyrolysis pilot furnace using leather waste	13,1	47,8	41,3	67,7		11,4	20,9	29656

3.3.a. Comparison of mass yields

Mass yield indicates the proportion of coal produced relative to the initial raw material. The higher the mass yield, the more efficient the carbonization process. The mass yield values varied among the different carbonization types.

The Magnien metal oven had an average mass efficiency of 24.7%.

The traditional grinding wheel has an average mass yield of 26%.

Casamance millstone displayed an average mass yield of 25.3%.

The pyrolysis pilot furnace using sawdust and leather waste had much higher average mass yields (47.2% and 47.8%, respectively).

3.3.b. Comparison of Weighted Mass Yields (%)

The weighted mass yields consider the mass yields and proportions of the raw materials used. They provided a more accurate measure of the efficiency of the carbonization process. The weighted mass yield values also varied among the different carbonization methods.

The Magnien metal oven displayed an average weighted mass yield of 24.3%.

The traditional grinding wheel had an average weighted mass yield of 25.8%.

The Casamance millstone displayed an average weighted mass yield of 24.5%.

The pilot pyrolysis furnace using sawdust and leather waste had average weighted mass efficiencies of 47.6% and 41.3%, respectively.

These data clearly show that the mass and weighted mass yields of the pilot pyrolysis furnace using sawdust and leather waste were significantly higher than those obtained using other carbonization methods. This suggests better efficiency in converting feedstock into coal for these two methods. The mass and factored efficiencies of cylindrical furnaces can be attributed to several factors, such as furnace design, temperature control, and raw material composition. Data on mass and weighted yields highlight the different performances of the different types of carbonization. Pyrolysis pilot furnaces using sawdust and leather waste stand out because of their high mass and weighted efficiencies, making them promising options for high-yield coal production.

3.4. Characterization and performance of the carbonization of sawdust and leather waste

Carbonization is a key process in converting biomass into coal, a renewable energy source and a useful material in various fields. In this study, we compared the carbonization performance of two different raw materials: sawdust and leather waste. We examined several parameters, including moisture content, mass and weighted yields, chemical composition, and lower calorific value (LCV), to assess the quality of coal produced by each type of biomass. The moisture content of the raw materials plays a crucial role in the carbonization process. Sawdust has an average moisture content of 17.1%, whereas leather waste has an average moisture content of 13.1%. This difference can be attributed to the density and intrinsic composition of biomass. The mass and weighted yields represent the quantity of coal produced relative to the initial mass of raw materials. The carbonization of leather waste resulted in slightly higher yields than the carbonization of sawdust, with mass yields of 47.8% versus 47.2%, and yields of 41.3% versus 47.6%. weighted masses. These results indicate a slightly better conversion efficiency for leather waste.

The chemical composition of coal, including the percentage of fixed carbon, ash, and volatile matter, is a crucial indicator of its quality. The coal obtained by the carbonization of sawdust had a higher percentage of fixed carbon (80.6%) than that obtained by the carbonization of leather waste (67.7%), suggesting a better energy quality. However, leather waste coals had a higher ash percentage (11.4%) than sawdust coals (1.5%), which may reflect their different mineral composition.

The PCI represents the amount of energy released during coal combustion. Charcoals made from sawdust had an average PCI of 32,992 kJ/kg, while charcoal made from leather waste had an average PCI of 29,656 kJ/kg. Despite their slightly lower mass and weighted yields, sawdust coals had a higher PCI, indicating a better energy quality.

Our results indicate that both carbonization methods are effective, but have different characteristics. The leather waste produced charcoal with a greater proportion of organic matter, whereas sawdust produced charcoal with a higher PCI and a higher percentage of fixed carbon. The choice between the two methods depends on specific requirements in terms of coal quality, availability of raw materials, and operational constraints.

IV. CONCLUSION

Faced with environmental problems caused by the use of wood as the main source of energy and the accumulation of waste, this study focuses on the development of a more sustainable alternative to wood and waste management. Carbonization of waste is an interesting approach. Thus, this study focuses on the configuration of a pyrolysis pilot furnace during carbonization. The objective was to develop a carbonizer that offers the best possible yields accessible and reproducible by the population. As a part of the configuration, the studied factors were the type of biomass, quantity of oven filling, and type of fuel used. These factors were chosen because of their significant influence on the yields (net mass, gross mass, weighted mass, energy, and technology) of carbonization. To identify the parameters allowing optimization of the carbonizer, a pilot furnace of 0.196 m^3 was created, and two different levels were assigned to each factor. For the “type of biomass” factor, the assigned levels were “sawdust” and “leather waste.” For the “fill quantity” factor, the levels were “33%” and “100%”. For the “fuel type” factor, the levels were “cardboard” and “plastic” plastic’.

The Taguchi method was applied to minimize the number of tests to be performed while retaining the maximum amount of information. The latter method is used because it enables the development of products and processes that are robust and insensitive to external disturbances. Taguchi's method suggested the use of an L4(2^3) design of experiments. Thus, we conducted four tests by varying the level of each factor. To obtain reliable results, each test was repeated thrice. The results showed that the first factor with the greatest influence on all yields considered in this study was the type of fuel, the most favorable level of which was cardboard. The quantity of filling is the second most influential factor, the level 100% of which is the most favorable for three of the four types of yields. Finally, biomass type was the third most influential factor on yield.

To assess the performance and efficiency of our carbonizer, its mass yields were compared with those of other types of carbonizers, namely the Magnian metal oven, traditional millstone, and Casamance millstone. The comparisons showed that the mass yields of the pyrolysis pilot furnace were significantly higher than those of other carbonizers. This demonstrates the opportunity offered by a pyrolysis pilot furnace to improve carbonization and waste management. Regarding the characteristics of coal obtained by the carbonization of sawdust and leather waste, the results showed that the mass yield (47.8%) of the carbonization of leather waste was slightly higher than that of carbonized sawdust (47.2%). However, the energy yield of sawdust carbonization (85%) is higher than that of leather waste carbonization (70.9%). Sawdust coals had an average PCI of 32992 kJ/kg which is higher than that of leather waste coals (29656 kJ/kg). This means that sawdust has better energy quality. The leather waste coal had a greater proportion of organic matter.

The results of this study are promising for waste management, the search for new and more sustainable energy sources, and more effective techniques for natural resource exploitation, forest preservation, and environmental protection. Further studies are required to model the pyrolysis pilot furnace, test the carbonization of other biomasses, and assess the profitability of large-scale carbonization.

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REFERENCES

[1] P. BURNY, P. MONTAGNE, R. CREHAY, H RANDRIANJA, A.-M. RASAMINDISA, La production de charbon de bois à Madagascar : amélioration technique et économique, *Environnemental Policies and Legislation*, 31-40, 2008

[2] https://www.wwf.mg/?821111/Des-solutions-pour-une-filiere-bois-energie-durable-a-Madargascar consulted on 5 Décembre 2023

[3] S. MOREAU, Ville et biodiversité : le bois-énergie à Madagascar, Réseau Cicle, *Coopération internationale Climat – Energie*, 2010

[4] B. STANFORD, "Les Forêts, les Charbonniers, et l'Avenir Une Analyse de la Filière Charbon Dans le District de Fianarantsoa" (2006). *Independent Study Project (ISP*) Collection. 258. [En ligne] https://digitalcollections.sit.edu/isp_collection/258 consulted on 28/02/2024

[5] Bonne pratique de carbonisation à Madagascar, projet CARAMCODEC, Programme Energie Intelligence – Europe, 2008 ;

[6] WWF, Madagascar, nouveau front de déforestation, [En ligne] https://www.wwf.mg/?1967916/Madagascar-nouveau-front-de-deforestation , consulted on 25/03/2024

[7] S. JANICOT, C. AUBERTIN, M. BERNOUX, E. DOUNIAS, J. GUÉGAN, T. LEBEL, M. REINERT, Chapitre 7. Les émissions de gaz à effet de serre. In Changement Climatique ; Quels défis pour le Sud ? IRD Editions, 2015. https://doi.org/10.4000/books.irdedition.29426

[8] J. C. SALAMA., Chapitre 10 : Déchets, Environnement, 369-399, *Ministère de l'Environnement et du Développement durable de Madagascar*, 2019

[9] L. QIN, M. WANG, J. ZHU, Y. WEI, X. ZHOU AND Z. HE, Towards Circular Economy through Waste to Biomass Energy in Madagascar, *Hindawi Complexity*, Volume 2021, Article ID 5822568, 10 pages https://doi.org/10.1155/2021/5822568

[10] Victor John Sundar, Arumugam Gnanamani, Chellappa Muralidharan, Narasiman Kannan Chandrababu, Asit Baran Mandal, Recovery and utilization of proteinous wastes of leather making: a review, Rev Environ Sci Biotechnol (2011) 10:151–163, https://doi.org/10.1007/s11157-010-9223-6

[11] J. E. CHOONG, C. C. ONN, S. YUSOFF, N.S. MOHD, (2019). Life Cycle Assessment of Waste-to-Energy: Energy Recovery from Wood Waste in Malaysia. Polish Journal of EnvironmentalStudies, 28(4), 2593-2602. https://doi.org/10.15244/pjoes/93925

[12] G. ANTONINI et M. HAZI, PYROLYSE – GAZEIFICATION DE DECHETS SOLIDES, Partie 1 : Etat de l'art des procédés existants, Faisabilité de traitement d'un déchet par Pyrolyse ou Gazéification, Etude ADEME/PROCEDIS, 2001

[13] https://greenpower.equipment/fr/articles/la-carbonisation-de-la-biomasse-un-moyen-daugmenter-la-fertilite-des-terres/ consulted on 28/02/2024

[14] C. MIC, Carbonization in *IUPAC Compendium of Chemical Terminogy*, 3rd ed. International Union of Pure and Applied Chemistry, 2014. https://doi.org/10.1351/goldbook.C00840

[15] J. SCHURE, D. HUBERT, H. DUCENNE, M. KIRIMI, A. AWONO, R. MPURUTA-KA-TITO, G. MUMBERE, M. NJENGA, Carbonisation 2.0 : Comment preoduire plus de charbon de bois tout en réduisant la quantité de bois et d'émissions de gaz à effet de serre ? Dossier N°1 : *Le bois-énergie durable, Projet Gouvernance des paysages multifonctionnels (GML)*, Bogor, Indonésie et Nairobi, Kenia : CIFOR-ICRAF, 2021

[16] FAO, Chapitre 5 : Charbonnières en fosse, [En Ligne] https://www.fao.org/3/X5328F/x5328f06.htm consulted on 29/02/2024

[17] S. ANDRIAMANDROSO, *Essais de valorisation des déchets de cuir et de semelle dans le béton*, Science et Ingénierie des Matériaux, Ecole Supérieure Polytechnique d'Antananarivo, 2023 [18] Projet RDD + de la vie, *Formation des charbonniers à la carbonisation améliorée*, Côte d'Ivoire 2019

[19] https://www.altimara.eu/blog/category/charbonniere-en-fosse/ consulted on 29/02/2024

[20] M. TEMMERMAN, R. ANDRIANIRINA, F. RICHTER, Performances techniques et environnementales du four de carbonisation Green Mad Retort à Madagascar, Cirad, *Bois et Forêts des Tropiques*, 340 : 43-55, 2018. https://doi.org/10.19182/btf2019.340.a31700

[21] Y. SCHENKEL, P. BERTAUX, S. VANWIJNSBERGHE, J. CARREN, Une évaluation de la technique de la carbonisation en meule, *Biotechnol. Agron. Soc. Envion*., 1(2), 113-124, 1997 ;

[22] P. GIRARD, Techniques et Matériels de Carbonisation, Contrôle de performances, *Revue Bois et Forêts des Tropiques*, n° 232, 2e trimestre 1992

[23] C.A. SANOGO, M. L. ELHADJI MAHAMANE, S. KHENNAS, H. KONADJI, J.R. VANDER PLAS, P. GIRARD, Techniques améliorées de carbonisation au Sahel, Ouagadougou, Burkina Faso, PREDAS, 2006

[24] C. RIUJI LOHRI, H. MTORO RAJABU ; D.J. SWEENEY, C. ZURBRÜGG, Char fuel production in developing countries – A review of urban biowaste cabonization, Renewable and Sustainable Energu Reviews, 59 : 1514-1530, 2016. https://doi.org/10.1016/j.rser.2016.01.088

[25] G. MADON, Le bois, énergie de première nécessité en Afrique. Une ressource trop souvent négligée. *Afrique Contemporaine*, 261-262 : 201-222, 2017. https://doi.org/10.3917/afco.261.0201

[26] FAO, The charcoal transition: greening the charcoal value chain to mitigate climate change and improve local livelihoods. Rome, Italy, FAO, 2017. [En ligne] http://www.fao.org/3/a-i6935e.pdf consulted on 19/03/2024.

[27] P. MONTAGNE, S. RAZAFIMAHATRATRA, A. RASAMINDISA, R. CREHAY, Arina, le charbon de bois à Madagascar : entre demande urbaine et gestion durable. Antananarivo, Madagascar, CITE-Cirad, 2010.

[28] P. MUNDHENK, O. GOMIS, M.C. SY, Comparaison des rendements de production de charbon de boisentre la meule traditionnelle et la meule Casamance dans la forêt communautaire de Sambandé. Dakar, Sénégal, PERACOD, 22 p, 2010. https://energypedia.info/images/3/38/Meule_casamancaise_PERACOD_Mundhenk

[29] H.K. Sjølie, Reducing greenhouse gas emission from households and industry by the use of charcoal from sawmill residues in Tanzania. *Journal of Cleaner Production*, 27: 109-117, 2012. https://doi.org/10.1016/j.jclepro.2012.01.008

[30] Y. SCHENKEL, M. TEMMERMAN, J. F. VAN BELLE, R. VANKERKOVE, New Indicator for Evaluation of the wood carbonization process, *Energy Sources*, 21: 935-943, 1999. https://doi.org/10.1080/00908319950014308

[31] M. G. Piketty, T. Fonseca Morello, J.-P. Bouillet, J.-P. Laclau, M. Behling, A. Caldeira Pires et al., Charbon de bois et sidérurgie en Amazonie brésilienne : quelles pistes d'améliorations environnementales ? L'exemple du pôle de Carajas. Paris, France, Agence française de développement, Document de travail 112, 87 p, 2011. [En ligne] https://www.afd.fr/fr/charbon-de-bois-et-siderurgie-en-amazonie-bresilienne-quelles-pistes-dameliorations-environnementales-lexemple-du-pole-de-carajas consulted on 19/03/2024

[32] D. M. PENNISE, K. R. SLITH, J. P. KITHINJI, M. E. REZENDE, T. J. RAAD, J. ZHANG et al., Emission of greenhouse gases and other airborne pollutants from charcoal making in Kenya and Brazil. Journal of Geophysical Research, 106: 24-143-155, 2001. https://doi.org/10.1029/2000JD000041

[33] M. Sparrevik, C. Adam, V. Martinsen, Jubaedah, G. Cornelissen, Emissions of gases and particles from charcoal/biochar production in rural areas using medium sized traditional and improved "retort" kilns. Biomass & Bioenergy, 72: 65-73, 2015. https://doi.org/10.1016/j.biombioe.2014.11.016

[34] V. Dhyani, T. Bhaskar, A comprehensive review on the pyrolysis of lignocellulosic biomass, Renewable Energy, Volume 129, Part B, 2018, Pages 695-716, ISSN 0960-1481, https://doi.org/10.1016/j.renene.2017.04.035.

[35] C. DUBY, La méthode Taguchi : valeur et limites, *Revue de statistique appliquée*, tome 37, no 2 (1989), p. 7-15

[36] M. PILLET. Les plans d'expériences par la méthode Taguchi, pp. 250, 2001 ⟨hal-00470004⟩

[37] R. SABRE, Plan d'expériences – Méthode de Taguchi, *Technique de l'Ingénieur*, 2007

[38] J.-C. CHAUVEAU, J.-P. CHASSAING, Introduction à la méthode des plans d'expériences par la méthode Taguchi, *C.N.E.D Génie Electrotechnique*

[39] T. LUNDSTEDT, « Experimental design and optimization », *Chemometrics and Intelligent Laboratory Systems*, vol. 42, nos 1-2, 1998, p. 3-40

[40] G. SAPORTA, Probabilités, analyse des données et statistique, p. 535

[41] P. MAIRE, Matrice de Hadamard et Applications, Master 1 Mathématiques appliquées, Statistiques, Université de Lille, 2018

[42] C. CONSTANT, La méthodologie Taguchi : introduction à la recherche technologique - gestion fonctionnelle de la qualité ou gestion « off-line », *Revue de statistique appliquée*, tome 37, no 2 (1989), p. 47-77

[43] Y. N. QUACH, O. LIM, An investigation of the Effect of Propylene Gas Flame on Emissions and Temperature Distribution of a Preheated Metal Plate, Sustainability, 2023. https://doi.org/10.3390/su151612306