

## Article

# Conversion of Post-Refining Waste MONG to Gaseous Fuel in a Rotary Gasifier

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**Abstract:** Biodiesel manufacturing frequently employs sustainable materials like soybeans, microorganisms, palm extract, jatropha plant, and recycled frying oils. The expansion of biodiesel manufacturing has escalated the volume of waste byproducts, encompassing glycerin and non-glycerin organic matter (MONG), jointly known as raw glycerin. MONG is characterized by a low calorific value, a high autoignition temperature, and significant viscosity at room temperature. As a waste product, it negatively affects the natural environment due to the lack of viable disposal methods. Hence, there is a need for its conversion into high-calorific gaseous fuel with significantly less environmental impact. One of the methods for converting MONG into gaseous fuel is the pyrolysis process. This study describes the pyrolytic conversion of MONG conducted on a test stand consisting of a rotating chamber with a shell filled with liquid lead as a heating medium. Based on the measurements and balance calculations, the amount of heat required to preserve the autothermal process was determined. The calorific value and composition of the pyrolytic gas were measured, revealing that 70% of the gas involves compounds characterized by a high calorific value. As a result, the calorific value of dry, purified gas equals 35.07 MJ/kg. A life cycle assessment has been conducted, in order to determine if the produced gaseous fuel matches sustainable development criteria. MONG-based gas is a sustainable replacement of, e.g., natural gas, lignite, or hard coal; however, it allows us to avoid 233–416 kg/h CO<sub>2</sub> emissions per 1 MW<sub>t</sub> of heat.

**Keywords:** MONG; pyrolysis; sustainable fuel; LCA analyses



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## 1. Introduction

The motivation to search for alternative energy sources is a result of the depletion of fossil resources, growing energy prices, and negative environmental impact [1,2]. The global irreversible, long-term trend for increase in energy consumption [3,4] requires new energy sources [5,6] in order to guarantee energy security with simultaneous environmental sustainability [7,8]. The dynamic growth of solar energy, hydro, and wind which are strongly affected by weather/season conditions [9] is still insufficient to phase out fossil fuels [10,11]. As a result, new energy materials are required, whose availability is independent from season or geographic, location, or climate conditions [12,13]. Furthermore, it is hoped that novel energy sources will be inexhaustible and sustainable and/or will permit the use of discarded materials [14,15].

One of the materials which matches the abovementioned requirements is matter organic non-glycerol [16], which is an example of a byproduct in the biodiesel production process [17,18]. Diesel fuel is one of the most widely used hydrocarbon fuels in transport as well as heat and power generation [19,20]. The annual (2021) average consumption of diesel and heating oil in 183 countries was 135,840 barrels per day [21] and is responsible for  $57.8 \cdot 10^6$  tons of CO<sub>2</sub> emissions [21]. For this reason, biodiesel is attracting particular attention as a sustainable alternative for conventional diesel fuel.

This alternative fuel is characterized by renewability, a lower emission of pollutants (no sulfur content, except for biodiesel derived from rapeseed oil), and biodegradability [22,23].

Biodiesel is manufactured in the transesterification process of triglycerides (lipids, oils, or fats) into methyl esters of fatty acids (FAME). In this process, the triglyceride feedstock undergoes reaction with alcohol (commonly methyl alcohol) and a basic catalyst (usually sodium or potassium hydroxide) to produce FAME (biodiesel) and glycerin (propane-1,2,3-triol) as a side-product [24,25]. Volumetrically, about 10% of input reagents are converted into glycerin. The resulting product has properties similar to conventional diesel oil [24,26]. Raw glycerol is the main side-product generated during the biodiesel industry transesterification and includes up to 95% glycerin, along with proportional water amounts, methanol, sulfuric ash, and non-glycerol organic matter (MONG).

The MONG content depends on the feedstock composition and transesterification process conditions [27–29]. MONG obtained from raw glycerol refining is usually treated as waste. In the case of jatropha oil, the mass concentration ranges from 11% to 21% [30]. Palm oil exhibits a very low MONG content below 2% [31]. MONG is also present in used frying oil at a quantity of 14.7% [32]. High mass concentrations of MONG are detected in soybean oil and used vegetable oil, amounting to 23.5% and 38.8%, respectively [33]. Significantly lower concentrations of MONG are found in saponification processes (3–4%) and hydrolysis (0.7–1.0%) [34].

Biodiesel may be produced from alternative renewable sources, e.g., jatropha, soy, palm oil, microalgae [35,36], and used cooking oils, etc. [37]. The development of biodiesel production has elevated the amount of different waste products, e.g., glycerol and MONG, collectively referred to as raw glycerol [38]. Currently, global biodiesel production is almost 33 billion liters annually [39].

Pure glycerol may be applied in various industries where derivatives of fatty acids are used, including pharmaceuticals, cosmetics, food products, animal feed, tobacco, paper, and textiles with outstanding properties (low generation of electrostatic charges, elasticity, and inherent stain resistance), as well as in the synthesis of biofuels such as biodiesel, biohydrogen, or bioethanol, etc. [40,41]. Despite the wide range of applications of glycerol and its results, this material is still treated as a waste product. Available studies suggest applications of MONG for manufacturing copolymers and fibers used in 3D printing, which is a potential solution to reduce the usage of synthetic polymers in 3D print technologies [26,42].

The use of technical glycerol or MONG as a fuel has significant potential, but there are considerable difficulties in their direct utilization as a fuel, for example, in the combustion process [24]. They are characterized by a low calorific value of 11.3 MJ/kg, a high autoignition temperature of approximately 370 °C compared to gasoline (280 °C) and diesel (210 °C), and high viscosity at room temperature [28].

A promising pathway for the utilization of MONG as an energy resource is its thermal conversion into value-added fuels, which would eliminate the abovementioned technical problems. A large variety of solutions have been suggested, including gasification [43] or conversion into liquid fuels [44,45], but transformation into gaseous fuels is expected to have the largest application potential. This opens the potential of use of gaseous fuels for the generation of heat and power in existing systems, substitution replacement of natural gas with purified process gas [46], or to use purified process gas to operate fuel cells [47].

The gasification process encompasses a set of thermochemical reactions. Its role is to transform is to convert a liquid or solid organic feedstock into gaseous products—process gas—and solid byproducts. The process gas composition results from the feedstock type, temperature, and pressure and, optionally, the gasifying agent—steam, carbon dioxide, air, and oxygen. The agent carrier is responsible for the organic material partial oxidation and is the initial stage of the gasification process. Then, the organic material in the feedstock undergoes drying, pyrolysis, oxidation, and reduction, which results in the formation of process gas. Its leading compounds include C<sub>2</sub>–C<sub>3</sub> hydrocarbons, hydrogen, carbon dioxide, methane, and tars (heavier hydrocarbons) of condensation in the range of 250–300 °C [48].

Depending on the raw materials applied, gaseous side-products, e.g., HCl, H<sub>2</sub>S, or N<sub>2</sub>, can also be present in the process gas [49,50], which is essential in the case of waste materials used as a feedstock.

The process gas composition depends not only on the type of feedstock used, but also on the process conditions. Apart from temperature and pressure, the design of the gasifier plays a crucial role. A large variety of gasifier types and designs are known, among which updraft/downdraft fixed bed gasifiers, circulating/bubbling fluidized bed, and rotary kiln gasifiers with an entrained flow bed are the most common design variants [51,52].

The rotary gasification reactor is one of the most versatile types, which combines all of the benefits of a fixed bed reactor and, simultaneously, remove its key issue, which is the stacking of the bed. This problem results from fuel heterogeneity or gasifying agent flow interruption, and it severely affects the operation of the reactor.

In contrast, the reactor chamber rotation allows the movement of the feedstock material and enhances mass and heat transfer. In effect, the rotary gasification reactor shares the benefits of both fixed fluidized bed reactors and bed reactors, and it does not need energy-demanding devices. The process of gasification is steady, weakly depending on the inhomogeneity of the fuel, and enables the adjustment of operation parameters, e.g., gasifying agent flow and gasification zone temperature, etc. The above-mentioned benefits make the gasification technology in the rotary chamber reactors especially capable for industrial applications, particularly where a perpetual process is needed [53].

Rotary reactors find primary application in waste-to-energy conversion systems. During combustion processes, devolatilization takes place, which involves the expulsion of volatiles from fuel or waste. The elevated temperature, capacity for handling feed materials, and consistent removal of ash make rotary reactors effective for eliminating hazardous compounds. Additionally, a rotary reactor can be outfitted with a secondary combustion chamber for the incineration of volatilized compounds from the primary chamber [54].

Thermal processing of liquid or semi-liquid products (slurries, pastes, etc.) requires the use of appropriate devices. There is no possibility of combustion in a burner for liquid fuels or on a grate as solid fuel. The suitable technology is the thermal decomposition of the slurry into a process gas, followed by its combustion. This process requires the use of a reactor in the form of a heated chamber in which the supplied fuel undergoes thermal decomposition in anaerobic conditions. Depending on the temperature range, this process is called either thermolysis or pyrolysis. Such reactors are frequently used in the thermal cracking of polyolefins [55,56] (including waste from plastics). These reactors are usually heated with flue gases from a burner, which burns a part of the gas generated in the pyrolysis process taking place inside. These devices require control of the reactor wall temperature, as local overheating leads to the formation of cokes adhering to the inner walls of the reactor. These cokes limit the heat transfer to the processed material and result in a decrease in process efficiency. Reactors of this type, heated with flue gases, require frequent cleaning of the inner walls. The use of a reactor with a heating shell allows us to achieve a uniform temperature distribution on the inner surface of the reactor and better control of the process temperature. For a temperature range up to 300 °C, the heating medium inside the reactor shell can be steam or thermal oil. Higher temperatures require the use of high-temperature-resistant agents, such as molten salts or metals.

The target of the research is to explore the potential of utilizing MONG as an energy resource, through its pyrolytic conversion into gas. In this paper, the study of the pyrolysis process of MONG in a pyrolysis reactor was performed, and then we determined selected properties of the resulting process gas, such as the chemical composition and calorific value. It has to be emphasized that studies on the application of MONG as an energy resource are limited in the literature, in particular using pyrolysis or gasification technology. This paper provides a comprehensive analysis of MONG as an energy resource including its environmental impact.

## 2. Materials and Methods

### 2.1. Test Setup

This paper presents the experiments performed on a test installation with a pyrolysis reactor. The installation setup is presented in Figure 1.

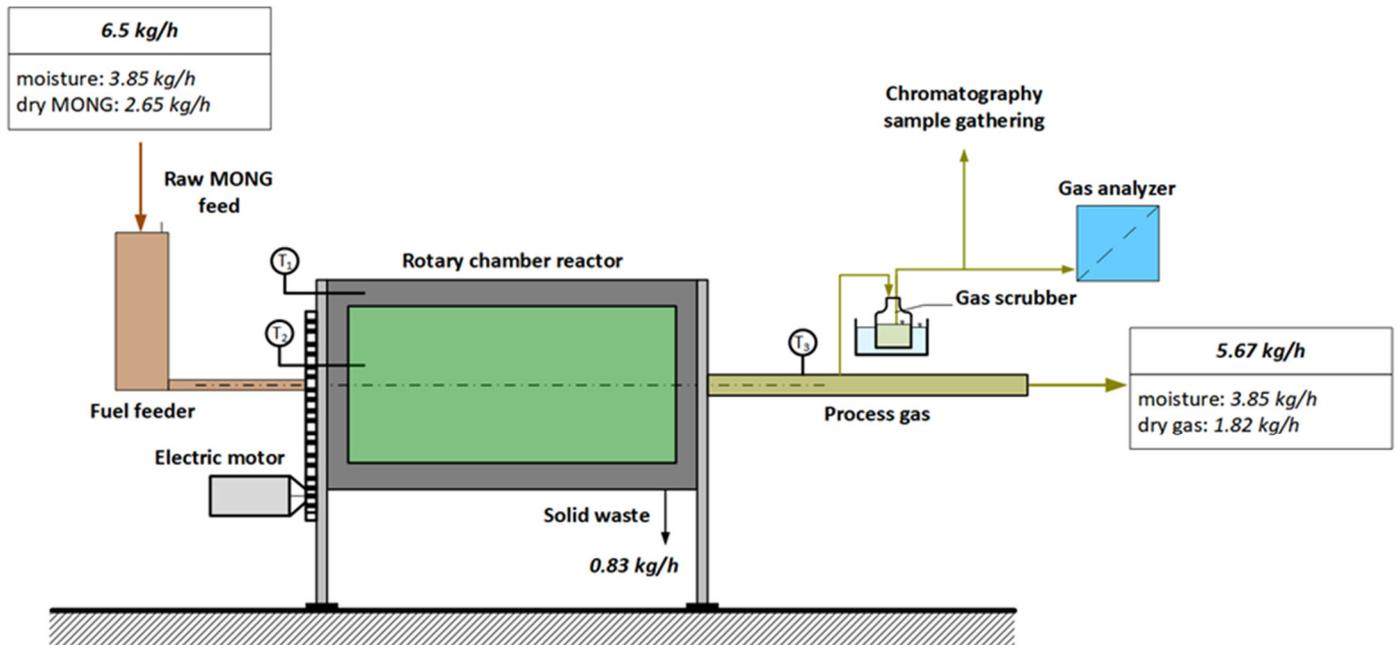


Figure 1. Diagram of the installation setup used in the experiments.

The pyrolysis reactor (Figure 2) consists of a rotating chamber with a heating shell filled with liquid lead. The operation of the installation was initiated using heat from the flue gases of an 30 kW oil burner to achieve the operating temperature. The rotation of the chamber forced the flow of liquid lead within the shell, for temperature stability on the inner walls of the chamber. The reactor allowed us to perform the pyrolysis process within a temperature from 350 °C and beyond.

### 2.2. Experimental Methodology

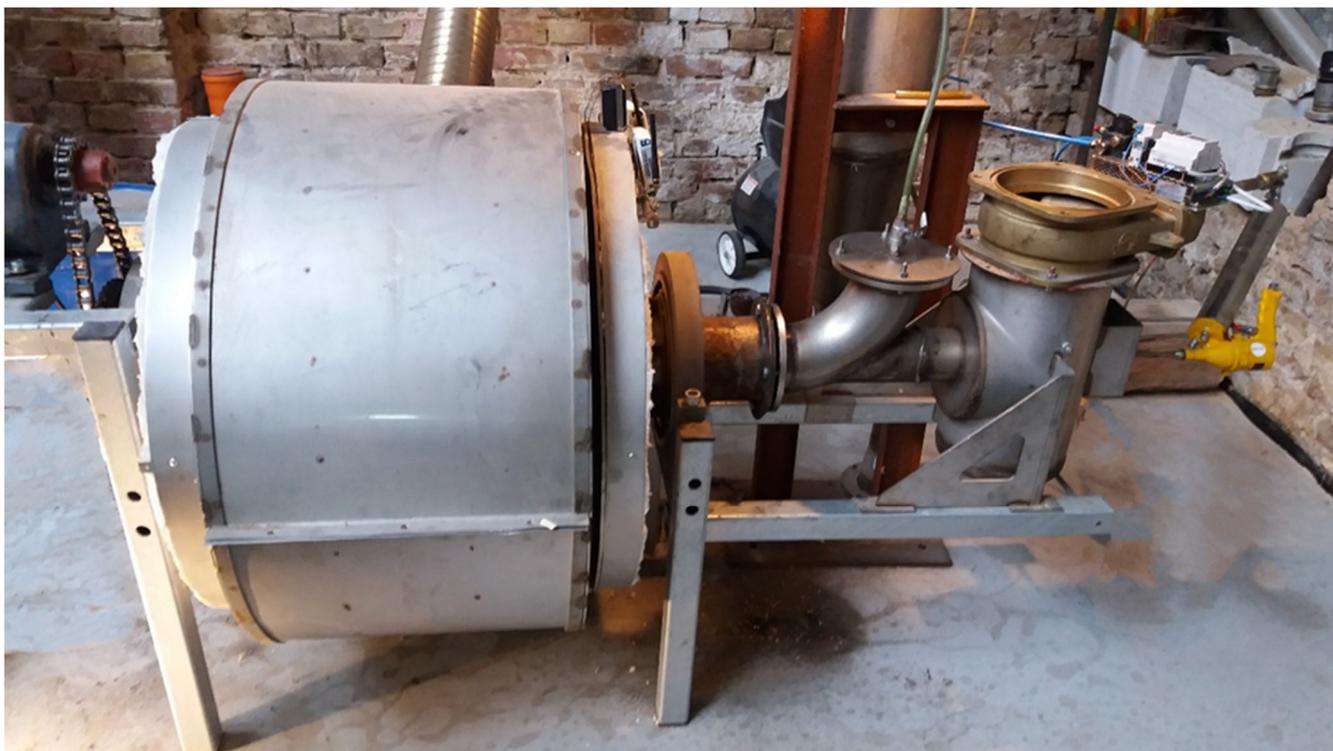
The analysis of the raw material included measurements of such properties as the mass loss during heating, ash content, and calorific value, as well as the volatile matter content. Additionally, a CHNS elementary composition was performed.

The mass loss of the sample was determined during heating in the range of RT–110 °C. Samples of 95.2 g of unprocessed MONG were collected and placed into a moisture analyzer of the type RADWAG MA, Radom, Poland, type 110R. The temperature program included heating of the sample from RT to 110 °C with a rate of heating equal to 10 °C/min.

The composition of the studied raw material was determined using a CHNS analysis performed in a Perkin Elmer analyzer series II 2400 (Inc. 940 Winter Street, Waltham, MA 02451, USA). The preparation of the samples involved a 24 h drying process carried out at 110 °C. According to the applied standard, three samples were collected and measured.

The pyrolysis process was performed using the test setup explained in Section 2.1. The feedstock was introduced into the pyrolysis reactor using a pulse pump at a mass flow rate of 6.5 kg/h. The temperature of the lead shell was stabilized at 580 °C ± 15 °C. The gas generated inside the reactor was directed to a scrubber. The aim of the research was to determine the composition of the gas after its purification in the scrubber rather than directly after the pyrolyzer. The use of gas for energy purposes requires its purification, hence the choice of the location for gas composition measurement. Gas samples were gathered from the gas outlet and analyzed using a GAS 3000 analyzer (Eko-Efekt Sp.zo.o., Lublin, Poland),

which measured the gas calorific value and its composition. The gas gathered for analysis was purified in a water-cooled scrubber, to remove tar and moisture that may affect the operation of the gas analyzer and chromatograph. During the experiment, the temperatures inside the pyrolysis reactor chamber and the reactor shell, as well as the composition of the process gas, were recorded. The experiment was conducted continuously during 120 min in a steady state.



**Figure 2.** The view of the test stand with a rotating gasification reactor and a liquid-metal shell.

### 2.3. Calculations of Energy and Mass Balance

The input data for the energy and mass balance computations were taken from the measurements and included gas composition and its calorific value, mass stream of solid waste, and MONG, as well as its calorific value. Based on the abovementioned data, the amount of heat required to maintain the autothermal process was determined (Figure 3).

On this basis, the energy and mass balance of the pyrolysis process was developed, and the energy required to preserve the autothermicity of the pyrolysis process was calculated. The mass flow of dry MONG was determined from the measurement of the mass flux of moist MONG inserted into the pyrolysis chamber and the moisture content contained in it.

$$q_{m1M} = q_{m1} - \varphi_1 q_{m1} \quad (1)$$

To determine the mass flux rate of dry pyrolytic gas, the measured mass flux rate of ash and the calculated moisture content in raw MONG were subtracted from the mass flux rate of the MONG. The gas stream was not directly measured due to technical limitations, i.e., raw gas moisture, tars, as well as low gas pressure and high temperature. The direct measurement of moisture was not possible, due to the fact that only a fraction of the raw pyrolysis gas was directed to the scrubber. The steam of raw gas was divided into the stream directed to the scrubber and the rest of raw gas which was directed to the outlet.

However, the moisture content in the raw pyrolysis gas was calculated based on the mass balance and measured moisture content in the raw MONG, which is completely

transferred during pyrolysis into a gas product. It has to be emphasized that the main target of the study was the measurement of the purified pyrolysis gas calorific value.

$$q_{m2G} = q_{m1} - \varphi_1 q_{m1} - q_{m3} \quad (2)$$

Hence, the heat flux transferred to the pyrolytic gas was equal to

$$Q_{2G} = q_{m1M} W_{2G}, \quad (3)$$

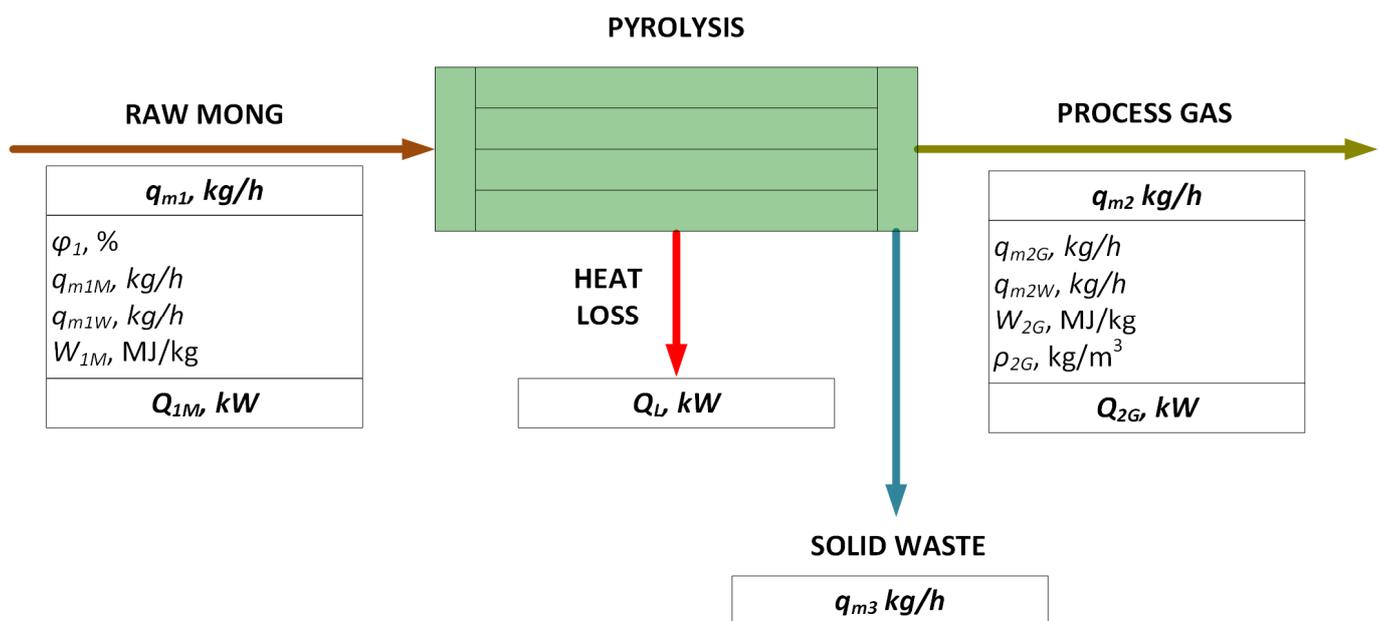
where  $W_{2G}$  is the measured gas calorific value obtained from the analyzer of the gas.

The pyrolysis process occurs at a constant temperature; hence, the heat of the reaction is equal to the heat loss  $Q_L$ . Based on the calorific value of the MONG,  $W_{1M}$ , the heat loss to the surroundings was determined.

$$Q_L = q_{m1} W_{1M} - Q_{2G} \quad (4)$$

This loss, expressed as a percentage of the energy in the wet feedstock, is equal to

$$k_{\%} = \frac{Q_s}{q_{m1M} W_{1M}}. \quad (5)$$



**Figure 3.** Balance scheme of the process,  $q_{m1}$ —MONG mass flow,  $\varphi_1$ —moisture of MONG, mass flow,  $q_{m1M}$ —dry MONG mass flow,  $q_{m1W}$ —moisture mass flow,  $W_{1M}$ —calorific value of dry MONG,  $Q_{1M}$ —heat flux of dry MONG,  $Q_L$ —heat loss,  $q_{m2}$ —pyrolytic gas mass flow,  $q_{m2G}$ —dry pyrolytic gas mass flow,  $q_{m2W}$ —mass flow of moisture pyrolytic gas,  $W_{2G}$ —calorific value of dry pyrolytic gas,  $\rho_{2G}$ —density of dry pyrolytic gas,  $Q_{2G}$ —heat flux of dry pyrolytic gas,  $q_{m3}$ —mass flow of ash.

#### 2.4. LCA Analysis

The aim of the LCA analysis was to compare the environmental impact of heat generation from MONG pyrolysis gas and most common fossil fuels: natural gas, lignite, and hard coal. In the study, the process of generation of 1 MW<sub>t</sub> of heat was investigated in four different variants. To calculate the required mass stream of each fuel for generation of 1 MW<sub>t</sub>, the following calorific values were taken: MONG pyrolysis gas 35.07 MJ/kg, natural gas 49.0 MJ/kg, lignite 7.33 MJ/kg, hard coal 21.5 MJ/kg.

The comparison involved CO<sub>2</sub> emissions from the analyzed fuels as well as CO, NO<sub>x</sub>, and SO<sub>2</sub>. The methodology of emissions calculations is based on data provided in [57].

In the case of MONG pyrolysis gas, the estimated emissions of CO, NO<sub>x</sub>, and SO<sub>2</sub> were assumed as for natural gas. Ash generated during MONG pyrolysis may be treated as a waste byproduct or may be utilized in the form of fertilizer, which allows us to mitigate the amount of waste generated during the entire process.

### 3. Results

To calculate the ash content, samples of the moist feedstock and that dried at 110 °C were used and then incinerated at 820 °C for 3 h. The mass concentration of ash in the raw sample was 12.6%, while in the dried sample, it increased to 31.5%. The mass concentration of volatile components was 86.1%. The moisture content of the MONG used in the experiment was 59%. The proximate analyses of raw MONG are provided in Table 1.

**Table 1.** Proximate analysis of raw MONG.

Ash (Raw Sample), %	Ash (Dried Sample), %	VM, %	Moisture, %
12.6	31.5	86.1	59.0

The CHNS analysis was performed on three sample series. The average results of analyzed samples are presented in Table 2.

**Table 2.** Elementary analysis, sample dried 24 h at 110 °C, %(m/m)—according to: PN-EN ISO 21663:2021-06 [58].

C	H	N	S
49.0	8.3	0.40	0

The dominant component of MONG is carbon at 49.0%(m/m); the hydrogen content is equal to 8.3%(m/m); while nitrogen content is at the level of 0.40%(m/m); and the sulphur content is below the detection limit.

In Tables 3 and 4, the values obtained from the energy and mass balance are presented. The mass flux rate of dry raw feedstock calculated from Equation (1) was 2.65 kg/h. The mass flux rate of the resulting pyrolytic gas, including moisture, was 5.67 kg/h. The mass flow rate of dry pyrolytic gas was obtained by subtracting the mass flux rates of other products generated in the process, moisture and ash (2), resulting in 1.82 kg/h. The measured calorific value of the pyrolytic gas was 35.07 MJ/kg and was significantly higher than that of raw MONG. The pyrolysis reaction was an exothermic process occurring at a constant temperature; hence, the heat of reaction equaled the heat loss. From Equation (4), the value of the heat loss flux was determined to be 6.33 kW, representing 26% of the energy in the wet raw material.

**Table 3.** Balance calculations of MONG.

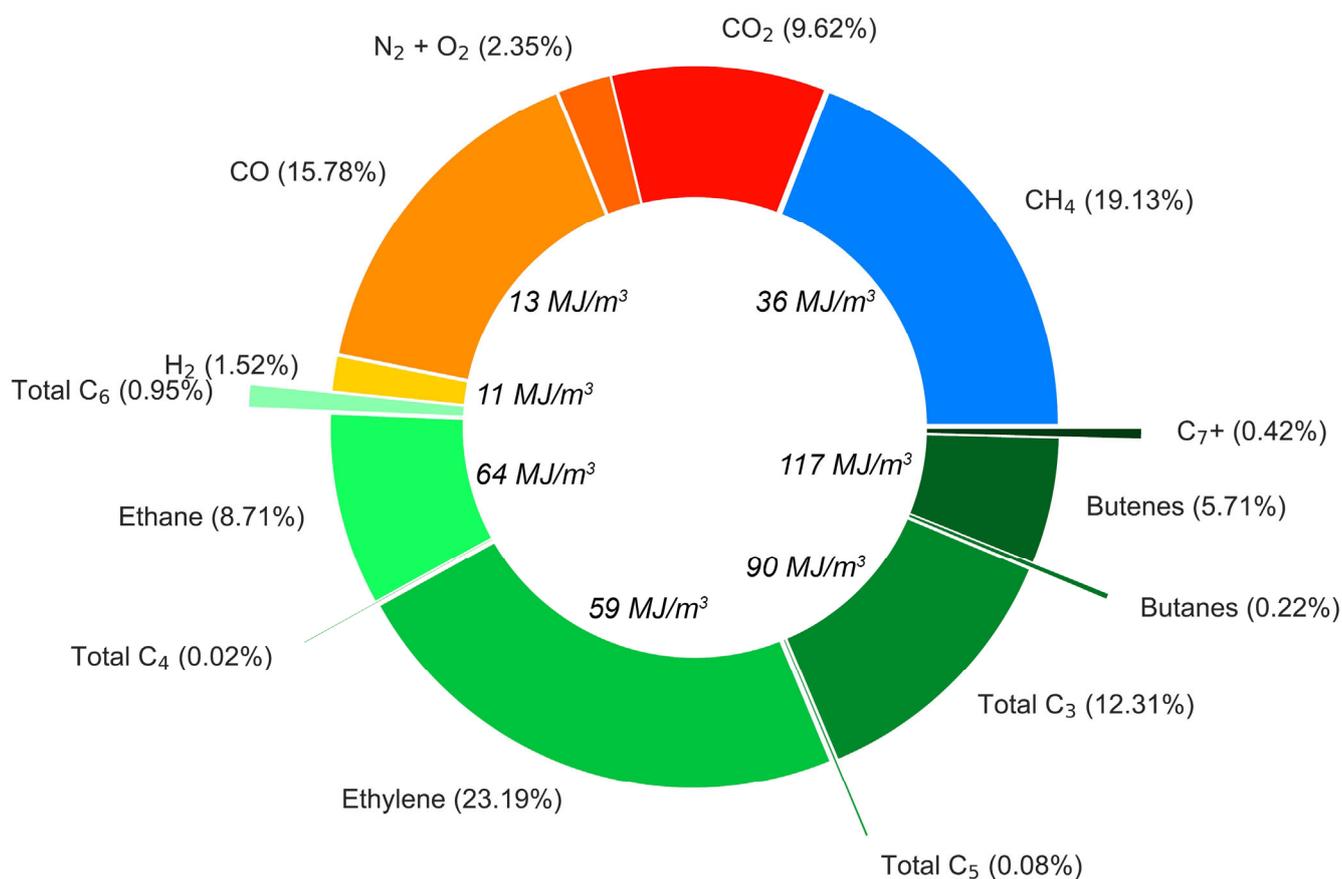
Parameter	Unit	Value
$\varphi_1$	-	0.59
$q_{m1}$	kg/h	6.50
$q_{m1M}$	kg/h	2.65
$q_{m1W}$	kg/h	3.85
$q_{m3}$	kg/h	0.83
$W_{1M}$	MJ/kg	13.30
$Q_{1M}$	kW	24.02

As a result, the fractions of the products of the MONG pyrolysis process are as follows: dry pyrolysis gas 28.0%, solid waste (ash) 12.8%, moisture 59.2%.

**Table 4.** Balance calculations of pyrolysis gas.

Parameter	Unit	Value
$q_{m2}$	kg/h	5.67
$q_{m2G}$	kg/h	1.82
$\rho_{2G}$	kg/m <sup>3</sup>	1.46
$W_{2G}$	MJ/kg	35.07
$Q_{2G}$	kW	17.69
$Q_L$	kW	6.33

Figure 4 presents the pyrolysis gas composition after refining in the scrubber. The gas is composed of 70.7% hydrocarbons, where ethylene (23.19%), methane (19.13%), C3 (12.31%), ethane (8.71%), and butenes (5.71%) are the main components. Negligible contents of higher hydrocarbons (C5, C6, C7) were detected. Non-hydrocarbon compounds include carbon monoxide (15.78%), carbon dioxide (9.62%), hydrogen (1.52%), nitrogen, and oxygen (2.35%). In total, the amount of combustible components is equal to 88%. The amount of oil fractions captured in the scrubber is relatively small; hence, it follows that the proportion of higher hydrocarbons is also low in the raw gas directly from pyrolysis.

**Figure 4.** Composition % (v/v) of process gas, refined in the scrubber.

The analysis of the calorific value of the main components of the process gas indicates that ca. 70% of the gas are compounds characterized by a high calorific value, the majority being light hydrocarbons.

#### 4. Discussion

The CHNS analysis indicates that MONG as a raw feedstock is characterized by a more sustainable composition comparing to poultry manure [59] in terms of nitrogen and

sulphur content. The nitrogen content in MONG is equal to 0.4%, while in poultry manure it is equal to 1.6%. The sulphur content in poultry manure is 0.45%, while in MONG no significant content of sulphur is detected. Additionally, MONG contains more carbon, 49% vs. 38.37% in poultry manure, as well as more hydrogen: 8.3% vs. 4.85% in poultry manure. As a result, MONG contains more calorific compounds and less emission components.

The pyrolysis gas from MONG is characterized by a calorific value at the level of 24.02 MJ/m<sup>3</sup> vs. poultry-manure-derived gas in the range of 6.47 MJ/m<sup>3</sup> to 9.47 MJ/m<sup>3</sup>. This allows us to conclude that MONG-derived gas is characterized by an over 2.5 times larger calorific value comparing to poultry-manure-derived gas. Additionally, significantly lower emissions are expected from MONG pyrolysis gas combustion.

The results provided in the Results Section indicate that the analyzed process gas has significant potential for its application as an alternative fuel for, e.g., heat generation in boilers. Its large calorific value and high hydrocarbons content make it an attractive fuel which may replace fossil fuels. An additional advantage of biomass-derived fuel is its reduced environmental impact, compared to conventional fuels. In order to evaluate the environmental effect of the application of MONG-derived gaseous fuel for heat generation, LCA analysis was performed.

In terms of gas composition, MONG-derived gas is characterized by a ca. 2 times larger content of methane (19.13% vs. ca. 10%), a significantly larger amount of higher hydrocarbons (50% vs. ca. 3%), and a larger amount of carbon monoxide (15.78% vs. ca. 10%). In contrast, the content of hydrogen in MONG pyrolysis gas is only 1.52%, while in poultry manure pyrolysis gas is ca. 15%. Poultry-manure-derived gas contains more inert compounds: CO<sub>2</sub> (40% vs. 9.62%), N<sub>2</sub> (15% vs. below 2.35%).

While the composition of pyrolysis gas from MONG is more sustainable and has a larger calorific value, MONG as a raw feedstock contains more ash compared to poultry manure (31.5% vs. 9.11%). This indicates that application of MONG as an energy resource results in a higher amount of solid waste. However, it is expected that both MONG and poultry manure ash are applicable for fertilizing purposes.

The target of the life cycle assessment (LCA) was to evaluate the environmental impact of heat generation based on the process gas from MONG pyrolysis compared to conventional fossil fuels. The reference process assumes the generation of 1 MW<sub>t</sub> of heat, using MONG pyrolysis gas versus natural gas, coal, and lignite. Table 5 presents the LCA analysis input data regarding the energy, materials, and resultant data: byproducts, energy, and emissions [57,60].

**Table 5.** Input and output data for LCA analysis: emissions, byproducts, materials, and energy.

<b>Process 1: Generation of 1 MW<sub>t</sub> of heat using MONG pyrolysis gas</b>	
Main substrate	RAW MONG: 366.6 kg/h MONG pyrolysis gas: 102.7 kg/h
Main product	Heat supply: 1 MW <sub>t</sub>
Solid byproducts/waste	Mass flux of ash (as fertilizer): 46.8 kg/h CO: 0.1–0.4 kg/h
Emission to the atmosphere	CO <sub>2</sub> : 0.0 kg/h (biomass emission, carbon neutral) NO <sub>x</sub> : 0.1 kg/h SO <sub>2</sub> : 0.0 kg/h
<b>Process 2: Generation of 1 MW<sub>t</sub> of heat using natural gas</b>	
Main substrate	Natural gas: 73.5 kg/h
Main product	Heat supply: 1 MW <sub>t</sub>
Solid waste	0 kg/h CO: 0.1–0.4 kg/h
Emission to the atmosphere	CO <sub>2</sub> : 233 kg/h NO <sub>x</sub> : 0.2–0.8 kg/h SO <sub>2</sub> : 1.8 kg/h

Table 5. Cont.

Process 3: Generation of 1 MW <sub>t</sub> of heat using lignite	
Main substrate	Lignite: 491.1 kg/h
Main product	Heat supply: 1 MW <sub>t</sub>
Solid waste	115.9 kg/h
	CO: 0.6 kg/h
Emission to the atmosphere	CO <sub>2</sub> : 307–416 kg/h
	NO <sub>x</sub> : 0.3–0.8 kg/h
	SO <sub>2</sub> : 0.4–0.7 kg/h
Process 4: Generation of 1 MW <sub>t</sub> of heat using hard coal	
Main substrate	Coal: 167.4 kg/h
Main product	Heat supply: 1 MW <sub>t</sub>
Solid waste	42.4 kg/h
	CO: 0.2–0.6 kg/h
Emission to the atmosphere	CO <sub>2</sub> : 260–331 kg/h
	NO <sub>x</sub> : 0.5–0.8 kg/h
	SO <sub>2</sub> : 0.4–0.7 kg/h

Table 6 presents input and output data for all compared processes referring to categories environmental of impact.

Table 6. Results of LCA analysis.

Environmental Impact	Comparison of Processes			
	Process 1	Process 2	Process 3	Process 4
Natural resources depletion	0.0 kg/h	73.5 kg/h	491.1 kg/h	167.4 kg/h
Waste deposition	0.0 kg/h *	0.0 kg/h	115.9 kg/h	42.4 kg/h
Global warming	0.0 kg/h CO <sub>2</sub> eq.	233 kg/h CO <sub>2</sub> eq.	307–416 CO <sub>2</sub> eq.	260–331 CO <sub>2</sub> eq.

\* under the condition that the MONG pyrolysis waste is used as fertilizer.

The comparison of the four studied processes indicates that the generation of 1 MW<sub>t</sub> of heat demonstrates a substantially diminished effect in all categories when compared to natural gas, lignite, and hard coal. The most essential advantage of the application of MONG-derived gaseous fuel as an energy resource is the substitute of fossil fuels by biomass-derived fuel.

Furthermore, the studied solution allows a significant reduction in emissions, in particular CO<sub>2</sub> and SO<sub>x</sub>, so that it matches sustainability criteria.

This allows us to mitigate emissions, in particular CO<sub>2</sub> and SO<sub>x</sub> and, as a result, reduce the environmental impact of the heat generation process. The replacement of fossil fuels by MONG pyrolysis process gas provides a sustainable alternative to fossil fuels, referring to natural resources depletion, waste deposition, and global warming.

## 5. Conclusions

The study describes the pyrolytic conversion of MONG into high-calorific gas conducted on a test stand consisting of a rotating chamber with a heating shell filled with liquid lead. This chamber construction allows a uniform temperature distribution, which is crucial for the stability of the pyrolysis process. Based on measurements and balance calculations, the amount of heat required to preserve the autothermal process was determined. The calculated heat flux necessary for sustaining the pyrolysis reaction was 6.33 kW, representing 26% of the energy in the wet feedstock. From the mass flux rate of dry MONG raw material (2.65 kg/h), 1.82 kg/h of dry pyrolytic gas with a calorific value of 35.07 MJ/kg was obtained. This value is substantially higher than the raw MONG calorific value.

The obtained gas is composed of 70.7% hydrocarbons, where ethylene (23.19%), methane (19.13%), C3 (12.31%), ethane (8.71%), and butenes (5.71%) are the main components. A negligible content of higher hydrocarbons (C5, C6, C7) was detected. Non-hydrocarbon compounds include carbon monoxide (15.78%), carbon dioxide (9.62%), hydrogen (1.52%), nitrogen, and oxygen (2.35%). In total, the amount of combustible components is equal to 88%. The analysis of the calorific value of the main components of the process gas indicates that approximately 70% of the gas consists of compounds characterized by a high calorific value, primarily light hydrocarbons. This opens the potential for the versatile application of the process gas, not only in burners and boilers for heat generation but also as an engine fuel, for example, for electrical energy or CHP generators or industrial applications. MONG is a waste generated during biodiesel production and is characterized by a low calorific value and a negative environmental impact. In contrast, process gas produced from its pyrolysis has a high calorific value and a significantly lower impact on the environment.

A life cycle assessment (LCA) was performed, which is crucial for evaluation of whether the produced gas fuel meets the criteria of sustainable development. The LCA analysis utilized tools such as energy and mass balance models and emission models.

The environmental impact of heat generation based on the process gas from MONG pyrolysis was compared to conventional fossil fuels. The reference process assumes the generation of 1 MW<sub>t</sub> of heat, using MONG pyrolysis gas versus natural gas, coal, and lignite. The most essential advantage of the application of MONG-derived gaseous fuel as an energy resource is the substitution of fossil fuels by biomass-waste-derived fuel. Furthermore, the studied solution allows a significant reduction in emissions, in particular CO<sub>2</sub> and SO<sub>x</sub>, so that it matches sustainability criteria. This allows us to mitigate emissions, in particular CO<sub>2</sub> and SO<sub>x</sub> and, as a result, reduce the environmental impact of the heat generation process. The replacement of fossil fuels by MONG pyrolysis process gas provides a sustainable alternative to fossil fuels, referring to natural resources depletion, waste deposition, and global warming.

The benefits of the application of MONG-derived pyrolysis gas include the following:

- Utilization of biodiesel manufacturing waste, which has currently no significant application;
- Production of high-calorific-value gaseous fuel;
- Production of sustainable fuel with a net zero emission of CO<sub>2</sub>;
- Potential application of solid waste ash for fertilizer production.

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