ALTERNATIVE MAIZE ENSILING TECHNIQUES FOR ANAEROBIC DIGESTION PROCESS: ECONOMIC AND ENERGETIC COMPARISON

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Abstract. Currently, biomasses contribute to the European energy supply-chain by an average amount of 4 %. With reference to the Italian situation, in the last years about 10 % of the overall maize area is earmarked to biogas production causing a changing in its harvesting operations. In particular, due to the wide surface to collect in a short harvesting period, the mowing, chopping, transport and ensiling operations must be well adapted in order to avoid bottlenecks that otherwise would lead to unproductive periods of delay, idle machines and, as a result, higher costs that could reduce the overall efficiency. Ensiling, in this sense, is one of the key issues that could affect the sustainability of such biomass, both from an economical and environmental point of view. In fact, several ensiling techniques can be carried out. However, among them, in Europe, the two most widespread are: bunker silos (traditional systems) and plastic bag-silos. While the bunker silos represent so far the most utilized solution, the plastic bag silos could be a potentially cheaper alternative to traditional silage storage systems. The aim of this study is to compare the economical and energy aspects of the two most important ensiling techniques for maize silage production aiming to detect the solution having lower costs and impact on the environment.

Keywords: maize silage, bunker silos, silobag, anaerobic digestion.

Introduction

Currently, biomass contribute to the European energy supply-chain amounts to 4 % and, considering the European Commission Renewable Energy Directive [1], its energy exploitation in future could grow [2]. Biogas deriving from anaerobic digestion has proved to be an interesting mean to generate energy from biomasses in rural areas, in particular when anaerobic digestion plants are fed with locally available feedstocks [3]. By the end of 2015, more than 15.000 biogas plants were active in Europe, while considering the Italian situation, nowadays more than 1.300 agricultural biogas plants are running (mainly in the north of Italy) and most of them operate in co-digestion. As a result, there is a remarkable need of energy crops (mainly cereal silage), agricultural residues (as animal sewage) and residues from the agro-industry [4; 5].

The growing demand for energy crops has produced a changing in the harvesting operations due to the need for wide areas to be harvested in short periods [6]. As a consequence, mowing, chopping, transport and ensiling operations must be properly adapted in order to avoid bottlenecks that otherwise would lead to unproductive periods of delay, idles and, therefore, higher costs [7; 8]. Ensiling, in this sense, is one of the key issues that could affect the sustainability of the whole process, both from an economical and an environmental point of view. In Europe, the most widespread technique for biogas plants is certainly horizontal silo, but there is a growing interest toward plastic bag-silos, due to their operative flexibility. Horizontal silos (or bunker silos) are concrete permanent structures mainly used to store forage biomasses such as chopped maize and grass. On the other hand, plastic bag silos (often referred as silobags) are a potentially cheaper alternative to traditional silage storage systems.

Implementation of silobags for the ensiling process brings to a series of positive consequences for biogas plants management [9]. Indeed, silobags allow to reduce nutrients losses due to the fact that the anaerobic environment that is created within the bags eliminates spoilage from the growth of yeasts, moulds and adverse bacteria [10]. Additionally, they can be placed anywhere (however, in a well graded and well drained ground surface) allowing fast ensiling and buffering of production peaks. As a consequence, they can potentially increase the efficiency and help and ease overall management of biogas plant feeding. However, quantitative comparison on the two systems is still missing: the aim of this study is to compare the economical and energy aspects of the two most widespread ensiling techniques for maize silage production, aiming to detect the solution having lower costs and impacts on the environment.

Materials and methods

The study was performed in a private farm located in the north-eastern Italy, in a typical Po Valley field (45.280989 N, 12.006930 E) during the maize silage harvesting season (august 2015). The experimental site was composed by two different fields: first area of 12.500 m^2 and second area of 24.000 m^2 with transport distances from the farm centre respectively of 100 m and 2500 m. A self-propelled forage harvester (SPFH) (mod. John Deere 7750 Prodrive, 460 kW) equipped with a 6 m corn header (mod. Kemper) was implemented for maize harvesting operations while three different tractors, each of them combined with a trailer of 23.5 m^3, were utilized alternately for transport operations.

The ensiling process was carried out according to two different strategies. In the first case, maize was ensiled and pressed in a bunker silo, while, in the second, maize was bagged into a silobag of 2.7 m diameter by a silage bagging machine (SBM) (mod. Apiesse 2C) operated by a tractor (mod. John Deere 7530, 143 kW).

The following field measurements were done during the harvesting operations:

- harvesting (with SPFH): effective working time, turning time, idle time, work speed;
- transport: transport time, speed;
- bunker silos filling and pressing, discharge time;
- silobag bagging: effective work time of the machine, idle time.

Subsequently, the operation performances have been computed according to the ASABE [11] standards in order to establish the productivity of the SPFH and of the SBM (in terms of fresh matter tonnes per hour). For the present study, a reference maize yield was assumed, according to the climate condition of the north-east of Italy, of 60 $t \cdot ha^{-1}$.

Supply scenarios of each ensiling system

An operative analysis for each ensiling system was performed, starting from the productivity computed for each operation. In order to evaluate different supply scenarios for maize silage, reference transport distances were assumed. The distances were considered in a range, which is typical of the majority of biogas plants, as follows:

- distance lower than 1 km (D0);
- distance of 5 km (D5);
- distance of 10 km (D10);
- distance of 30 km (D30).

The transport capacity of every vehicle was set to 32 m^3, while the number of vehicles necessary for transport operations was defined based on the achievement of the best performances for the whole ensiling system. The number of vehicles necessary for the maize pressing in the bunker silo was computed considering that 60 kg per kW of SPFH power is necessary [12].

Economic and energetic balance

The hourly costs of the machineries were calculated according to the methods proposed by ASABE [12;13]. Purchase costs of the machinery were based on the Italian price lists while the life span and the annual usage of the machines were based on a survey among the farmers. Material costs for silobag and bunker-silo systems were estimated considering the quantity of raw material needed in every system and the depreciation of the structures.

The considered silobag features a tubular plastic film shape, with a diameter of 2.7 m, a length of 75 m and a thickness of the film of 200 µm. The bunker silo (life span 30 years) has a rectangular shape with a total volume of 1890 m^3 (length 45 m, width 14 m, height 3 m); it is built on a concrete platform and, for three out of four sides, it presents walls made by concrete with a thickness of 0.3 m.

Dry matter (DM) losses for each ensiling system were estimated to be respectively 10 % for the bunker silo [14; 15] and 5% for the silobag system [15].

The energetic comparison was carried out considering the gross energy requirement [16-21]. An energy value was assigned to each input or operation involved in the whole process: human labour, direct and indirect use of mechanization, other input. Coefficients for oils, concrete and plastics were taken from Pimentel and Canakci reference works [22; 23]; fuel, labour and tractor coefficients were taken from other works reporting working conditions comparable to those present in our experimental site [24-26] (Tab. 1).

Table 1

Average energy content of the inputs required for the ensiling systems.

Inputs	Energy required, $MJ \cdot kg^{-1}$	Sources
Oils	78.13	[22]
Concrete	4.88	[23]
Plastic	90.00	[23]
Labour	1.93	[24]
Fuel	50.23	[25]
Tractor	80.23	[26]

Results and discussion

Machine performances

The harvesting effective time monitored of the SPFH was 0.36 $h \cdot ha^{-1}$ while the average turning time in the headlands was 0.19 $h \cdot ha^{-1}$. This corresponds to 70 % field efficiency. The SPFH average working speed was of 1.25 $m \cdot s^{-1}$. Consequently, the harvesting SPFH productivity has been calculated to be 113 $t \cdot h^{-1}$. On other hand, the effective working time of the SBM was of 0.01 $h \cdot t^{-1}$, that allows a bagging capacity of 83 $t \cdot h^{-1}$.

The determination of the machine performances allowed the development of two models for every silage system (Tab.2). The bunker silo system requires a higher number of vehicles than the silobag system, according to the different supply scenarios. This is due to the necessity of maintaining the harvesting productivity of the SPFH. In addition, two tractors are needed during the ensiling operations for biomass pressing. On the other hand, the silobag system requires a lower number of transport vehicles. The SBM machines have a lower operative performance. In order to minimize the idle times, the transport system was calculated to guarantee the ensiling capacity of the SBM.

Table 2

Ensiling systems performance and supply scenarios.

Operating parameters	Bunker silo	Silobag
Ensiling capacity, $t \cdot h^{-1}$	113	83
No of transport vehicles at different supply scenarios:		
D0	2	2
D5	8	6
D10	13	10
D30	37	28
No of tractors	2	1
Total tractors power, kW	440	143

Economic analysis

The graph (Fig. 1) shows the distribution of the costs for harvesting, transporting, ensiling and the percentage value of DM losses for each ensiling system at different supply scenarios. It can be noticed how the transport distance is the factor that most negatively influences the global costs. A comparison between each system shows that in the traditional system the DM losses have a greater impact than the silobag. This is due to the better preserving performances of silobags. Indeed, they can minimize aerobic losses thanks to the reduced wideness of the exposition face compared to the traditional system. Nevertheless, in the silobag system the harvesting and ensiling costs more markedly influence the total costs. This is due to a lower harvest productivity of the overall ensiling process.

The economic balance (Fig. 2) remarks the convenience for the adoption of the silobag with respect to the bunker silo at different supply distances. Indeed, the results show how the silobag ensiling system presents lower total costs if compared to the bunker silo process. As highlighted by the graph, the costs gradually tend to increase steadily from D0 to D30 scenario, with a break-even point between the two systems occurring only at higher transport distances. As a consequence, the silobag ensiling system is in general cheaper than the bunker silo, decreasing the costs by 7 % on average.

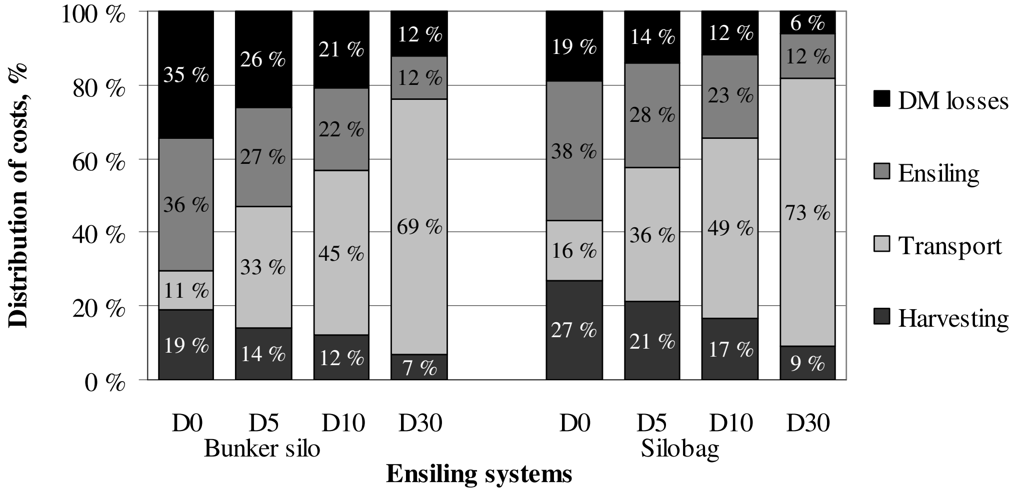

Fig. 1. **Distribution of the costs to each ensiling system at different supply scenarios**

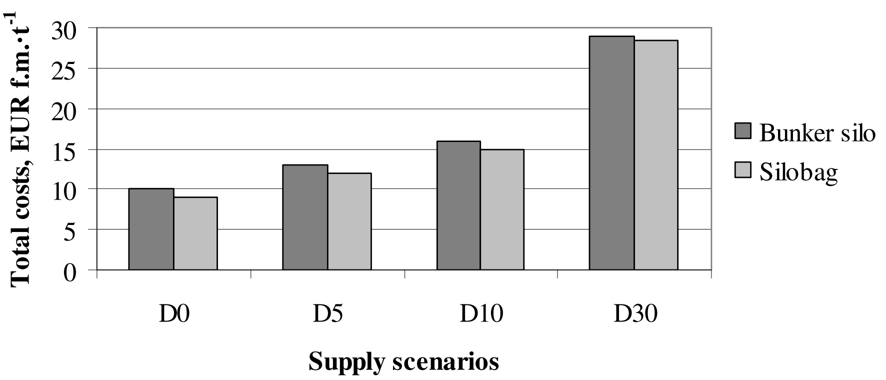

Fig. 2. **Total cost for each ensiling system at different supply scenarios**

Energy analysis

The energy analysis (Fig. 3) confirms a general better sustainability of the silobag ensiling system compared to the bunker silo.

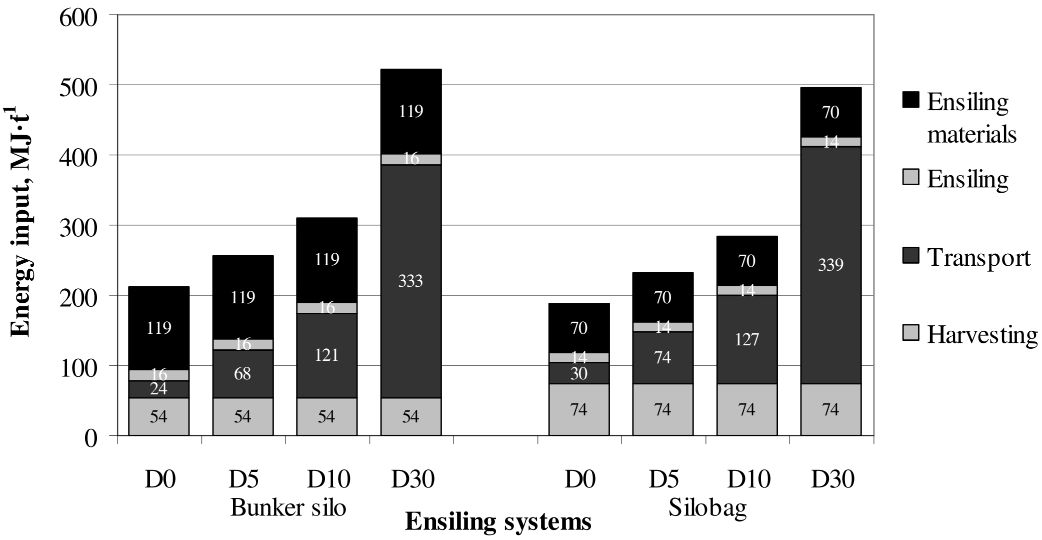

Fig. 3. **Total cost for each ensiling system at different supply scenarios**

In fact, the silobag allows an average reduction by 8 % of energy input. The foremost input requirement for the traditional system influences its balance negatively. Indeed, while for the silobag usually only the ensiling plastic material is needed, in the case of bunker silos permanent buildings are necessary, having a higher energy requirement for the construction.

In general, the supply distance of each system negatively affects the transport input. Conversely, the harvesting inputs are higher in the case of the silobag system: this is due to the higher idle time of the SPFH in the silobag system than in the bunker silo.

Conclusions

The aim of the research was to compare from a quantitative point of view the economical and energy aspects of the two most interesting ensiling techniques for maize silage production in biogas plants at different supply scenarios aiming to detect the solutions with lower costs and effects on the environment.

1. From the economic point of view, the silobag ensiling system presents, on average, lower total costs than the bunker silo process, allowing an average 7 % reduction of the costs. Nonetheless, it is important to consider that the silobag system presents a lower ensiling capacity: this factor could affect negatively the harvesting operations in short harvesting periods. However, a less powerful SPFH would be required with a presumable positive impact on the costs and energy inputs.
2. The energy analysis also confirms a general better sustainability of the silobag ensiling system compared to the bunker silo. In fact, on average, the silobag allows a reduction by 8 % of energy inputs, thanks to the lower material requirement for ensiling.
3. As obvious, the supply distance negatively affects both the economic and energy performances of each system: costs and energy impact double respectively after 15.8 and 20.3 km for the bunker silos and after 14.4 and 18 km for the silobag. Additionally, dry matter losses affect the results especially in the case of the bunker silos: the silobag dimensions allow minimization of losses, for a higher environmental compatibility.

It is worth noting that an improvement of the economic and energy efficiency of the ensiling systems can be achieved, considering ad hoc solutions such as optimized logistic systems or reduced volumes in the transport operations.

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