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Anaerobic digestion of spoiled milk in batch reactors: technical and economic feasibility

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Abstract

The economic feasibility of the energy conversion through anaerobic digestion of spoiled milk was assessed for the microscale biogas production and heating value was determined experimentally on a pilot plant with a mixture of spoiled milk and an inoculum previously optimized with Anaerobic Biomethanation Potential tests. Results shows that the feasibility of a 100 kWel plant is characterized by a quite short return time of the investment. Considering a discount rate of 5% and a timespan of investment equal to 20 years, payback period is equal to 8-9 years, Net Present Value is equal to 806,903 € and Internal Rate of Return is equal to 16 %.

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Keywords: Spoiled milk; ABP test; Anaerobic digestion; food waste.

1. Introduction

Biomass and waste are distributed energy resources that could be used locally for CHP application with and increased sustainability of the supply chain with respect to that of centralized plants; technologies are available ranging from biochemical to thermochemical processes to transform biomass and waste into a usable gaseous or

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liquid fuel [1-9]. However, when considering a gaseous fuel (syngas, biogas, landfill gas, etc.), its use in engines and gas turbines requires handling a contaminated gas. Tars, water and particulate contamination is typical for syngas from pyrolysis and gasification while water, hydrogen sulfide and siloxanes are typical for biogas-landfill gas contamination. Moreover these fuel gases show a lower LHV, when compared to natural gas, and a varying composition with different fuel gases in the mixture that will show different combustion behavior (flame speed, ignition delay, etc.). This turns into costly gas cleaning systems and combustion chamber modifications [10-21] which further penalize the small scale business plan scenario. Therefore, residual biomasses and wastes, with next-to-zero economic value, or else showing a disposal cost, are most interesting for small to micro scale conversion.

Spoiled milk is classified as waste by Directive 2008/98/CE and most of it is disposed in landfills or used for the production of animal feed. As an example, according to a survey conducted by the National Institute of Statistics ISTAT, Italy's national production of milk for the year 2011 amounted to 2.653.000 t; approximately 2.5-3.0% of this amount is returned to the processing plant as spoiled. This requires disposal of the unsold product and additional costs for the separation of the packaging from the milk. This data are similar and may be easily extended to other countries.

However milk is easily biodegradable and pollutant in aerobic conditions, due to decomposition and mineralization, therefore a valid alternative to the disposal of this waste is its energy valorization through biochemical processes. Spoiled milk consists mainly of water, fats, carbohydrates and proteins hence the Anaerobic Digestion (AD) is a suitable conversion treatment process, which generates a significant amount of methane and also allows the stabilization of the organic substance. Anaerobic treatment of spoiled milk is currently being investigated because there are still few experimental data available on the anaerobic digestion of this waste [22-26]. Literature shows that the biggest problem in the AD of spoiled milk, and generally in the anaerobic treatment of all by-products of the dairy industry is the acidification of the substrate. Lactose fermentation, produces fatty acids of various nature, that eventually inhibit the fermentation causing pH reduction, when present in high concentrations [25, 26]. This criticality occurs mainly in single phase AD systems (batch), where it is not possible to control separately different phases of the digestion process. Similarly fat content of milk may cause the inhibition of AD, leading to the formation of large amounts of Long-Chain Fatty Acids (LCFAs). For these reasons dairy industry waste is usually digested with other organic substances through a co-digestion process [27, 28].

Nomenclature

ABP	Anaerobic Biogasification Potential
AD	Anaerobic Digestion
CSTR	Continuous Stirred Tank Reactor
FC	Fixed Carbon
S:I	Substrate/Inoculums
TS	Total content of Solids (%)
VS	Volatile Solids (%)
U	Moisture (%)

2. Materials and methods

The aim of the paper is to evaluate the performance of different portions of spoiled milk in AD in different concentrations with respect to the inoculum. The experimental campaign was carried out at the Biomass Research Centre (CRB) Laboratories, University of Perugia. Several tests were carried out: chemical and physical analysis, in order to characterize the substrate, ABP in bottles and AD tests in a pilot plant, to evaluate the biogas production and the methane yield. The effect of pH was also investigated and the results were compared to data from the Literature.

2.1. Substrate and inoculum characteristics

Spoiled milk for the present investigation is whole fresh milk, that is not suitable for human consumption, being past its expiring date; it was collected from the storage warehouse of a supermarket; its nutritional characteristics are shown in Table 1.

Table 1. Nutritional characteristics of spoiled milk [6]

Organic component	(*g*/l)
Carbohydrates	4.90
Proteins	3.20
Fats	1.5

Biogas and methane yields depend on the specific characteristics of the biomass and in particular on the amount of the organic components, such as fats, proteins and carbohydrates [29].

Spoiled milk was digested with an inoculum namely: the digestate from the secondary fermenter of an anaerobic digestion plant operating in mesophilic conditions, and fed with corn and sorghum silage. This substance, in addition to being used as inoculum or as a bacterial vector to start the process also controls the pH during the acidogenic phase.

2.2. Instrumentations

The chemical and physical properties were measured at the Laboratory of the Biomass Research Centre, described in previous works [30-32, 36], by means of TGA 701 LECO for proximate analysis and Truspec CHN LECO for ultimate analysis. Moisture, ash and total and volatile solids content, were determined according to CEN/TS 14774 [33], CEN/TS 14775 [34] and CEN/TS 15148 [35].

The experimental campaign was conducted by using two different instrumentations: small batch reactors, used to test biomethanization (ABP test), and a laboratory pilot digester designed at the Biomass Research Centre of the Perugia University. Through ABP test the ratio substrate / inoculum (S: I) that maximizes the biogas and methane production was identified and considered for testing in the pilot plant (Fig.1).

Fig.1. (a) bottle for ABP tests; (b) thermostatic bath; (c) anaerobic digester.

The anaerobic digestion test was carried out in a laboratory batch pilot plant [31, 32, 36]. It is a cylindrical vessel (17 l capacity), realized in stainless steel, equipped with an airtight lid and a pH-meter (Hanna Instruments pH212, double junction electrode). Biogas is collected in a gas storage system, made of two cylindrical coaxial chambers. Data were acquired by a digital system and a purposely-developed software. Biogas analysis was performed using gas-chromatography (Agilent 490 PRO Micro-GC).

3. Results and discussion

The physical-chemical characteristics of the spoiled milk and of the inoculum are shown in table 2.

Table 2. Characteristics physic-chemical of spoiled milk and inoculums [6].

Substance	U (%)	TS (%)	VS (%)	Ash (%)	F.C (%)	pH
Spoiled milk	89.04	10.96	10.56	0.30	0.10	6.76
Inoculums	97.47	2.53	1.62	0.91	0	7.60

In ABP, test 2 produced the highest quantity of biogas with a maximum methane percentage of 60.33% and the results are showed in the Table 3.

Table 3. Biogas and methane yields in ABP tests [6].

Test	Biogas($Nm^3/KgVS$))	CH_4 ($Nm^3/KgVS$)
1 (S:I=1:2)+H2O	0.118	0.014
2 (S:I=1:3)	0.476	0.231
3 (Blank)	0.08	0.02

The mixture with S:I=1:3 (test 2) was replicated on pilot scale being characterized by the highest biogas and methane production in ABP test in order to obtain results more easily scalable to the a real case scenario. The test was carried out in the same conditions using the same sample of digestate previously frozen not to alter its bacterial content and to avoid fermentation processes [37-40].

Table 4. Composition AD tests [6]

Mixture Composition			U (%)	VS (%)	pH
(S:I=1:3)	Spoiled milk Digestate	2000 gr 6000 gr	95.36	3.85	7.8

The reactor was preliminary flushed with nitrogen up to a pressure of 0.2 atm for about ten minutes, to eliminate oxygen and the AD test was carried out at a temperature of 35 °C for a duration of 40 days.

Biogas plant and daily and cumulative production curves are shown respectively in Fig. 2 and in the Table 5.

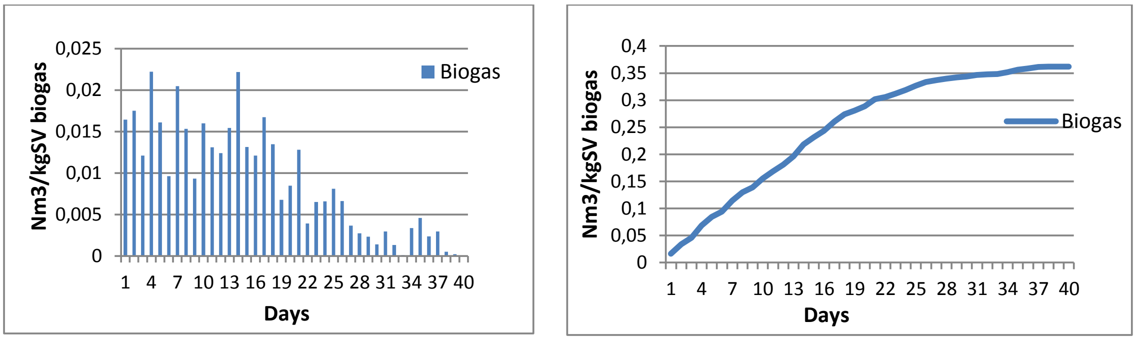

Fig. 2. (a) daily biogas production (AD tests); (b) Cumulative biogas production (AD tests)[6].

Table 5. Biogas and methane yield in pilot plant tests [6]

Mixture composition			Biogas ($Nm^3/kgVS$)	CH_4 ($Nm^3/kgVS$)
(S:I=1:3)	Spoiled milk	2000 g	0.362	0.246
	Digestate	6000 g		

The yields of methane (maximum content equal to 67.95%), is higher than previous experimental campaigns, due to the higher stability of the process. A right amount of organic matter has avoided the acidification of the substrate maintaining the pH between 6.5 and 7.5 [41], without any correction.

4.Technical and economic feasibility of anaerobic digestion system for a medium dairy industry

4.1. Technical Analysis

The AD plant considered consists of a CSTR reactor, with a pre-tank load, a primary digester and a post-fermenter that work in mesophilic condition, a cogeneration unit to produce electrical and thermal energy, a biogas storage system and a solid-liquid mechanical separator for post treatment of the digestate.

The plant is located near a cluster of small to medium-size dairy facilities, processing an average of 15.000 ton/year of milk per dairy. An average 10% of the product becomes waste and it is considered to be fed to the primary reactor with a ratio sub strate / inoculum equal to 1/3.

The size of the power unit was considered in the micro scale range and (below 200 Kw) to benefit of the simplified authorization procedure according to the Italian legislative scenario for renewable energies incentives [20-21].

The engine chosen as cogeneration unit is a MAN, model E0836 LE202, characterized by a net electrical output power of 105 kWe and a thermal power of 127 kWth respectively.

The biogas required to fuel the engine is produced by the AD at around 5000 tons of waste milk per year (Table 6). This quantity of spoiled milk is recoverable from around 3 medium-sized dairy factories, each characterized by an average production of waste milk around 1.500 tons/year. Each facility will collect waste milk from the retailers during the incoming trips of the transport fleet back to the dairy plant.

Table 6. Calculation parameters

Parameters	Value
Assumed power plant	105 KWe
Annual operating hours of the system (7 cycles/40days)	6.720 h
Electrical motor yield	37.40%
Calorific Value (biogas CH_4~68%)	23.78MJ/Nm^3
Biogas yield	0.36 Nm^3/KgVS
Percentage of volatile substance in the mixture ratio (S/I= 1:3)	3.85%
Waste milk quantity	5,110 ton/y

4.2. Economic Analysis

The economic analysis was carried out considering an AD plant installed in a rural area next to a dairy factory (dairy factory A), which will own and operate the system and acquire from other three companies (dairy factories B, C, D) the raw material required for its operation. The dairy factories are close to each other (maximum 50 km) and it was assumed that milk transportation costs are charged to dairy factory A. The benefit for factories B, C, and D are the avoided transportation costs of their waste to landfill. The investment was analyzed through the profitability analysis actualized doing a costs and benefits analysis. Table 7 shows the cost items relating to the construction of the AD power plant obtained from providers and selected Literature.

Table 7. Cost of plant

Costs	
Plant cost	735,000 €
	(Amount of monthly payment = 4,851 €)
	(Annual financing cost = 58,208 €)
Ordinary operating and maintenance costs	49,549 €
Extraordinary management costs	6,090 €
All risks insurance	3,000 €
Spoiled milk transportation costs	14,826 €

In the revenues assessment (Table 8), the Italian legislative incentives scenario for electricity production from renewable sources of energy plants with power not exceeding 1 kWe and operating after 31st December 2012 was considered at a flat rate corresponding to 0.236 €/kWh (MD 06/06/2012 [23])

Table 8 shows the main revenue obtained from the management of the proposed anaerobic digester for the disposal of spoiled milk.

Table 8. Revenues

Revenues	
All inclusive rate	153,200 €
Milk disposal	102,200 €

The revenue from the incentives was calculated considering that about 8% of the electric power is consumed for plant operation. Among the revenues the disposal costs charged to the dairy factories B, C and D are considered (equal to 0.02 € /kg) but not the transportation costs.

4.3. Financial Analysis

Financial analysis indexes used to verify investment economic feasibility are: Return Time, Net Present Value (NPV) and Internal Rate of Profit (IRP) considering a discount rate of 5% and a timespan of investment equal to 20 years. Table 9 summarizes the financial indexes calculated.

Table 9. Financial indicators

Indices	Values
Payback period (years)	8-9
NPV (€)	806,903
IRR (%)	16

The indexes confirm that the proposed investment is economically feasible.

5. Conclusions

This work evaluates the feasibility of an AD power plant processing spoiled milk considering experimental results obtained from a pilot plant tests.

Namely, the experimental campaign has evaluated biogas and methane yields of a mixture with a substrate/inoculums ratio equal to 1:3, which has produced around 0.420 Nm^3/ kgVS of biogas and 0.240 Nm^3/ kgVS of methane. This mixture was the considered the best performing after a preliminary test of ABP tests in bottles.

Results confirms the feasibility an AD power plant to service four medium sized dairy companies (overall 5000 ton/year of spoiled milk) showing interesting financial indicators for the investment.

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