

Recycling of Hydrocarbon Waste from Thermal Power Plant: Case of the Maria Gléta Thermal Power Plant in the Republic of Benin

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Abstract

The elimination of hydrocarbon waste is difficult, and it is a great source of greenhouse gas emissions due to its toxicity. The study characterised oily sludge from a Beninese thermal plant and tested small-scale pyrolysis to identify conversion conditions that minimise toxic residues. Laboratory analyses quantified moisture ($\approx 25\%$), sulphur (0.3%), selected heavy metals, and very high viscosity. Pyrolysis at 400°C for 30 min produced $\sim 70\%$ oil + gas, 5% char and 25% water, whereas 500°C yielded only ash. The authors recommend the $400^\circ\text{C}/30$ min option as a practical recovery route.

Keywords

Valorization, Oily Sludge, Pyrolysis, Thermal Power Plant

1. Introduction

Access to reliable and sustainable energy is a strategic issue for the economic and social development of many countries. The latter have set up initiatives aimed at strengthening national energy capacities in order to guarantee electricity autonomy and a competitive and quality supply of energy to the population [1]. It is in this context that the Maria Gléta thermal power plant was built to meet Benin's growing electricity needs. It is largely based on the use of hydrocarbons as an energy source that leads to the production of hydrocarbon wastes, including oily sludge and other oil residues. The inadequate management of this waste represents a major challenge due to its environmental and health impacts. Indeed, this sludge con-

tains toxic hydrocarbons, heavy metals and sometimes radionuclides [2]. Their dispersion in the environment can cause pollution of groundwater, soil and atmosphere, thus compromising biodiversity and human health [3]. Currently, this waste is little or not recovered; they are difficult to dispose of and its treatment can result in greenhouse gas emissions. In addition, their persistence and high mobility in the soil increase the risk of contamination of local ecosystems. Faced with these challenges, it is becoming imperative to find innovative and sustainable solutions that not only minimize the negative impacts of this waste but also derive added value from it through appropriate recovery processes. Different technologies, such as incineration, pyrolysis, gasification and solvent extraction have been developed in order to recover reusable hydrocarbons or to produce secondary energy sources.

Kumar *et al.* presented several technological approaches to extract energy from non-recyclable waste. In their study, they distinguish between thermal processes such as incineration, pyrolysis, gasification and hydrothermal carbonization on the one hand, and non-thermal processes, including anaerobic digestion, on the other. Despite the emission problems, incineration remains the predominant method adopted by many countries [4]. Similarly, Lombardi *et al.* found that incineration, combined with energy recovery by a steam cycle, is the most common heat treatment. When it comes to gasifying waste, the syngas produced is usually burned in a boiler in order to generate steam for energy recovery. For these two techniques, incineration and gasification, cogeneration appears to be an effective solution for optimizing energy recovery, particularly in small-scale installations [5]. It is therefore imperative to improve the energy efficiency of current facilities while expanding the use of new technologies such as gasification and pyrolysis. Hossam *et al.* compared the two processes by showing that, during incineration, solid waste is burned in the presence of oxygen at atmospheric pressure, whereas gasification is based on partial oxidation (with an air/fuel ratio between 0.5 - 0.8) in order to produce syngas, thermal energy and tar. In addition, the presence of nitrogen in the air leads to the formation of nitrous oxides (N_2O and NO_x) and this process releases significant amounts of CO_2 while presenting high operating costs and ash problems. On the other hand, gasification, although it emits less CO and CO_2 , can generate other toxic gases such as dioxins, furans, sulfur oxides, and nitrous oxides [6]. Other studies highlight interesting alternative processes. For example, Gourram *et al.* have developed a hydrothermal pyrolysis technique operating between $200^\circ C$ and $300^\circ C$, making it possible to convert up to 72% of the organic matter contained in sewage sludge into oil and gas. These products, rich in alkanes, alkenes and aromatic compounds, also have a low content of heavy metals and sulphur [7]. An experimental study by Lede *et al.* evaluated the flash pyrolysis of wood waste using concentrated solar energy. This process, which consists of heating Douglas pine sawdust between $700^\circ C$ and $1000^\circ C$, makes it possible to obtain an 80% yield of gases rich in CO , H_2 and light hydrocarbons, while providing an in-depth analysis of its chemical and energy value [8].

However, each of these methods has limitations in terms of effectiveness, costs and environmental impacts. For example, existing treatment methods, such as incineration and centrifugation, do not allow for complete separation of the water, oil and solids phases, while being limited in terms of economic, energy and environmental efficiency [9]. The choice of appropriate technology must be made to minimize its impacts on the environment and human health. **Table 1** summarizes the methods of treatment of these wastes according to their products, areas of application, advantages and limitations.

Table 1. Summary and comparison of oily sludge recovery technologies.

Methods	Produce	Application	Benefits	Bounds	References
Incineration	Flue gas	Production of steam, electricity.	<ul style="list-style-type: none"> - Complete removal of hydrocarbons and harmful chemical compounds; - Heat recovery for steam and electricity production; - Significant reduction in the volume of sludge. 	<ul style="list-style-type: none"> - Greenhouse gas emissions; - Requires auxiliary fuel for sludge combustion; - Requires additional treatment of gas emissions and combustion residues; - Requires the direct use of the heat produced; - Requires a high capital and operating cost of more than \$800 per tonne of sludge incineration; - Production of a significant amount of ash requiring further management. 	BOUTIN <i>et al.</i> (2002) [10], Hu <i>et al.</i> (2013) [11], Samolada <i>et al.</i> (2013) [12], Kumar <i>et al.</i> (2019) [4], Lidia and Lombardi. (2015) [5]
Pyrolysis	<ul style="list-style-type: none"> - Pyrolysis gas - Pyrolysis oil - Pyrolysis charcoal 	<ul style="list-style-type: none"> - Heat and electricity production; - Diesel engines, power generation; - Soil amendment, electricity production. 	<ul style="list-style-type: none"> - Reduction of the volume of sludge; - Destruction of toxic organic compounds; - Fixation of heavy metals in the final solid residue (ash). 	<ul style="list-style-type: none"> - Requires an oxidizing agent; - High initial and operating costs; - Risk of explosion. 	BOUTIN <i>et al.</i> (2002) [10], Samolada <i>et al.</i> (2013) [12], Santiago (2022) [14]
Gaseification	Syngas	Power generation	<ul style="list-style-type: none"> - Easy to apply; - Fast and efficient. 	<ul style="list-style-type: none"> - Requires a large amount of solvent; - High cost; - Not environmentally friendly. 	Hu <i>et al.</i> (2013) [11]
Solvent extraction	Oil	<ul style="list-style-type: none"> - Diesel engines; - Electricity production. 			

The study of these different technologies was combined with a SWOT analysis, to identify their strengths, weaknesses and opportunities [15]. This approach was applied in this study based on three main criteria: technical, ecological and economic. To guide the choice of the most suitable technology, these criteria must follow an order of priority. In our case, the ecological aspect is the priority criterion, followed by the technical and economic criteria. Pyrolysis was therefore chosen as the recovery method.

2. Materials and Methods

2.1. Materials

These are oily sludge (**Figure 1**) and various equipment used for the waste characterization and the realization of pyrolysis on a sludge sample.



Figure 1. Oily sludge from Maria Gléta's thermal power plant contained in a bottle.

2.2. Methodology

2.2.1. Sampling Method

At the Maria Gléta thermal power plant, liquid waste (water, oily sludge) is stored in two tanks, where the denser water settles at the bottom. The samples were taken in tank n°2, after purging the water until the first oily sludge appeared. Two samples taken at different dates made it possible to obtain a better chemical characterization of the sludge, which is essential for its recovery. The quantity of produced sludge was evaluated from January to May 2023 and is estimated at 170 m³ for 5575 m³ of heavy fuel oil used.

2.2.2. Sludge Characterization Methods

The parameters analyzed in this study are summarized in **Table 2**:

Table 2. Some parameters for the characterization of oily sludge.

Parameters	Principles
Water content	Drying in the oven
Sulphur content	X-ray fluorescence analysis

Continued

Heavy metals	Atomic absorption spectrophotometry
Viscosity	Center of Inertia Theorem (Inclined Plane)

- The moisture content was determined using Equation (1):

$$T = \frac{m_1 - m_2}{m_1} \times 100 \quad (1)$$

where m_1 is the mass (g) of the sample before drying, m_2 the mass (g) of the sample after drying, and T the moisture content (%).

- The determination of viscosity by inertial balance on an inclined plane, as recommended in Section 10 of API RP 13I, is particularly suitable for highly viscous slurries because it mobilizes a high and localized shear, sufficient to break the particle network and access the actual viscosity of the fluid, it does not require complex equipment (such as rotational viscometers), often ineffective against suspensions with a high freezing point [16].

So, viscosity can be determined by the theorem of the center of inertia applied to an inclined plane (see **Figure 2**):

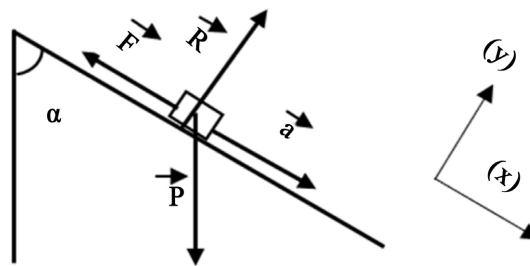


Figure 2. Inclined plane.

The viscosity force F is determined by the following formula [17]:

$$F = \mu \cdot S \cdot \frac{V_f - V_i}{e} \quad (2)$$

where S is the surface (m^2) of the cube in contact with the mud; V_f and V_i are respectively the final and initial velocities (m/s) of the cube and e is the thickness (m) of the layer of mud whitewashed on the inclined plane.

- The dynamic viscosity is calculated by formula 3:

$$\mu = \frac{m_c \cdot e (g \cos \alpha - a)}{S \cdot V_f} \quad (3)$$

- The kinematic viscosity of the slurry was therefore calculated by formula 4:

$$\nu = \frac{\mu}{\rho_b} \quad (4)$$

where ν is the kinematic viscosity of the slurry in cSt and ρ is the density of the slurry in kg/m^3 .

Three tests were carried out and the average was taken.

The experiments were carried out at room temperature (31 °C).

- Sulphur content is the proportion of sulphur contained in a given substance. The method used for the determination of the sulphur content is the X-ray fluorescence analysis method (see **Figure 3**).

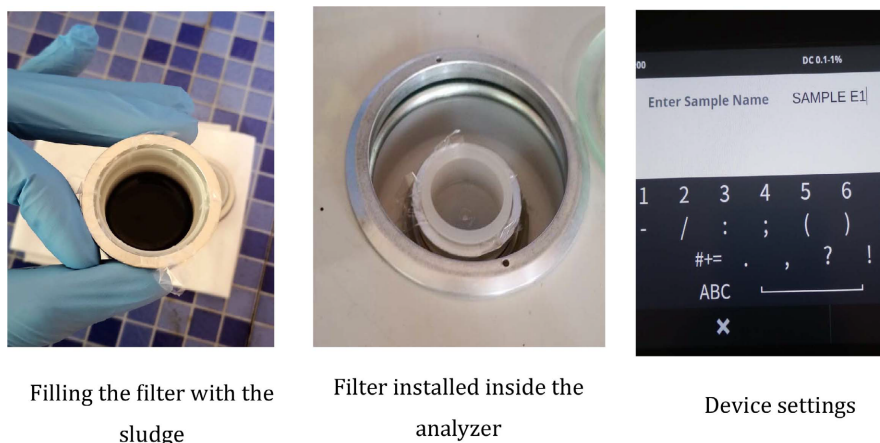


Figure 3. Some steps in determining the sulphur content.

- Heavy metals are metallic chemicals that have a high density and can be toxic to living things at high concentrations. The method used in this study for the determination of heavy metals is atomic absorption spectrophotometry. The sludge sample taken was incinerated in a muffle furnace at 550 °C for 24 hours. The ash thus obtained was dissolved in 5 ml of hydrochloric acid and evaporated on a hot plate at 125 °C; the more or less viscous residue obtained was dissolved and recovered using HNO₃ (0.1 M) in a 100 ml vial. The solution obtained was used to measure heavy metals using Atomic Absorption Spectrophotometry.

3. Results and Discussions

3.1. Characterization of Oily Sludge

The results obtained after each method of analysis of the different parameters are presented in **Table 3**:

Table 3. Results of the characterization of oily sludge.

Parameters	Average values	Units	
Water content	24.971 ± 0.862	(%)	
Sulphur content	0.376	(%)	
Heavy metals	Pb	4.256 ± 0.078	
	CD	0.384 ± 0.002	(mg/kg)
	Cu	4.814 ± 0.057	

Continued

	Zn	208.925 ± 1.216	
	Neither	16.857 ± 0.169	
	Cr	3.563 ± 0.020	
Viscosity		2446.05	(cSt)

The sludge from the Maria Gléta thermal power plant has a water content of 25%, lower than the values in the literature (30% to 90%) [18], which nevertheless requires pre-treatment to remove residual water and avoid contamination. Their sulphur content is about 0.3%, well below the 1% to 2% reported in the literature [19], but treatment is required to reduce its environmental impact. The concentration of heavy metals is relatively low (<0.5 g/kg) with a predominance of Zn (208.925 mg/kg) and a low presence of Cd (0.3 mg/kg). Although these levels are lower than existing benchmarks [19], further reduction during pyrolysis is recommended. Finally, with a viscosity of 2446 cSt, the sludge is very viscous and requires heating to facilitate its handling.

In conclusion, although these sludges contain fewer toxic substances than those studied in the literature, pre-treatment remains crucial before pyrolysis. An environmental study was carried out, based on the available data, in order to define the optimal pyrolysis conditions for effective recovery.

Oily sludge contains pollutants such as heavy metals, sulfur which are harmful to the environment and human health. Their environmental impacts are grouped in **Table 4** [14] [17]:

Table 4. Environmental impacts of chemical elements in oily sludge.

Chemical elements	Environmental impacts	Impacts on human health
Heavy metals	<ul style="list-style-type: none"> - Long-term soil pollution; - Not suitable for plant and animal survival; - Volcanic eruptions. 	<ul style="list-style-type: none"> - Difficult to eliminate once entering the body; - Nervous system affect; - Cause carcinogenic diseases.
Sulphur	<ul style="list-style-type: none"> - Significant impacts on the environment due to its smell; - Sulfur is one of the main causes of acid rain. 	<ul style="list-style-type: none"> - Irritation of the upper respiratory tract; - Cardiovascular diseases.

Heavy metals like Cu, Zn, Cr, and Ni are essential for plants and animals but at low levels, while Cd and Pb are non-essential [20]. Heavy metal concentrations below 1 mg/kg do not have a significant impact on sludge recovery, unlike those above 110 mg/kg [19].

During pyrolysis, heavy metals mainly migrate to pyrolysis coal, requiring a reduction in its production to limit their environmental impact. Sulphur also mi-

grates during pyrolysis, degrading the quality of the obtained products and making reduction essential. The use of a catalyst would reduce heavy metal and sulphur contents, improve the quality of the final products and reduce gaseous emissions [18]. A thorough study is required to identify a catalyst that optimizes oil and syngas production.

3.2. Valorization of Oily Sludge by Pyrolysis

Pyrolysis Carried Out on Sludge Samples

Influence of pyrolysis conditions on the products obtained

Studies on the pyrolysis of oily sludge indicate an optimal temperature range between 500°C and 700°C with an ideal temperature of 500°C [18]. However, due to the specificities of the plant's sludge, several experiments were conducted, starting with 500°C, to identify the optimal temperature (see **Figure 4**).

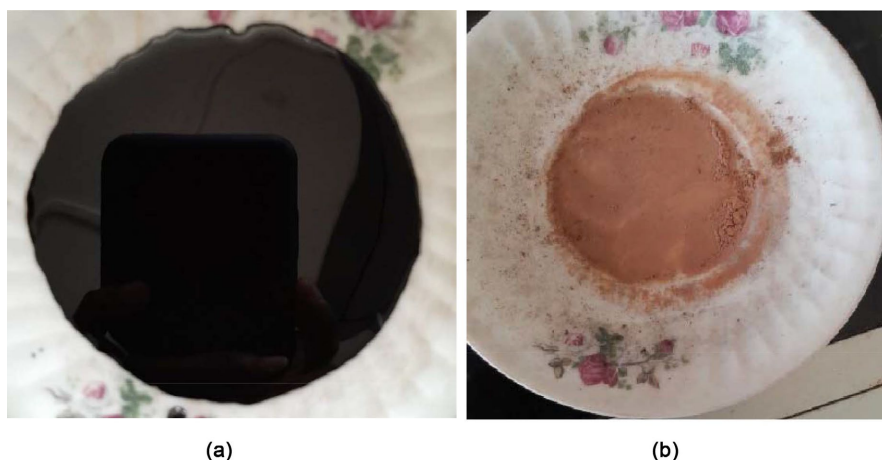


Figure 4. Effects of pyrolysis conditions of 500°C for 1 hour on sludge: (a) Oily sludge before pyrolysis; (b) Ash obtained after pyrolysis.

1st experience:

In the first experiment, carried out at 500°C for 1 hour, the product obtained was only ash, indicating an excessive conversion of organic matter. This suggests that the temperature and duration of pyrolysis were too high for the formation of coal. Additional tests were carried out to refine these parameters by adjusting the pyrolysis time.

2nd experience:

In the second experiment, carried out at 500°C for 30 minutes, pyrolysis also produced only ash. These two experiments lead to the conclusion that the temperature of 500°C, regardless of the duration, is too high to promote the complete conversion of organic matter into coal. Thus, the ideal pyrolysis temperature for the oily sludge from the plant seems to be below 500°C, in contrast to the temperature range of 500°C to 700°C mentioned in the literature. A third experiment was therefore carried out at a temperature below 500°C.

3rd experience:

The third experiment, carried out at 400°C for 30 minutes on 20.051g of sludge, showed that the reduction of the pyrolysis temperature favored the production of coal. The pyrolysis time of 30 minutes was found to be sufficient for the conversion of organic matter to charcoal without promoting ash formation. This experiment demonstrates that pyrolysis conditions at 400°C for 30 minutes are more suitable for the plant's sludge than those at 500°C (see **Figure 5**).



(a) Oily sludge before pyrolysis at 400°C for 30 min

(b) Charcoal obtained after

Figure 5. Effect of pyrolysis conditions of 400°C for 30 min on sludge.

4th experience:

During this fourth experiment, carried out at 400°C for 1 hour on 20.003 g of mud, coal was also obtained. This confirms that the temperature of 400°C is suitable for the pyrolysis of the plant's sludge (see **Figure 6**).



Figure 6. Coal obtained after pyrolysis of the sludge at 400°C for 1 hour.

The choice of pyrolysis duration aims to minimize coal production while maximizing gas and oil production, due to the migration of heavy metals to coal.

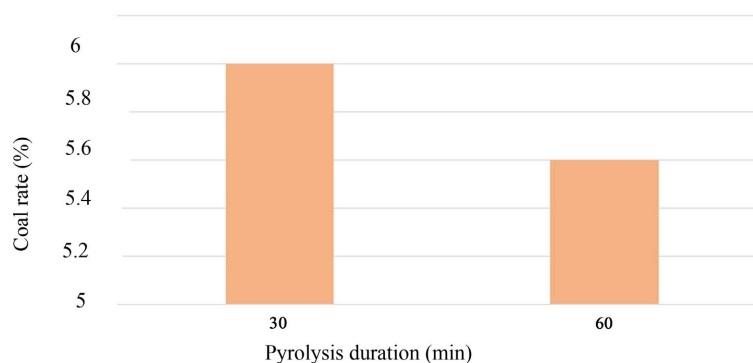
Table 5 is for the mass balance showing the mass of the initial sample and the percentages of coal, oil, gas and water for each experiment.

Effects of pyrolysis duration on pyrolysis product yields

Figure 7 Highlights the influence of pyrolysis duration on coal rate.

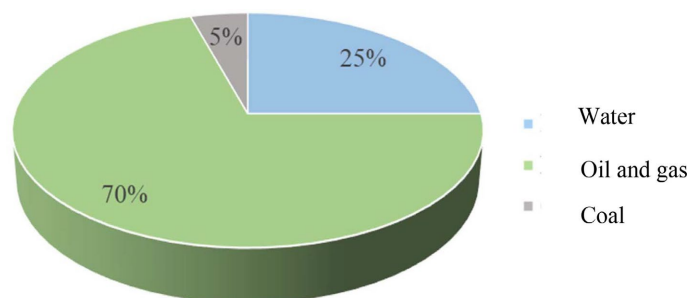
Table 5. Mass balance.

Experiences	Conditions	Initial mass (g)	Coal (%)	Gas + oil (%)	Water (%)
1 st	500 °C, 60 min	20.001	-	-	-
2 nd	500 °C, 30 min	20.000	-	-	-
3 rd	400 °C, 30 min	20.051	6.0	69.0	25.0
4 th	400 °C, 60 min	20.003	5.6	69.4	25.0

**Figure 7.** Influence of pyrolysis duration on coal rate.

The results show a decrease in the coal rate with increasing pyrolysis time. Indeed, the yield has decreased from 6% at 30 minutes to 5.6% at 1 hour, suggesting that longer pyrolysis leads to increased degradation of organic compounds, producing more gas and oil at the expense of coal. Although the extension of pyrolysis slightly increases gas and oil production, this improvement of only 0.4% does not justify a longer duration. Thus, for economic and ecological reasons, it is preferable to carry out pyrolysis at 400 °C for 30 minutes.

Figure 8 shows that the pyrolysis of the oily sludge from Maria Gléta would give a yield of 70% in oil and pyrolysis gas, 5% in coal on the stock of 170 m³ for 5575 m³ of heavy fuel oil used.

**Figure 8.** Distribution of products from the recovery of oily sludge from the Maria Gléta thermal power plant.

Environmental and economic implications of scaling up

- **Environmental.**
- ✓ Significant reduction in the volume of sludge to be stored and its associated

- heavy metals;
- ✓ Need for pyrolysis gas aftertreatment (tar trapping, H₂S, NO_x cleaning, etc.) to comply with regulatory emissions;
- ✓ Production of biochar that can potentially be used as an amendment, but must be controlled to avoid metal leaching.
- **Economical:**
- ✓ Investment in pyrolysis units (furnace, condensers, possible catalysts) and energy costs related to maintaining 400 °C;
- ✓ Income from the sale or self-production of energy (gas, oil);
- ✓ Savings on the costs of treatment and discharge of the sludge, and possible resale of the tank or steam.

Finally, in our study, no detailed characterization of gaseous or liquid effluents was carried out to check their composition or verify compliance with standards (Air Liquide, IED directive, etc.). To this end, we propose that a series of analyses (GC-MS, FTIR for PAHs, SO_x/NO_x assay, etc.) be carried out in a pilot phase to ensure compliance.

4. Conclusion

The Maria Gléta thermal power plant, which runs on heavy fuel oil, generates oily sludge with worrying environmental and health impacts. Pyrolysis was chosen as the optimal solution in this study, as it allows the production of coal, gas and pyrolysis oil, with reduced gaseous emissions. The characterization of the sludge revealed a water content of 25%, a sulphur concentration of 0.3%, heavy metals in moderate proportions (<0.5 g/kg) and a viscosity 2000 times higher than that of water. Experiments were carried out to identify the optimal pyrolysis conditions: a temperature of 400 °C for 30 minutes resulted in a yield of 5% in coal and 75% in pyrolysis gas and oil. To deepen this work, several perspectives are envisaged, including the analysis of the obtained coal, a more in-depth characterization of the sludge, the study of catalysts to improve the quality of the final products, the determination of the thermal capacity of the sludge to optimize its drying and the sizing of a suitable pyrolyzer.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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