Potential biogas and methane yield of maize stover fractions and evaluation of some possible stover harvest chains

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Potential Biogas and Methane Yield of Corn Stover Fractions and Evaluation of Some Possible Stover Harvest Chains

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Abstract (max 250 words)

Yearly global corn stover production is about 75 million tonnes of dry matter that remains a major untapped agricultural resource. While its use as a feedstock for biogas production has been well studied, the methane potential of each single stover fraction begs further analysis. This study evaluated the composition of maize cobs, husks, leaves, and stalks and the potential of those components to produce biogas and methane. These analyses allowed an estimate of the preferred corn stover harvest chain conditions for quantity and quality. Fraction methane yields ranged between 206.6 and 307.0 l_N kg^{-1} VS, with husks being the most productive. In total, our estimates suggest that these fractions produce about 3,000 m^3 ha^{-1} of methane from the biogas conveniently collected by different harvest chains.

Keywords: Corn stover, anaerobic digestion, harvest chain, methane, stover fractionation

1. Introduction

Global corn production increased more than 40% in the past ten years, reaching 863 million tonnes (USDA, 2013) in 2013. In Europe alone, 2013 corn production totalled 64.6 million tonnes, with an increase of 10% from 2012 (USDA, 2013). The most recent forecast from the USDA indicates that 2014 European corn production will increase beyond that of 2013 (USDA, 2014). These elements indicate that probably grain corn production will continue to increase in the next years and the maize residues production as well. The management of this huge amount of biomass and its environmentally friendly use has to be taken into account.

The corn harvest occurs by combines, which separate kernels from the rest of the plant and collect grains into the tank. In good harvesting conditions, stalks and leaves are left directly on the ground below head, while ears and, a little amount of stalks and leaves above ear insertion, enter into trashing and cleaning system for the grains separation. After grains separation, cobs, husks, stalks and leaves, broken and partially chopped, are discharged to the ground from straw walker and sieves, forming a windrow just behind the combine rear wheels (Gramig, Reeling, Cibin, & Chaubey, 2013). Cobs, husks, leaves and stalks, commonly called stover, are important residues of corn processing. Stover harvest takes place in a second pass, by a shredder which can allow collecting up to 70-80% of the material left on the ground, depending on operative conditions (Sokhansanj, Turhollow, Cushman, & Cundiff, 2002). The shredder has to be kept at a proper distance from the ground, to reduce the stover losses and, at the same time, to avoid soil particle collection. The collected stover can be successively baled in round or square bales or siled, depending on the following use.

Several studies indicate that the heterogeneous composition of corn biomass impacts enzymatic hydrolysis and degradability (Li et al., 2014; Mourtzinis et al., 2014;

Duguid et al., 2009; Bootsma & Shanks, 2005). Most authors agree that corn grains represent 50-53% of the plant (dry weight basis), depending on agricultural practices and climate conditions. A similar consensus exists in stover composition literature. Sokhansanj, Mani, Tagore, and Turhollow (2010) reported that for every 1 kg of dry corn grains, about 0.15 kg of cobs, 0.22 kg of leaves, 0.14 kg of husks, and 0.50 kg of stalks are produced. Zych (2008) two years earlier found similar values, with a slightly higher percentage of cobs and leaves and a lower percentage of husks and stalks. Actually, these residues have several applications. Corn cobs are used as building materials and activated carbon (Pinto et al., 2012; Cao, Xie, Lv, & Bao, 2006), leaves serve as a source of fermentable sugars and fibre for paper (Shinners & Binversie, 2007), and stalks, leaves, and husks are transformed into bio-fertilizers or livestock litter (Chen et al., 2010). Although these residues are part of some productive processes, a mere 6% of the total is usually collected and removed from the field (Sokhansanj, Turhollow, Cushman, & Cundiff, 2002). The more common practice leaves stover on the ground surface to be buried into the soil where it becomes a source of organic matter and nutrients for the following crops. It has been estimated that worldwide approximately 204 million tonnes of dry matter is returned to the ground each year through corn residues (Sorensen et al., 2009). Clearly, crop residues play an important role in protecting and improving soil quality. At the same time, the negative soil quality effects of residue removal and crop productivity have been significant topics in long-term research (Mann, Tolbert, & Cushman, 2002), while in the last few years, maize residues removal for energy production has become a major subject of interest (Monforti, Bódis, Scarlat, & Dallemand, 2013; Zhang, Ghaly, & Li, 2012; Zych, 2008). Taken in aggregate, the literature indicates that stover collection systems must be designed with the goal of optimising biomass production and maintaining crop residues for soil sustainability. To do so, requires removing the corn stover portion with the highest fermentable sugar content. Harvest chains capable of collecting single maize fractions are in common use for cobs and the lower stalk. In the case of the other fractions, prototypes are being studied for a variety of purposes, as well as for energy production.

The main uses of maize residues in energy are ethanol production (Lamsal, Wang, & Johnson, 2011) and thermochemical conversion, such as gasification and pyrolysis (Kumar, Wang, Dzenis, Jones, & Hanna, 2008; Ioannidou et al., 2009). In the monthly WASDE report released on November 8, the USDA World Agricultural Outlook Board estimated that 118 million tonnes of corn were used to produce ethanol and co-products of ethanol during the 2012-13 marketing year (USDA, 2013). Recently, the interest in biogas production from corn stover has also increased. As reported in several papers (Zhang, Ghaly, & Li, 2012; Li, Zhu, Wan, & Park, 2011; Yuan et al., 2011), corn residues have the potential to be used as alternative feedstocks in anaerobic digestion plants for biogas production.

Anaerobic digestion (AD) is a clean technology that allows biogas production through organic matter degradation; the biogas produced can then feed a co-generator (CHP) to obtain electrical and thermal energy. In contrast with other kinds of renewable energies, when crop residues are used to produce biogas, the organic matter (OM) removed by the field returns to the soil at the end of the process through digestate application and avoids the risk of soil OM depletion. Although some researches were published on the use of maize stover in biogas plants, detailed data on biogas and methane production from corn stover fractions remains scarce. Detailed information on the relative energy value of maize fractions might prove useful to balance OM soil removal with the use of the residues as feedstocks for energy production. Furthermore, such data might inform approach to new harvesting machinery prototypes.

This research aimed to analyse potential biogas and methane yields of corn stover fractions to identify the most efficient producer among them and inform the development of harvesting systems designed for energy production. In addition, we estimated the amount of corn residue collected using three different harvest chains. This allowed us to estimate the energetic value of corn residue fractions in cubic meters of methane and electric energy from a surface of 4.5 hectares.

2. Materials and methods

2.1 Corn stover fractions collection

Different corn residues (Fao class 600) were collected after the grains harvest in a farm close to Novara, Piemonte, Northwest Italy. Cob, husk, stalk, and leaf residues were separately collected after grain harvest. The residues were successively dried and chopped with an electric shredder to a particle size of 15-20 mm, and then stored under vacuum until the AD batch trials started. A grain sample from the same field was also collected to allow comparison of the known highest methane-yielding fraction of the corn plant with the methane yields of the other stover fractions. The corn grains were not manipulated for the biogas production trials.

Liquid separated solid fraction of digestate was collected in an agricultural biogas plant (fed with animal manure and maize silage) and used as inoculum for the AD batch trials. Inoculum, before the biogas production trials, has been stored for ten days in a room at 40°C to deplete its residual biogas yield.

2.2 Chemical Analysis

Samples were analysed for dry matter (DM), raw ashes (XA), volatile solids (VS), cellulose, hemicellulose, and lignin. DM content was determined by chamber drying it at 105°C until a constant weight was reached. The dried material was successively burned in a muffle furnace at 550°C for its raw ash content determination. VS were calculated by subtracting the raw ash content from the dry matter. Cellulose, hemicellulose and lignin were determined by the standard procedures of AOAC Official Methods of Analysis (2006). The difference between neutral detergent fibre (NDF) and acid detergent fibre (ADF) equated to hemicellulose while the difference between acid detergent fibre and acid detergent lignin determined cellulose. Raw proteins, fats and soluble sugars were also determined, according to AOAC (2006). Biomass pHs were determined by pH-meter HI 9026 (Hanna, Italia) in a suspension of 50:50 (% w:w), as reported in AOAC (2006).

Inoculum was analysed for DM, XA, VS, pH, organic carbon, and organic, ammonium and total nitrogen (Table 1).

2.3 Biochemical methane potential test

Batch trials were conducted in accordance with VDI 4630 (2006), employing batch digesters of 2.0 l capacity. The biochemical methane potential test was performed at 40°C and was managed for 40 days with manual stirring at least once per day. Manual horizontal and circular motions were used in the stirring of each batch digester to ensure complete mixing of the digestate and to avoid a clogged tap for biogas expulsion. Each sample and inoculum was weighed in batches at a ratio of 1:2 (on VS basis). The volume of produced biogas was monitored with a Ritter Drum-type Gas (TG05/5) volume meter every 1-2 day, depending on daily biogas production. At the same time, the relative concentrations of CH_4, CO_2, O_2, H_2S, and H_2 in biogas was measured by a gas analyser with infrared sensors (model XAM 7000) produced by Drägerwerk AG & Co. KgaA, Lübeck, Germany.

Each thesis, along with its control sample (inoculum), was digested in triplicate. The inoculum biogas yield was measured and subtracted from that obtained from the samples. Both biogas and methane productions were expressed as normal litres (273 K and 1,013 kPa) per kg of volatile solids (l_N kg^{-1} VS). The methane concentration was corrected by a factor related to batch headspace, as reported in VDI 4630 (2006). Theoretical methane potential (TMP) was calculated using the organic composition of the samples (Möller, Sommer, & Ahring, 2004; VDI 4630, 2006) with Eq(1):

$$TMP = (lipids \cdot 1000.8) + (proteins \cdot 480) + (carbohydrates \cdot 375) \quad (1)$$

where TMP is expressed as l_N kg^{-1} VS and lipids, proteins and carbohydrates are expressed as kgVS. The VS degradation was calculated as the ratio between the methane yield determined by Biochemical Methane Potential test results and the TMP.

2.4 Energetic evaluation of the biomass potentially collected by different stover harvest chains

Some evaluations of the potential methane and energy production from the corn stover were carried out in an irrigated field in the western Po Valley in Northwest Italy. The potential methane yields of maize stover fractions were referred to one hectare of fresh matter production, according to the Biochemical Methane Potential test results. Electrical and thermal energy was calculated considering 39.79 kJ l^{-1} as Higher Heating Value (HHV) of CH_4 and respectively a CH_4–fuelled CHP electrical efficiency (η_{el}) 42% and a thermal one (η_{th}) of 50% (Office of Industrial Technologies, 1999). Respectively, the calculated electrical output for one m^3 of CH_4 was 4.4 kWh_{el} and the thermal output was 5.5 kWh_{th}.

Three different scenarios were considered for the determination of maize residues that can be collected and successively used for energetic purposes in biogas facilities.

1. Recovery of stover left on the ground by an axial flow combine with a modified head. The eight row header was equipped with shredding stalk rolls and four disk cutters that cut the stalks at 5-10 cm above the ground. Two belt conveyors, one for each head side, transport the chopped stalks and leaves in two central rows, creating windrows on which cobs, husks, and other corn residues are separately discharged from the grains. Stover was successively collected by a 651 kW forage harvester that discharged the stover into a cart pulled by a tractor that provided transport to the storage unit (chain 1).
2. Recovery of the stover passed through an axial flow combine, with a conventional maize head with stalk roller (that collect ears and a small amount of leaves and stalks), fitted with a chopper/blower device placed below the rotor end, to blow chopped material on a trailed stover cart pulled by a tractor aside the combine (chain 2).
3. Recovery of the stover passed through an axial flow combine, with a forage harvester head (that collect the whole maize plant above the cut), fitted with a chopper/blower attachment placed below the rotor end, to blow chopped material on a trailed stover cart pulled by a tractor (chain 3).

The material was transported into the storage facility by 14 t legal load trailers towed by 88 kW FWA (Front Wheel Assist) tractors. To avoid dry matter losses, the bulk materials were stacked in a bunker silo, consisting of a reinforced concrete platform with precast concrete walls covered with polyethylene film. An 81 kW FWA tractor with a front loader was used to fill the bunker silo and to compact the material in it.

The trial was carried out in the Piedmont in a 4.5 ha flood-irrigated sandy loam field, 250 m long and situated at a distance of 1,450 m from the bunker silo where the stover was stacked. In October 2013, an April planted FAO 600 class hybrid was harvested. Working time was recorded following ASABE Standard indications (ASABE, 2012) and considered the entire chain process: collection, transport, and storage (Grisso et al., 2008). A worksheet was developed to value the effect of operating conditions on machine efficiency and transport chain capacity.

The energetic costs of the chains were determined taking into account both direct costs – fuel and lubricant consumption – and indirect costs – machine and equipment energy inputs. Fuel consumption was determined via filling of the fuel tanks, while oil consumption was calculated following ASABE Standard indications (ASABE, 2012). Fuel consumption of the combine chopper attachment (chains 2 and 3) was determined as the difference between fuel consumed by the modified device and that of a combine of the same type under identical operating conditions.

The total energy content of fuel and lubricants were 51.2 and 52.9 MJ/kg, respectively. Energy content values of 160 and 80 MJ kg^{-1} were used for tractor and self-propelled machines and implements, respectively (Barber, 2004). The life of the self-propelled harvester, tractor, and implements were also estimated following ASABE Standard indications (ASABE, 2012). Table 2 shows the configuration of different chains.

We assumed that the bunker silos embodied an energy content of 1.24 MJ kg^{-1} for the pavement concrete and that the precast concrete walls embodied 2.0 MJ/kg of energy with an expected life of 30 years. The low density polyethylene film was assumed to embody an energy of 89.3 MJ kg^{-1} and that it required annual replacement (Hammond and Jones, 2008).

2.5 Statistical analysis

The data were compared by means the confidence interval of the three replicates. Biogas and methane yields of untreated (15 mm) and milled (0.2 mm) cobs were analysed by one way analysis of variance ($p < 0.05$).

Linear regression graphs between biogas and methane yields and stover fractions chemical compounds were created to evaluate the existing relations.

3. *Results and Discussion*

3.1 Chemical composition of corn stover fractions

The moisture of the maize residues ranged between 25.5% (stalks) and 63.3% (leaves) (Table 3). The ash content was lower than 2% of DM, except for leaves and stalks in which the ash contents were, respectively, 5.1% and 3.7%. For these two fractions, ash determination may have been slightly affected by the presence of soil particles. Proteins ranged from 2.27% (cob) and 8.72% (grains) of DM. Considering just the stover fractions, the highest proteins value was found in leaves, 5.61%. The same trend was observed for fats, which ranged from 0.48% to 3.10% of DM. Compared to the other maize fractions, cobs were the poorest in terms of protein and fat contents. Several animal feeding studies have confirmed the low energetic values of corn cobs and their high fibre amounts (Millet, Raes, De Smet, & Janssens, 2005; Wienhold, Varvel, & Jin, 2011). Soluble sugars ranged from 1.06% (husks) to 2.32% (stalks); grains showed only 1.68% soluble sugars on DM. Carbohydrates in grains were mainly represented by starch that was more than 70% of the grains DM content. Maize residues showed quite similar fibre compositions, except for grains which had a very low fibres and lignin content at only 14.1% of DM. NDF was higher in husks and cobs at 86.3% and 87.2%, respectively, and lower in stalks and leaves at 78.4% and 79.0%, respectively. However, the highest lignin values were observed precisely in these two fractions, 8.0% in stalks and 5.8% in leaves. In the other corn fractions lignin was less than 5%. The same distribution of cellulose, hemicellulose, and lignin in corn fractions was reported also in previous studies (Li, Xu, Liu, Fang, & Wang, 2014; Triolo, Sommer, Möller, Weisbjerg, & Jiang, 2011; Duguid, Montross, Radtke, Crofcheck, Wendt, et al. 2009; Burroughs, Gerlaugh, Schalk, Silver, & Kunkle, 1945). Mourtzinis, Cantrell, Arriaga, Balkcom, and Novak, et al. (2014) also observed higher holocellulose content in cobs and husks and higher lignin in the plant bottom. In the present study, relevant values of hemicellulose and cellulose were spotted compared to these previous studies; but it is well known that differences can result from hybrid, crop maturity, climate effect differences or other effects (Duguid, Montross, Radtke, Crofcheck, Wendt, et al. 2009). Nevertheless, the differences were not substantial.

3.2 Biochemical methane potential of corn stover fractions

Biogas production of corn stover fractions ranged between 379.8 and 544.4 l_N kg VS^{-1} (Table 4). The lowest yield was observed for cobs while the highest for husks. Grains biogas production was strongly higher at 709.3 l_N kg VS^{-1}. The percentage of methane in the biogas ranged between 54.4 and 56.4%, with the remaining biogas composition completely represented by CO_2, between 42.0 and 44.0%. The O_2 percentage was less than 1-2% during the entire anaerobic process; H_2 and H_2S fell between 0-1000 ppm and 0-500 ppm, respectively.

Grains obviously showed the highest methane yield, 393.0 l_N kg VS^{-1} as well as the highest organic matter degradation, about 90% of initial organic matter excluding lignin. Grain biogas and methane productions were significantly ($p < 0.05$) different from each corn stover fraction production. Maize grain represent the richest fraction of the corn plant in nutritional value since the carbohydrates are quite completely composed of starch and a small amount of lignocellulose,(< 14% and lignin = 2%). Observed biogas and methane yields of the stover fractions indicated significant (p <

0.05) differences. Among the corn fractions, husk showed the highest methane yield, 307.0 l_N kg VS^{-1}. It differed significantly from the other fraction yields. Stalks, leaves, and cobs showed no significant differences ($p < 0.05$) in methane yield. On the contrary, the degraded DM showed strong variation and statistically ($p < 0.05$) significant differences. Obviously, grains displayed the best DM degradation (86.8%) due to the low fibre and lignin amounts in their chemical structure. Cobs and stalks showed the lowest DM degradation percentages 51.3% and 53.9%, respectively.

Scarce literature information is available on the digestibility of maize stover fractions, and in particular, their use as feedstock to produce ethanol or biogas energy. Petersen and Keuning (2013) performed an experiment to evaluate the rumen digestibility of maize stover fractions, incubating the samples for 48 hours in buffered rumen fluid from beef cattle. They calculated the digestibility of each fraction and expressed it as percentage of DM. The results obtained in this study on the VS degradation in anaerobic conditions were re-calculated, showed they referred to the DM degradation, and compared favourably to the results available in the literature. The DM degradation of corn stover fraction correlated strictly to degradation values determined by Petersen and Keuning (2013). The calculated Pearson's r (r = 0.9869) confirmed this correlation. The correlation trendline equation revealed that apparently our experimental anaerobic conditions in batch were more suitable for the DM degradation than were the conditions in the rumen fluid. Also, under these conditions (rumen fluid) cobs showed the lowest digestibility level compared among the stover fractions.

Li, Xu, Liu, Fang, and Wang, (2014) analysed the various fractions of the entire corn plant for DM, NDF, and ADF degradability in ruminally cannulated cows. In their study, husk and leaf fractions showed the highest DM degradation, which mirrors our results. However, in contrast to our observations, Li, Xu, Liu, Fang and Wang, (2014) also found good degradability of cobs. The NDF and ADF degradation showed the same trend. The better degradability of cobs found by Li and his team is probably due to the very lower content of holocellulose (70.5%) and the slightly lower lignin content (4.3%) as compared to our cob sample.

Duguid, Montross, Radtke, Crofcheck, Wendt, et al. (2009) assessed the hydrolysis of corn fractions for ethanol production purposes and observed that without pre-treatment cobs and husks resulted in the lowest values of extractible DM. However, degradability of both of these fractions is strongly improved by pre-treatment with a low NaOH concentration solution. In particular DM degradability in corn cobs can be improved by as much as 66%.

International scientific literature regarding biogas production of individual corn stover fractions is limited. While few studies have been conducted on cobs and stalks, partial and preliminary results have been shown by several (Leke, Ogbanje, Terfa, & Ikyaagba, 2013; Eze, & Ojike, 2012; Bootsma, & Shanks, 2005). All observed cobs and stalks to be less productive in biogas, mainly due to their high fibre contents and lignifications that limits enzymatic hydrolysis and degradability (Bootsma, & Shanks, 2005).

Biogas and methane specific yields were analysed as dependent variables of organic matter compounds. For these residues, the organic compounds that highly and positively affected the yields were raw proteins ($R^2 = 0.582$) and fats ($R^2 = 0.696$). On the contrary, but as expected, lignin negatively affected the yields ($R^2 = -0.599$). This result further confirms its action as a barrier for fibre degradation.

The theoretical methane potential of maize stover fractions, calculated according to Möller, Sommer, & Ahring (2004), ranged from 377.9 to 421.1 l_N kg VS^{-1}. The range is very narrow compared to the range of analytically determined CH_4 yields. This revealed that the degradability level of each organic compound is highly variable compared to the theoretical one. In particular, cellulose availability is usually dramatically reduced by the lignin barrier (Triolo, Sommer, Möller, Weisbjerg, & Jiang, 2011).

3.3 Stover harvesting capacity

The harvested maize hybrid was characterised by a density of 6.2 plants m^{-2} with a yield of 14.0 t ha^{-1} and a DM content of 70.2% (9.9 tDM ha^{-1}). Kernels had an incidence of 49% on the whole plant (DM basis), while the incidence of cob, husks, leaves and stalks were 7.5%, 3.5%, 9.0% and 31.0% (all on DM basis), respectively. Sokhansanj, Turhllow, Cushman, and Cundiff (2002) obtained comparable results..

Chain 1 operated with a field capacity of 3.4 ha h^{-1} and with a field efficiency of 86.3%, corresponding to a throughput capacity of 81.8 t h^{-1}. This chain allowed collection of 24.3 t ha^{-1} of stover at 33.0% DM, corresponding to 8.0 tDM ha^{-1}, or nearly 78% of stover dry matter. The collected material had a potential methane production of about 122.9 m^3_N t^{-1} with a gross energy content of 3,880 MJ t^{-1}, which corresponded to about 94 GJ ha^{-1} or equivalent to potential electric power of 1.3 kW_{el} ha^{-1}, assuming an engine efficiency of 42% and complete utilisation of organic matter.

Chain 2 was measured to have a field capacity of 1.8 ha h^{-1} and field efficiency of 76.9%, corresponding to a throughput capacity of 11.8 t h^{-1}. This chain collected 6.4 t ha^{-1} of stover at 44.4% DM, corresponding to 2.8 tDM ha^{-1} or 27.7% of stover dry matter. The collected material would produce about 138.0 m^3_N t^{-1} methane production with a gross energy content of 44,370 MJ t^{-1} or about 28.0 GJ ha^{-1}. This energy value equates to a potential electric power of 0.4 kW_{el} ha^{-1} from a 42% efficient engine and complete utilisation of organic matter.

In chain 3, we observed a field capacity 1.3 ha h^{-1} and a field efficiency of 83.8%, for a throughput capacity of 35.8 t h^{-1}. With chain 3, 28.4 t ha^{-1} of stover at 32.2% DM were collected, corresponding to 9.2 tDM ha^{-1}. The collected material allowed a methane production of 121.6 m^3_N t^{-1}, with a gross energy content of 3,850 MJ t^{-1}, which corresponds to about 109.5 GJ ha^{-1} or a potential electric power of 1.5 kW_{el} ha^{-1} in a 42% efficient engine and complete utilisation of organic matter.

Chain 1 showed the higher working capacity. In fact, it was double that of the two other analysed chains. In chain 1, the separation of stover harvest from grain harvest allows the speed to be higher and the collected biomass volumes and times to be maximised. Indeed chain 1 allowed collected the largest volume of biomass per considered unit of time. While chain 1 is more flexible than the other two chains, it requires two enteries in the field, which increases soil compression. Moreover, as the stover is collected from the soil, there is a risk of collecting soil and stones inside the digester that might create problems.

Chain 3 exhibited the lowest working velocity because nearly the entire corn plant enters the combine, which requires that grains be separated inside from the rest of the plant. This operation, in order to be efficient for the grain harvest (and not have large grain losses), requires a low speed combine. Despite the velocity loss, the amount of collected biomass per unit harvested was higher than that obtained using chain 1.

Chain 2 was the least efficient because due to low speed and low capacity.

Surprisingly, from the perspective of obtainable energy estimates, the corn stover collected from 4.5 ha across the three different chains resulted in very similar values. The quality of the biomass collected with chain 2 showed only a slightly higher methane quality, but was insufficiently different to justify choosing chain 2 over the others. Considering the energy produced per hectare, chain 1 and chain 3 are similar, whereas chain 2 was inefficient for corn stover harvest.

Considering the 1,450 m distance between the harvested field and the storage area, three stover trailers were required for chain 1 that each had a transport cycle of 16.7 min as opposed to the two trailers needed for chains 2 and 3, with transport cycles of 55.6 and 27.0 min, respectively. The high loading time in chain 2 (50% more than chains 1 and 3) resulted from the low throughput capacity of the machinery. It is recommended that a cart be towed directly by the combine to offset the low volume of collected material (Fig. 1).

Assuming a maize harvesting season to be 60 days or 270 hours long, chain 2 allows harvest of about 500 ha or the equivalent potential electric power of 186 kW_{el}, considering an engine efficiency of 42% and complete utilisation of organic matter, as opposed to the 650 ha harvested by a conventional combine. Chain 3 harvested 340 ha - equal to a potential electric power of 495 kW_{el}. Chain 1, on the other hand, undertaken after grain harvest, took about 70 days or 294 hours to complete. From these values, chain 1 could harvest 1,000 ha of maize stover or the electric power equivalent of 1,250 kW_{el}.

Chain 2 resulted in the highest harvest energy costs from transport and storage of 779 MJ t^{-1}DM (60.3% harvest and transport; 39.7% storage), followed by chain 3 with 545 MJ t^{-1}DM (53.1% harvest and transport; 46.9% storage), and chain 1 at 476 MJ t^{-1}DM , (49.3% harvest and transport; 50.7% storage). The incidence of the energy demand for the three chains was 7.9%, 4.6%, and 4.0% on total methane energy content of stover collected by each chain, and of 18.9%, 10.9% and 9.6 % on electric energy produced, for chain 1, chain 2, and chain 3, respectively.

Chain 1 was the most efficient chain among those analysed when the goal is to remove the field stover after the grain harvest. Chain 1, being separated from the grain harvest is most flexible, but requires two field entries and increases soil compression. The removal of a large amount of organic matter from the field is a negative, but it can be offset if distributed to the soil as digestate after biogas production. Chain 3 represents an interesting option with relation to volume and quality of collected biomass, but its yields a low working capacity that compromises the entire corn harvest.

4. Conclusions

Corn stover fractions were characterised by different specific methane potentials. The most productive fraction was husk, whereas cob was the lowest. The biogas total amount that can be obtained by AD of corn stover ranged from 880 to 3,450 m^3 ha^{-1}, according to the harvest chains considered. The use of a combine fitted with a forage harvester head potentially allows collection of the highest stover amount, but results in a notable reduction of combine field capacity. For collecting material of high energetic value, the best option is recovery of the material passed through a combine fitted with a conventional head that reduces nutrient and organic matter removal and minimises the effect on combine field capacity. This seems to be the better option, even if the stover transport chain needs improvement to enhance capacity while reducing waiting time. Indeed this choice, as is true for the previous one, indicates that plans must be undertaken with both the stover harvest chain and maize grain harvest in mind. The use of a combine with a head able to form a swath of stover under the machine reduces organisational problems, but increases the risks of ingestion of soils and stones by the machine.

Parameters		
DM	% wet weight	6.18 ±0.04
VS	% wet weight	4.20 ±0.01
Organic Carbon	% wet weight	6.30 ± 0.06
Total Nitrogen	% wet weight	0.39 ±0.01
Organic Nitrogen	% wet weight	0.30 ±0.01
Ammonium Nitrogen	% wet weight	0.09 ±0.00
C/N		21 ±0.9

Table 1. Chemical composition of the inoculum used in the study. Standard deviation is also reported.

		Power (kW)	Weight (t)
Chain 1	Forage harvester	651	13.2
	Head		2.2
	FWA tractor - transport	88	4.8
	Trailer		3.5
	FWA tractor - silos	81	4.3
	Loader		1.2
Chain 2	Chopper attachment	-	0.8
	FWA tractor - transport	88	4.8
	Trailer		3.5
	FWA tractor - silos	81	4.3
	Loader		1.2
Chain 3	Chopper attachment	-	1.8
	FWA tractor - transport	88	4.8
	Trailer		3.5
	FWA tractor - silos	81	4.3
	Loader		1.2

Table 2. Configuration of the three analysed chains.

Maize fractions	DM	XA	Proteins	Fats	Soluble sugars	Hemicellulose	Cellulose	Lignin
	% wet weight	% dry weight	% dry weight	% dry weight	% dry weight	% dry weight	% dry weight	% dry weight
Stalks	25.5 ±0.8	3.7 ±0.2	3.63 ±0.04	1.35 ±0.02	2.32 ±0.07	34.2 ±0.6	36.2 ±0.4	8.0 ±1.1
Leaves	63.3 ±0.8	5.1 ±0.8	5.61 ±0.06	1.30 ±0.03	1.93 ±0.05	37.5 ±0.6	35.7 ±0.5	5.8 ±0.9
Husks	58.2 ±0.6	1.7 ±0.1	2.81 ±0.11	0.84 ±0.01	1.06 ±0.03	42.9 ±1.3	40.3 ±0.8	3.1 ±0.8
Cobs	43.5 ±0.2	1.9 ±0.1	2.27 ±0.04	0.48 ±0.01	1.17 ±0.03	46.0 ±1.4	36.4 ±0.5	4.8 ±0.8
Grains	87.4 ±0.8	1.4 ±0.0	8.72 ±0.18	3.10 ±0.03	1.68 ±0.05	6.3 ±0.3	5.7 ±0.1	2.1 ±0.0

Table 3. Chemical composition of the maize fractions analysed in the study. Standard deviation is also reported.

Maize fractions	Biogas	CH_4	CH_4	This study degraded DM	Peterson and Keuning (2013) degraded DM
	l_N kg^{-1} VS	%	l_N kg^{-1} VS	%	%
Stalks	424.3^c	55.1^b	233.8^c	53.9^d	35.6
Leaves	442.9^{bc}	55.2^b	244.5^c	57.0^c	42.0
Husks	544.4^b	56.4^a	307.0^b	70.4^b	53.8
Cobs	379.8^c	54.4^b	206.6^c	51.3^e	32.2
Grains	709.3^a	55.4^{ab}	393.0^a	86.8^a	87.5

Table 4. Biogas and methane yields of corn stover fractions and grains and percentage of dry matter degraded during the anaerobic digestion in batch compared to the results obtained in rumen fluid in Petersen and Keuning (2013). Different letters on the same column indicate significant differences ($p < 0.05$).

Figure captions

Fig. 1. Incidence of unloading, travel, loading, repair and maintenance, and waiting on the entire time in the analysed chains. Total times: chain 1 18.2 min.; chain 2 55.2 min.; chain 3 29.4 min.

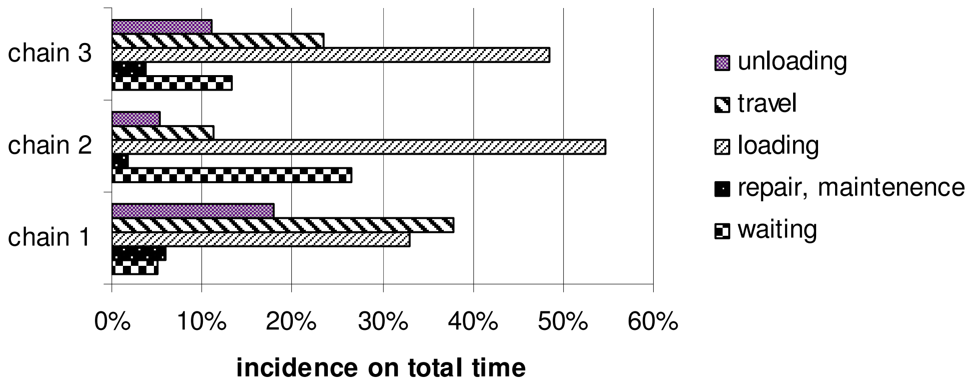
chain 3
chain 2
chain 1
0%
10%
20%
30%
40%
50%
60%
incidence on total time
unloading
travel
loading
repair, maintenence
waiting

Fig. 1