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Energy Generation Potential Through Cattle Manure Solid Phase Gasification

Marco Puglia[1*], Filippo Ottani[1], Donato Cantisani[1], Nicolò Morselli[1], Filippo Raguzzoni[2], Simone Pedrazzi[1], Giulio Allesina[1], Alberto Muscio[1], Paolo Tartarini[1]

[1] BEELab (Bio Energy Efficiency Laboratory), Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Modena 41125, Italy
[2] Hombre s.r.l., via Strada Corletto Sud, 320, Modena 41126, Italy

Corresponding Author Email: marco.puglia@unimore.it

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ABSTRACT

A common practice for cattle manure management, especially for farms with a small number of animals, is simply the separation of the manure solid phase from the liquid one and the subsequent spreading on the land. However, this biomass has a chemical composition similar to more valuable ones like woodchips, with the downside of the high ash content. For this reason, gasification of cattle manure solid phase in a small-scale gasifier was explored. Through this solution it is possible to provide both electrical and thermal energy to the farm, constantly throughout both the day and the year as opposed to other renewable sources like solar and wind power. In addition, a byproduct of this process is biochar, whose main application is in agriculture as soil improver and therefore it could be a valuable substitute of a fraction of the manure currently used as fertilizer. The quantity of manure available was assumed considering the typical size of an Italian dairy farm while the efficiency of the CHP system was calculated through an experimental test with a gasifier prototype. The results have been utilized for a basic comparison between the energy available through gasification and through anaerobic digestion.

1. INTRODUCTION

Agriculture is responsible for about one third of the greenhouse gases emission, and a significant share is due to cattle breeding [1]. There are multiple approaches that can be put into practice for an effective decarbonization of this sector. In this work, a different strategy of cattle manure management was explored. This byproduct is extremely abundant worldwide, and every year about 7.6 billion tons are produced [2]. Cattle manure is commonly spread on the land after a partial separation from the liquid phase and used as a bio-fertilizer [3]. The separation for the material studied in this work was performed through a screw press separator by mechanical compression. The separated solid phase has a moisture content around 60-65% at the end of the process (Figure 1).

Figure 1. Cattle manure separated solid

The elemental composition of dried cattle manure is similar to woody biomass (e.g., vine pruning), except for the ash content that is considerably higher for cattle manure [4].

Biomass gasification is a thermochemical process that consists in the partial oxidation of the material. The outputs of the process are a fuel gas composed of carbon monoxide, carbon dioxide, hydrogen, methane and nitrogen and biochar, which is a carbon-rich and porous material that can be extremely valuable as soil amendment [5, 6]. This combustible gas, called syngas, can be used as bio-energy source in combined heat and power (CHP) and combined cooling heat and power (CCHP) systems. Biochar production and its subsequent soil application can be considered a process that removes carbon dioxide directly from the atmosphere [7, 8].

In this work, the use of cattle manure separated solid phase as fuel for gasification systems was explored by testing this biomass in a laboratory scale prototype with a fixed bed downdraft reactor. Downdraft architecture comes with a couple of primary drawbacks: it can be challenging to increase its power capacity, and frequently, biomass pelletization is required to enhance its flowability. Despite that, downdraft gasifiers produce a very clean gas, that even with a low energy content it is suitable for internal combustion engine [9, 10]. The updraft gasifiers are scalable but the tar concentration in the gas is considerably higher [9, 10] therefore their application for energy generation using internal combustion engines is challenging. Fluidized bed gasifiers are very complex and require high-end operation and maintenance [9], for this reason in this work was not considered the ideal equipment for a medium-size farm.

2. MATERIALS AND METHODS

2.1 Material preparation

The separated solid cow manure studied in this work was obtained with a Cri-Man SM260FA separator, equipped with a 7.5 kW motor and able to process up to 42 m^3/h of slurry.

In order to make the cattle manure suitable for the small-scale downdraft gasifier prototype it was dried and pelletized with a 7.5 kW Cissonius PP-200, a machine with a pelletization capacity of 100-150 kg/h with wood and of 100-250 kg/h with fodder [11]. The appearance of the produced pellets is shown in Figure 2.

Figure 2. Cattle manure pellets

Ultimate and ash analyses were performed on the produced pellets to verify that its chemical-physical characteristics were not altered by the process.

Knowing its elemental composition, it was possible to estimate the higher heating value in MJ/kg (HHV) by means of the Channiwala and Parikh correlation (Eq. (1)) [12].

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N - 0.0211A \quad (1)$$

where, C, H, S, O, A are the percentage mass fraction of carbon, hydrogen, sulfur, oxygen, nitrogen and ash obtained after ultimate and ash analysis.

2.2 Gasification test

The gasification test was performed using the "Femto Gasifier" (Figure 3), that is a small scale Imbert downdraft gasifier.

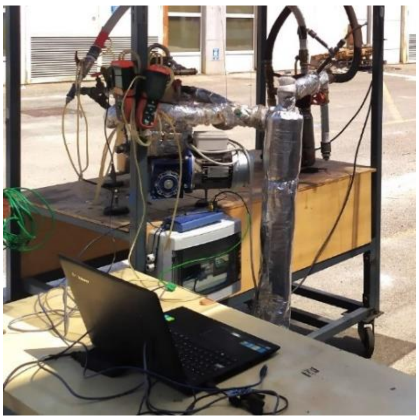

Figure 3. Femto Gasifier

The gas volume flow was assessed by measuring the gas composition through a microGC gas analyzer and the air volume flow, assuming negligible the nitrogen content in the gas [13]. The air volume flow was calculated by measuring the pressure drop across an orifice meter.

The high heating value of the syngas was calculated as the weighted average of hydrogen, methane and carbon monoxide heating values, considering their volumetric fraction [14].

The air flow was monitored through an orifice meter. The temperature at the grate of the gasifier was measured using a K-Type thermocouple. The pressure drop across the reactor was measured to control the behavior of the gasifier. An Arduino board was used to monitor pressure drops and temperature. A scheme of the instrumented gasifier used for the test is represented in Figure 4.

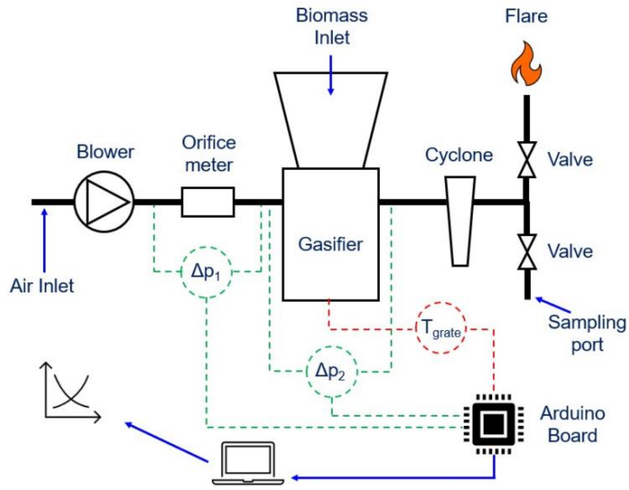

Figure 4. Scheme of the instrumented gasifier

The performance of the gasifier operating with cattle manure pellets was evaluated using the cold gas efficiency η_{CG} calculated as [15]:

$$\eta_{CG} = \frac{Gas\ flow\ energy\ content}{Biomass\ flow\ energy\ content} = \frac{\dot{V}_{gas} \cdot HHV_{gas}}{\dot{m}_{bio} \cdot HHV_{bio}} \quad (2)$$

where, $\dot{V}_{gas}$ and $\dot{m}_{bio}$ are respectively the volume flow of the gas and the mass flow of the biomass measured during the fraction of the test considered suitable for the measurement (steady state and gas calorific enough to sustain the combustion in the flare). After the test, the ultimate and ash analysis were performed also on the biochar obtained. Considering the suboptimal characteristics of the gasifier for this kind of material, the gasification test was used as a feasibility test rather than research on the specific value of gasification efficiency.

2.3 Energy potential assessment

One of the limitations that prevents downdraft gasifier diffusion is the cost of pelleting [9]. For this reason, the energy expenditure associated with the pelletization process was also analyzed considering a conservative estimation of 100 kg of pellets produced with 7.5 kWh. The annual (for 365 days) energy expenditure for the pelletization process E_p was calculated as:

$$E_p = m_{day} \cdot n \cdot 365 \cdot \frac{7.5\ kWh}{100\ kg} \quad (3)$$

where, m_{day} is the manure excreted by a lactating cow every day that amounts to about 8 kg of dry matter [16]. n is the number of cows considered for the estimation; in this case it was chosen a population of 100 animals.

The yearly potential energy production E_g through the gasification process applied to cow manure using a downdraft gasifier was calculated as follows:

$$E_g = m_{day} \cdot n \cdot 365 \cdot v_g \cdot HHV_{gas} \cdot \eta_{el} \quad (4)$$

where, v_g is the m^3 of syngas produced per kg of manure gasified, this value was obtained through the gasification test. η_{el} is the electric efficiency of a CHP system that can be used to convert the chemical energy of the gasifier into electric energy.

The energy that can be produced through the gasification process was then compared to the amount that can be obtained through the anaerobic digestion process $E_{a\ d}$. Anaerobic digestion is one of the most established processes for a virtuous treatment of livestock manure [17]. $E_{a\ d}$ was calculated with the formula:

$$E_{a\ d} = n \cdot 365 \cdot v_{a\ d} \cdot HHV_{biogas} \cdot \eta_{el} \quad (5)$$

The biogas that can be obtained per animal per day ($v_{a\ d}$) is usually in the range between 1.51 Nm^3/animal and 2.17 Nm^3/animal. It is a mixture containing primarily methane and carbon dioxide with a heating value of 23.4 MJ/Nm^3 [17-19].

2.4 Biochar analysis

The utilization of cow manure as fuel in a gasification system could potentially lead to a shortage of fertilizer. For this reason, a preliminary analysis on biochar was carried out to evaluate this material as a possible substitute of at least a fraction of cow manure typically spread on the field. In addition to ultimate and ash analyses, both pH and germinability analysis were performed on the produced biochar. The pH was measured using a Crison BASIC 20 (resolution 0.01), diluting 1 g of biochar in 10 ml of deionized water. The solution was stirred and filtered after 30 minutes, then the probe was immersed in the solution. Germinability test was carried out on alfalfa seeds (*Medicago sativa*), this because alfalfa is a typical forage used for cows' nutrition [20]. Filter paper was placed in 5 Petri dishes (diameter 6 cm), each containing 20 seeds. Biochar was agitated in water for 30 minutes at a 1:5 concentration, and then it was filtered. This filtered water was used to moisten the contents of the Petri dishes (2 ml per dish). The dishes were closed with parafilm and placed in an incubator at 25°C for 72 hours. Subsequently, the number of germinated seeds were counted and the length of the radicles was measured. These results were compared with a control group, with separated solid manure and with digestate obtained from a biogas power plant that can be considered a stable soil fertilizer [21].

A pH analysis was also conducted on these two materials.

A BET (Brunauer–Emmett–Teller) analysis was performed to measure the biochar specific surface area. It was carried out in triplicate, using a Micrometrics ChemiSorb 2750.

Biochar microstructure was studied with a Scansion Electron Microscope with Field Emission Gun (FEG) (FEI Nova NanoSEM 450). The magnifications used were 500×, 1000×, 2000×, 4000× and 8000×.

A rough estimation of the char yield was made by dividing the ash content of the manure pellets by the ash content after the gasification process.

$$Char\ yield = \frac{Manure\ pellet\ ash}{Biochar\ ash} \times 100 \quad (6)$$

3. RESULTS

3.1 Gasification test results

The elemental composition and the ash content of the cattle manure pellets and of the biochar obtained after the gasification process are summarized in Table 1 together with the HHV estimated with the Channiwala and Parikh correlation.

Table 1. Cattle manure pellets and biochar characteristics

Parameter	Manure Pellets	Biochar
Nitrogen	1.29%	0.38%
Carbon	43.63%	47.6%
Hydrogen	5.79%	0.76%
Sulphur	0%	0%
Oxygen	41.51%	1.79%
Ash	7.78%	49.47%
HHV	17.6 MJ/kg	16.3 MJ/kg

The heating value of cattle manure pellet is quite typical of lignocellulosic biomass commonly used in gasification process [22, 23]. The estimated char yield resulted in 15.7%.

Table 2 summarizes the syngas composition of the three gas samples analysed during the tests and their HHV calculated as the weighted average of the HHV of the fuel gases.

Table 2. Sample gas compositions and HHV

Parameter	Sample 1	Sample 2	Sample 3
H_2 [%]	9.8	10.4	8.9
N_2 [%]	58.1	56.5	57.4
CO [%]	18.4	19.8	18.5
CO_2 [%]	13.8	12.9	13.9
CH_4 [%]	/	/	/
HHV [MJ/m^3]	3.6	3.8	3.5

In Figures 5 and 6, the temperature trend at the grate of the gasifier and the pressure drop across the reactor are shown. In both the graphs a yellow rectangle indicates the test fraction where the efficiency measurement was performed.

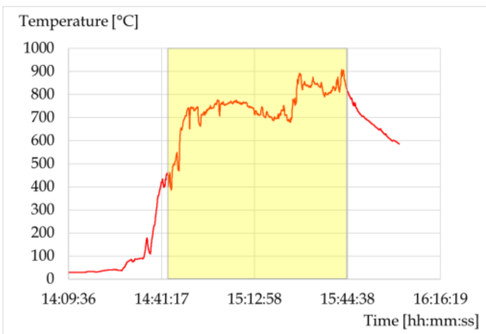

Figure 5. Grate temperature

From the figure above it is possible to notice a quite smooth trend of the temperature at the gasifier grate. The average value of 740°C is in line with the typical temperature in the reduction zone for this kind of reactor [24].

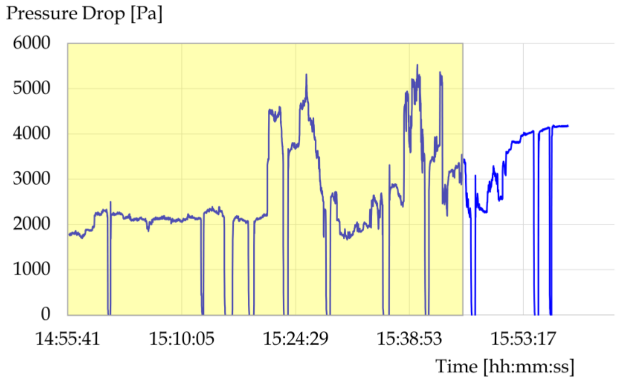

Figure 6. Reactor pressure drop

Reactor pressure drop, on the other hand, was stable for the first half of the test, then the reactor started to clog, probably due to clinker formation. Downdraft gasifiers are designed to operate with biomass with an ash content up to 5% [25] while the biomass processed in this case has an ash content over 7%. One of the drawbacks of having a high ash content is the clinker formation that clog the reactor throat.

One potential solution to prevent clinker formation could involve reducing the residence time of biomass in high-temperature zones, for example, by implementing frequent grate shaking [26].

The phases when the pressure drop falls to zero correspond to the loading operations that are carried out shutting down the blower upstream the reactor.

Table 3. Gasification test parameters

Parameter	Value
Efficiency test duration	63 min
Biomass flow	2.010 kg/h
Syngas flow	5.70 m^3/h
v_g	2.8 m^3/kg
η_{CG} [%]	59.8%

Table 3 summarizes the other main test parameters measured during the efficiency assessment.

The average grate temperature was typical for this kind of gasifier. The gasifier efficiency resulted slightly below values that can be found in literature for the considered architecture [24, 27]. This can be explained through the small size of the prototype that results in higher heat losses, but the main reason is probably the quite high ash content of the biomass that require specific measures. Therefore, an efficiency of 59.8% can be considered a satisfactory efficiency result.

3.2 Gasification energy potential assessment

The preliminary results obtained showed that for every kg of cattle manure pellets it is possible to produce 2.8 m^3 of syngas with an average heating value of 3.6 MJ/m^3, totaling 10.1 MJ for every kg of biomass. Considering a medium-small size farm with 100 dairy cows, approximately 200 MWh of electric energy can be generated annually using a CHP system. However, an energy expenditure of about 22MWh is due to the pelletization process, resulting in a reduction of available power by approximately 10-11%.

On the other hand, through anaerobic digestion, between 4.4 and 6.3 MJ can be obtained for every kg of solid manure, resulting in an electric power production up to about 130 MWh every year, which is 70 MWh less than gasification. This power reduction is significant, especially considering that the gasification system used was not optimized for this kind of biomass. For this reason, further investigation on the gasification of cattle manure is promising. Another possible solution can be the application of the gasification process on digestate obtained from the anaerobic digestion of manure.

3.3 Biochar analysis results

Table 4 reports the measured pH values of manure biochar, manure pellet and digestate.

Table 4. Gasification test parameters

Sample	pH
Manure biochar	11.54
Manure pellet	7.55
Digestate	7.96

Biochar resulted strongly alkaline, as expected.

Figures 7 and 8 show the results of the germination analysis.

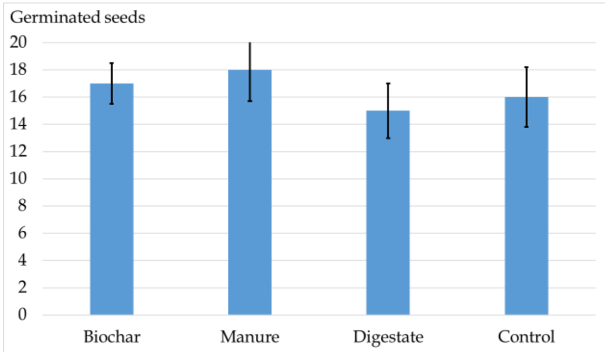

Figure 7. Seeds germination

As can be seen from the germination test, biochar does not inhibit alfalfa germination. Error bars represent the standard deviation between the various petri dishes.

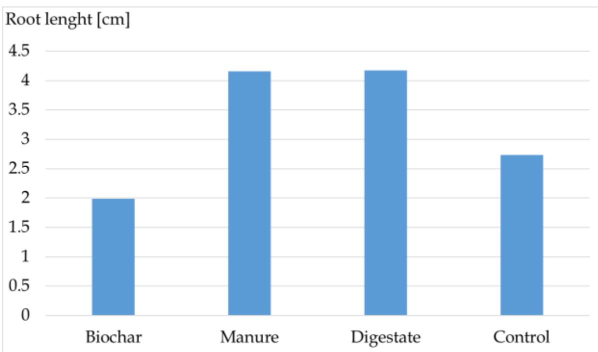

Figure 8. Radicles length of the germinated seeds

For the radicle's length parameter, biochar showed lower performance compared to manure and digestate, but similar to control. Additional field tests are required to assess the overall impact of biochar on the growth of alfalfa (e.g., when biochar is applied to acidic soil, it can have a beneficial impact by adjusting the pH).

Specific surface area analysis resulted in: 60.1 ± 5.5 m^2/g. This value is remarkable but not as high as other literature references, probably due to the pelletization process conducted on the starting biomass.

Figure 9 depicts a biochar sample under 2000× magnification, revealing the porous structure of the material.

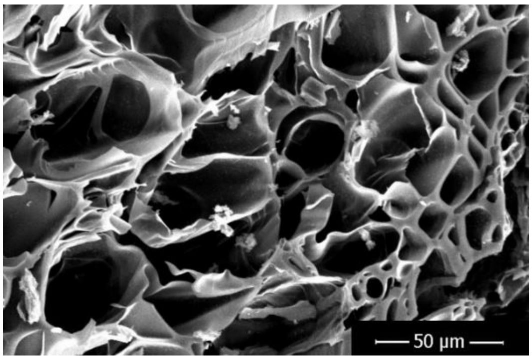

Figure 9. Biochar microstructure, 2000× magnification

4. CONCLUSIONS

In this study, a possible alternative energy pathway for cattle manure was explored. The dry matter was pelletized and used as fuel in a small-scale downdraft reactor to evaluate the feasibility of the gasification process applied to this kind of agricultural by-product. The energetic output was compared to the biogas production potential. The measured performances proved to be satisfactory. The comparison showed a higher energetic output through the thermochemical process rather than the anaerobic digestion. Furthermore, a preliminary assessment of biochar application on alfalfa seeds was carried out showing promising results. Future work will focus on the possible combination of gasification and anaerobic digestion, evaluating digestate as fuel for a downdraft gasifier.

ACKNOWLEDGMENT

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NOMENCLATURE

CHP	Combined heat and power
CCHP	Combined cooling heat and power
HHV	Higher heating value [MJ/kg] [MJ/m^3]
C	Carbon mass fraction [%]
H	Hydrogen mass fraction [%]
S	Sulfur mass fraction [%]
O	Oxygen mass fraction [%]
N	Nitrogen mass fraction [%]
A	Ashes mass fraction [%]
$\dot{V}_{gas}$	Syngas volume flow [m^3/h]
$\dot{m}_{bio}$	Biomass mass flow [kg/h]
E_p	Energy expenditure for pelletization [kWh]
m_{day}	Manure excreted per day
n	Cows number
E_g	Energy production through gasification [kWh]
v_g	Syngas produced per kg of manure [m^3/kg]
$E_{a\,d}$	Energy production through anaerobic digestion [kWh]
$v_{a\,d}$	Biogas produced per cow through anaerobic digestion [m^3/cow]
BET	Brunauer–Emmett–Teller
H_2	Hydrogen volume fraction [%]
N_2	Nitrogen volume fraction [%]
CO	Carbon monoxide volume fraction [%]
CO_2	Carbon dioxide volume fraction [%]
CH_4	Methane volume fraction [%]

Greek symbols

η_{CG}	Cold gas efficiency
η_{el}	Electric efficiency

Subscripts

CG	Cold gas
gas	Syngas
bio	Biomass
p	Pelletization process
day	Daily
el	Electric
a d	Anaerobic digestion