An Analysis of the Energy Potential of Anaerobic Digestion of Agricultural By-Products and Organic Waste

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An analysis of the energy potential of anaerobic digestion of agricultural by-products and organic waste

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Abstract

Anaerobic digestion is a promising option for recycling agricultural by-products and some organic wastes. While both agricultural by-products and wastes have no direct commercial value, their management is both complicated and costly. One option to simplify by-product management and reduce the costs associated with biogas plant feedstock is to substitute dedicated crops with vegetal by-products. Given that the chemical composition of some of these by-products can differ considerably from more typical biogas plant feedstock (such as maize silage), more complete knowledge of these alternatives to produce environmentally friendly energy is warranted.

To this end, batch trials under mesophilic conditions were conducted to evaluate the potential biogas yield of many agricultural by-products: maize stalks, rice chaff, wheat straw, kiwi fruit, onions, and two expired organic waste products (dairy and dry bread) from the retail mass-market. Among the considered biomasses, the highest methane producer was the expired dairy product mixture, which yielded 554 $l_NCH_4 \cdot kg^{-1}VS$. Maize stalks and wheat straw produced the lowest yields of 214 and 285 $l_NCH_4 \cdot kg^{-1}VS$, respectively. An assessment of the biogas and methane yields of each biomass was also undertaken to account for the specific chemical composition of each biomass as it can affect the anaerobic digestion operating system. Finally, the total Italian green energy production that might be derived from feeding all these biomasses to a biogas digester was estimated, in order to understand its potential impact.

Key words: anaerobic digestion; agricultural by-products; organic waste; biogas; energy potential

Introduction

Biogas plants across Europe are mainly fed with animal effluents and dedicated energy crops [1]. However, as the number of biogas plants has increased over the past decade, the quantity of energy crops dedicated to energy production rather than animal feed has also increased. This shift to energy crops may cause serious problems for both the agricultural sector and the world economy [2] by incentivizing producers in a way that upsets the delicate balance the world maintains to feed all peoples. Consequently, research on new substrates for anaerobic digestion plants (ADPs) is necessary. Currently, large quantities of agro-industrial by-products with no commercial value are destined for landfills, or in the case of cereal straws and maize stalks, abandoned in fields after harvest. Energy production from agricultural by-products is generally combustion-based as their low water content (12-14%) makes them well suited for burning [3]. The combustion plants usually produce only thermal energy, are suited for use within only a few kilometre radius, and are not economically-incentivized by politics. On the contrary, electrical energy producers receive economic incentives and, as a consequence, thermal energy is often transformed to electrical. However, this is a complicated process that makes combustion-based electric energy production very inefficient [4]. In fact, to obtain electrical energy in a combustion-based plant from by-products requires that they burn in order to heat water until it forms steam so that it drives a turbine, which in turn connects to an alternator that collects and stores the electric energy for later use. Not surprising, given this dynamic, combustion plants that burn vegetal by-products in Italy are few and at distances far from by-product sources, which further undermines the economics of the process. The electrical energy efficiency of a methane-powered engine, normally used in biogas plants, is higher (η_{el} = 35-40%) than that of an electrical-powered engine [5].

Moreover, the valorisation of the produced biogas is energy efficient and environmentally friendly because of the low emission of hazardous pollutants. The emissions of volatile organic compounds are very limited since 99% of the volatile compounds are completely oxidized during combustion in the co-generator. This is in contrast to incinerators that suffer from the emission of hazardous compounds like dioxins, and hence, require extensive flue gas purification [6]. Furthermore, the digestate, main biogas plant by-product, is nitrogen rich and can be utilized in agriculture as a nutrient fertilizer or organic amendment [7].

A major improvement to the economics of energy production from these biomasses in ADPs occurs if they are substituted for energy crops [8]. The use of agricultural by-products to produce electrical energy through anaerobic digestion, enhanced by simple biomass pre-treatment to improve bacterial digestibility and optimize methane yields (such as mechanical shredding), could be an economically and environmentally attractive alternative [9]. Estimates suggest that agro-industrial by-products and animal slurries could contribute more than 20% of the 2020 Italian renewable energy goal established by the European Settlement [10] which equates to 17% of the country's total energy production. Döhler et al. [11] demonstrated another important environmental benefit when energy crops are replaced with by-products as the main feedstock of a biogas plant—green house gas (GHG) emissions are reduced significantly (40%). This finding highlighted the positive influence that by-product utilization also has on GHG atmospheric emissions.

In principle, many different agricultural by-products can be used in biogas plants; however, knowledge of the anaerobic degradation of the substrates, plus their biogas (mixture of CH_4, CO_2, H_2, O_2, and H_2S) and methane production potentials is still limited. Furthermore, the potential negative effects of utilizing little known by-products in biogas plants are not fully understood. Clearly, a detailed evaluation of the technical and economic merits of each is needed before their use can be optimized.

This study, performed as part of the EU-Agrobiogas project (www.eu-agrobiogas.net), investigated the issues outlined above by analysing the biogas and methane yields of five agricultural by-products in batch trials under mesophilic conditions. The products included kiwi fruit and onions that did not meet market standards, maize stalks, rice chaff, and wheat straw as well as two sources of organic waste that originated from mass-market retail channels: expired bread and a mixture of expired dairy products (milk, cheese, yogurt).

The study showed that the chemical compositions of several of the by-products considered influenced the results. Several have rather low pH values (kiwi, onions, dairy products) and some contain high protein levels (dairy products), and both of which can cause, in the case of overloading, reduced methane production secondary to digester acidification [12]. Moreover, the high lignin content of some by-products, such as straw, stalks, and rice chaff can negatively affect anaerobic digestion [13], as its presence reduces hemicellulose and cellulose degradability [14]. To avoid low pH and high lignin content problems in ADPs, the biodegradability of these by-products was investigated in the laboratory. The principal parameters that required control because they indicate possible inhibition phenomena were pH level and ammonia concentration. Finally, since methane concentrations in biogas is a useful parameter to understand the trend of the process, they can assist in the evaluation of the economics of a biogas plant overall. The results obtained in this study were used to estimate the total Italian green energy production potential that feeding all these biomasses to biogas digesters might have.

2. Materials and methods

Each agricultural by-product (Table 1) sample was collected from farms and areas throughout the Piedmont Region of northwest Italy as described specifically below. Maize stalks were collected from a farm in Oleggio (Novara) at the start of October, one week after maize harvest. A sample of rice chaff was also taken in October, but from a biogas plant in Piverone (Torino) where it was used as digester feed. This same farm was also the source of the wheat straw sample, but it was collected four days after the July harvest. In November, following the main kiwi harvest at a farm in Cavallermaggiore (Cuneo), the fruit that remained on the trees that failed to meet market standards was collected. Onions, also too small for market, were collected from a farm in Andezeno (Torino) in July. The expired wheat bread sample, came from a Turin supermarket located where supermarket operators assemble all their organic waste for disposal. Finally, the dairy product mixture was sampled from a firm situated in Alessandria where a machine built by Nordischer Maschinenbau Rud.Baader GmbH of Lübeck, Germany) was used to separate the inorganic packaging from the organic dairy product fraction. The dairy product sample was composed of about 50% milk, 30% yogurt, and 20% fresh mozzarella cheese.

The study inoculum was collected from a 500 kW_{el} biogas plant fitted with a primary and secondary anaerobic fermenter for a combined total volume of 5000 m^3. It was situated in Bra (Cuneo) and was fed with 70% swine slurry, 18% maize silage, 5% whey, 4% grass silage, and 3% cattle manure. The anaerobic fermenters worked at 40.0 °C and had a total hydraulic retention time of 40 days. Each day of operation, 130 m^3 of digestate was produced. Following collection, the inoculum stored under anaerobic conditions for 20 days at 40.0 °C in a thermostated room to deplete its methane production potential.

All biomass samples were collected and prepared for analysis according to the German guidelines for a batch fermentation process [12]. Some of the biomasses, such as the rice chaff and the dairy waste mixture, were suitable for batch trials in the form in which they were sampled; the size of other samples required reduction to make them manageable for batch trials. The maize stalks were cut into smaller pieces with dimensions of 5 cm in length and 1 cm in width; wheat straw was reduced to a 1-2 cm size, kiwi fruits and onions were pieced to a 1-2 cm size, and the dry bread was ground in a knifed food mill.

At trial start, a biomass and inoculum quantity were prepared according to a calculated 1:3 ratio (biomass to inoculum) based on their volatile solid content [12]. Mixed in a 2-litre reactor, 300 ml of deionised water was successively added to improve the blending and homogeneity of each blend. Glass reactors were finally sealed with glass tops connected to Tedlar® gas bags (1, 3, 5 litre capacity) by tygon tubing (6.4 mm inner diameter). Reactors were manually stirred at least twice daily.

Biogas and methane were produced in the reactors in a thermostat-controlled room under mesophilic conditions (40.0 °C) according to [12]. The batch trials were conducted until the specific methane yield per day was less than 1% of the cumulative specific methane yield (about 40-70 days). Headspace volume accounted for in the calculations of methane yields by a correction factor as reported in [12]. All produced biogas was collected into gas bags and was regularly measured using a volume meter (Drum-type Gas Meter, Ritter). At the beginning of the anaerobic digestion, the biogas volume readings were performed about every two days since the biogas production was high. In the second part of the trial (after 10 days from the start of anaerobic digestion), when the biogas production decreased, the readings were performed less frequently. At the same time, the methane concentration of each bag was determined by using a Dräger XAM 7000 gas analyser. The daily biogas data volumes were converted to normal litres (l_N) (dry gas: Temperature = 0 °C and Pressure = 1,013 hPa) according to [12].

A control sample, composed only of inoculum and 300 ml of deionised water, was also prepared and analysed. The net biogas and methane yields of the tested biomasses were obtained by subtracting their biogas and methane volumes from that produced by the control. Although the control values were very low, it was necessary to eliminate every possible effect of the inoculum on the biogas and methane yields of the biomasses. All biomasses, including the control, were analysed in triplicate.

The biomass samples were characterised according to their more important physical and chemical parameters. The dry matter (DM) content of each mixture was determined after drying in an oven at 105°C for 24 hours. The weight of the ashes of each biomass sample was calculated after burning the DM in a muffle furnace at 550°C for 5 hours, which allowed determination of the volatile solids (VS) calculated as the difference between DM and ashes.

According to accepted analytical methods [15], the pH in water of each biomass was determined by a by a portable pH meter (Hanna Instruments HI 9026) using a glass electrode combined with a thermal automatic compensation system. A CHN analyser was used to determine the total nitrogen (N_{tot}) and total carbon (C_{tot}) for the elemental analysis. The pH in water was determined by pH-meter HI 9026 (Hanna, Italia). Hemicellulose (H-CEL), cellulose (CEL), and lignin (ADL) were analyzed by Van Soest methods [16]. Hemicelluloses and celluloses were calculated as the difference between NDF (neutron detergent fibre) and ADF (acid detergent fibre), and ADF and ADL (acid detergent lignin), respectively. Digestates at the end of the batch trials were analysed for DM and VS content to determine the VS degradation during anaerobic digestion. The pH, ammonium nitrogen (NH_4^+-N) [17], and N_{tot}, were also measured to better understand the process trend.

Differences in the specific biogas and methane yields were tested with a pair wise comparison of regression parameters by the Tukey-HSD-test. The level of significance was set to 0.05 [1].

3. Results and discussion

3.1. Biomasses chemical analysis

Table 1 reports the inoculum and biomass chemical analysis results. The following were batch trial inoculum key values: 6.7% DM, 70.7% VS content, and 7.9 pH. The DM of the biomasses varied highly, and was measured as low as 9.1% (onions) and as high as 87.7% (maize stalks). Rice chaff and wheat straw also displayed high DM contents at 87.1% and 86.6%, respectively. As expected according to the DM content, the VS contents were also very different and ranged between 8.5% on FM (onion) and 84.6% on FM (dry bread). Ideally, biomasses suitable for anaerobic digestion should have C/N ratios between 20 and 30 [18]. Calculated C/N ratios in present study ranged between 9 and 92. In this regard, maize stalks and wheat straw, which carried high C/N values at 35 and 92, respectively, were not very fit for anaerobic digestion. Dairy products showed very low C/N ratios (11) due to their high N_{tot} value (5.4%), which can also inhibit anaerobic digestion. The remaining biomasses had C/N ratios in the anaerobic suitability range.

The NDF parameter represents the percentage sum of H-CEL, CEL, and ADL in a compound and is an indicator of its "digestibility." Results showed onions and dry bread had very low values of NDF at 10.1% and 6.0%, respectively. On the other hand, all the other considered biomasses were greater than 39.5%. The biomass with the highest NDF value was wheat straw at 88.9%. Among the various NDF components, H-CEL, CEL, and ADL percentages across the biomasses were non-homogeneous. Specifically, the H-CEL value was between 3.3% (onion) and 32.2% (rice chaff), the CEL value between 0.7% (dry bread) and 49.8% (wheat straw), and the ADL value ranged between 0.6% (dry bread) and 12.8% (kiwi). Kiwi had the lowest NDF value, as well as high lignin content, and 14% volatile solids content.

Biomass pH values varied widely; kiwi (3.2) and onion (3.4) were highly acidic. Prior to the start of anaerobic digestion trials, the pH of each inoculum-biomass blend was determined to identify eventual negative effects by these two more acidic biomasses. The other biomass had pH values that ranged from 7.7 to 7.9, which are optimal values for AD [1] as described previously.

3.2. Specific biogas and methane yields

The organic waste anaerobic batch trials digested quickly due to their high, easy-to-digest organic compound content and lower, not easy-to-digest ligno-cellulosic compound content. This was evident in the number of days for which organic waste (onions and dairy products) measurements were taken (45-55 days) compared to the length of days that agricultural by-product (maize stalks, rice chaff, wheat straw, and kiwi) measurements were performed (55-60 days).

3.2.1. Specific biogas and methane yields of agricultural by-products

Agricultural by-product yields ranged between 420 $l_N \cdot kg^{-1}VS$ and 809 $l_N \cdot kg^{-1}VS$ for biogas and between 214 $l_N \cdot kg^{-1}VS$ and 381 $l_N \cdot kg^{-1}VS$ for methane (Figure 1). Maize stalks produced the lowest methane yields of all agricultural by-products. Rice chaff, wheat straw, kiwi, and onion showed no significant differences among their methane yields based on Tukey's test (α=5%). Similar values have been reported in the literature for onions and wheat straw [6; 19; 20]. The specific methane yields compared to the specific biogas yields of the biomasses were influenced by their gas compositions, and methane content in particular. Kiwi and onion biogases contained 46% and 47% methane, respectively; rice chaff contained 55% methane. With their low ligno-cellulosic content compounds (NDF) of 10.1% and ADL of 0.3%, the onions produced the highest biogas specific yield. Kiwi also presented a high biogas yield (800 $l_N \cdot kg^{-1}VS$), even with a large ADL percentage (nearly 13.0%). While these two biomasses had acidic pH values, they did not appear to inhibit the methanogenic process. When employing acidic biomasses in ADPs, it is mandatory to pay attention to the volume used to avoid digestate over-acidification. All biomass pH levels were determined at the end of the experiment and highlighted no significant problems.

Figure 2 displays the cumulative methane produced and daily specific methane produced by the agricultural by-products. Several biomasses stood out in particular. The rice chaff methane yield at 381 $l_N \cdot kg^{-1}VS$ did not vary significantly from other biomass yields, but its chemical composition did as it included an organic fraction with the following principal components: N_{tot} of 2.6%, fats of 19.3%, H-CEL of 32.2%, and an ADL of only 6.1%. The earliness with which rice chaff commenced methane production compared to the other biomasses indicated that the ideal initial conditions for hydrolytic bacteria activity were optimized. The very small size of the rice chaff itself also promoted speedy degradation.

Onions and kiwi displayed comparable trends in their cumulative methane production curves. Both curves showed a peak at about the fifth day, whereas after the 25^{th} day the methane daily production dropped quickly and approached zero. Their chemical compositions, C/N ratios between 20 and 25, and low ligno-cellulosic compound content all promote a fast start to methane production [21].

The daily methane yield curves of wheat straw and maize stalks differed considerably from the other samples. Either methane yields obtained in this study agreed to results showed in literature [6]. They failed to really peak, but instead displayed a gradual increase in the methane production, which extended and then slowed after day 35. These two biomasses have an organic matter composition that is rich in fibres and poor in compounds rapidly digestible by bacteria, which limited methane production. In general, the ratio of fibre and lignin determined the digestibility of every biomass and its required degradation time [22]. Consequently, those biomasses with high content of these two compounds lacked initial degradation peaks; instead, its methane production increased slowly, was extended for a period, and then stabilized.

On the contrary, kiwi and rice chaff, which also contained high ADL values (12.8% and 6.10%, respectively), but a low NDF, showed higher methane yields compared to maize stalks and wheat straw samples. The chemistry of ligno-cellulosic compounds varied considerably from one biomass to another [22; 23], which might explain why it is currently assumed that lignin concentration does not necessarily predict the degree to which lignin inhibits cellulose bioavailability. If a compound is lignin-incrusted, then cellulases will limit cellulose fibre access. If the cellulose is mainly in a crystalline form, then cellulases can attach to the compound and hydrolyse it relatively quickly [24]. The chemical composition of a compound, the fibrous fraction in particular, is essential to estimate the biogas potential of a biomass as many other studies have reported [25; 26].

3.2.2. Biogas and methane yields of organic wastes

As expected, dairy products produced high biogas and methane yields due to their high protein (33.9 %) and fat (18.2 %) contents coupled with fibre amounts so low that they were undeterminable. Also true of the dairy products, the methane percentage atop the biogas (56%) was higher relative to the other biomasses. During the first phase of the anaerobic process, dairy product methane production was very slow and irregular, which probably relates to their large nutrient and protein concentrations available to the bacteria. A rapid hydrolytic phase might have then caused a temporary pH decrease and volatile fatty acid increase, which caused an inhibited and slackened methanogenic phase [27; 28; 29]. In normal conditions, after this first phase, the pH increases again and comes back to initial values or slightly higher [30]. Analysis of pH levels (7.7) and NH_4^+-N concentrations (0.23%) at the end of anaerobic digestion (Table 2) made clear that these inhibitory conditions were, in fact, limited in time and did not compromise the entire process. The NH_4^+-N concentrations increases during the anaerobic process in batch, as reported in [30], and in some cases can reach toxic values for the methanogenic bacteria, inhibiting the methane production. This value is evaluated close to 3.0 g/l.

The dry bread specific biogas resulted in 650 $l_N \cdot kg^{-1}VS$, which is very close to another dry bread biogas yield during anaerobic digestion in batch reported in the literature of about 700-750 $l_N \cdot kg^{-1}VS$ [31]. The specific methane production was 313 $l_N \cdot kg^{-1}VS$ and the methane percentage was 47%. The biogas yield of dry bread was not significantly different than those of maize stalks, rice chaff, and wheat straw (α=0.05), but the dry bread methane percentage was unexpected. Other studies have indicated that the amount and quality of the starch contained in dry bread can affect specific methane yield, and that starch quality can influence its digestibility in anaerobic conditions [32].

3.2.3. Organic matter degradation and digestate parameter evaluation

At the end of batch trials the digested biomasses were analysed and the results are shown in Table 2. The digestate DM percentages ranged between 4.4% and 6.4%, respectively, for wheat straw and dry bread. The biomass organic components represented, on average, about 67% of dry matter content. Comparing the VS content in digestate and the VS content at the beginning of the batch trials, the organic matter degradation was estimated. These values were very different among the biomasses analysed and indicated that between 24% and 85% of organic matter was digested during the batch anaerobic digestion. The large range of organic matter degradation is due to the various biomass organic compositions, and in particular, the fibres and lignin content (NDF), which affected little the degradability of organic substances. Figure 3 displays the correlation between the organic matter degradation of the analysed biomasses and their NDF percentages.

PH values were higher than 7.7 for each digestate; consequently, it was possible to exclude the problem of acidification, even for acid biomasses such as kiwi fruit and onions [1]. Although the low pH of both biomasses, respectively 3.4 and 3.2, the low amount of biomass used in batch trial did not significantly affect the pH of blend inoculum-biomass in the batch digester. The NH_4^+-N determination was also performed to control the anaerobic process and highlight inhibitory conditions for bacteria activity. According to the biomass digestate pH values, it is reported that these negative conditions occur when the concentration of NH_4^+-N is greater than 3.0 g/l [32]. The NH_4^+-N concentration in the digestate of each biomass was lower than the inhibitory limit; this was also true for the dairy product digestates, which had a value of 2.3 g/l.

3.3. Estimation of the electrical energy potential obtainable from the analysed biomasses in Italy

To extend the study results, an estimate of the actual potential of the biomasses analysed to produce biogas and methane in Italy in a meaningful way, was prepared. Therefore, calculation would need to be based on actual volumes and quantities available within the country. It is also chosen to express the specific production of the various biomasses in $m^3_N \cdot t^{-1}$ fm (cubic meters per ton of fresh biomass) rather than in $l_N \cdot kg^{-1}$VS (litres per kilogram of volatile solids), which made the water content of the fresh biomasses play an important role in these estimates.

The dry bread showed high biogas and methane production due to its very low (12.5%) water content (Figure 4). Rice chaff and wheat straw produced 291 m^3_N and 236 m^3_N of methane (CH_4) per ton of fresh matter. In these cases, their yields appeared higher because of their large total solids content (87.1% and 86.6%, respectively). Maize stalks also had low water content (12.3%) and a very low specific yield, but they still produced more than 160 $m^3_N \cdot t^{-1}$ fm. On the contrary, onions and kiwi produced the lowest yields per ton of fresh matter added to the digester due to their low total and volatile solids content. The dairy product mixture also produced low yields when expressed on fresh matter due to its high water content (85%).

Based on study results and the supplies of these various biomasses in Italy, it was possible to estimate their total energy potential (Table 3). For the calculation, data came from several different sources: (i) the annual Italian agriculture census [33] provided an annual volume of maize stalks, rice chaff, wheat straw, kiwi, and onions that could be destined to biogas plants; (ii) the available quantity of dairy products was based on data obtained from an Italian project on bio-fuel and biogas [34]; and (iii) the dry bread amount was sourced from the annual Italian Report of urban wastes [35].

The available amount of agricultural by-products is very large; in particular, maize stalks are more than 7.7 million tons of fresh matter per year and wheat straw is more than 2.5 million tons of fresh matter per year. The yearly production of rice chaff is also large at more than 64,000 tons per year. Although these by-products produced low methane yields, their national availability is so large that their energy potential represents about 99% of the electrical energy potential of the biomasses analysed in this study. This value represents about 2.2% of the total electric energy demand in Italy [36]. While currently quite restrictive, Italian legislation governing the use of organic wastes in biogas plants will likely make these substrates members of a widening circle of by-products that contribute income to biogas plants. Considering the Italian availability of just the maize stalks, rice chaff, and wheat straw biomasses studied here, they alone could replace, at least in part, for the energy crops currently used as feedstock in biogas plants. Their total energy potential would approach 7,500 GW_{el} per year.

While this study analysed the biogas production of individual biomasses only; however, further studies should be performed to evaluate the possible synergies that can be obtained from the blend of by-products and organic wastes to feed anaerobic digesters. The study of specific blends may also reduce the critical factors of different biomasses, e.g. low pH, high protein content, and also solve the problems associated with by-product seasonality.

4. Conclusions

The results of this study highlighted the energy potential of a number of agricultural by-products and organic wastes that could be used as substitutes to energy crops in an ADP to produce electric energy.

Biomass chemical composition, particularly true in ligno-cellulosic compounds contained in maize stalks and wheat straw organic matter, affected methane yields, but the sheer size of their production annually makes them potentially attractive as contributors to the total Italian energy demand. Their employment as anaerobic digester feedstock should be hardly considered. Similarly, the high potential methane yield of rice chaff, combined with its high volume production per year in Italy, make it another suitable feedstock for biogas plants. Kiwi and onions too showed attractive specific methane yields, but their use in an ADP should be well managed and combined with other biomasses having a basic pH to avoid excessive acidification inside the digester. Dairy products contain high methane potentials, but their small available volumes and high water content, make them less suitable for a real scale biogas plant. On the other hand, dry bread appeared to have more potential as a biogas digester feedstock.

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Table captions

Table 1. Chemical composition of the biomasses analysed in batch trials.

Table 2. Analysis of digestate at the end of anaerobic digestion trials.

Table 3. Energy potential of analyzed biomasses.

Biomass	DM	VS	Ntot	Ctot	C/N	FAT	NDF*	H-CEL	CEL	ADL	pH	NH_4^+-N
	(% FM)	(% TS)	(% TS)	(% TS)		(% TS)	(% TS)	(% TS)	(% TS)	(% TS)		(% FM)
Inoculum	6.7	70.7	6.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	7.9	0.17
Maize stalks	87.7	89.0	1.2	42.5	35	1.1	76.3	26.7	44.0	5.6	7.3	n.d.
Rice chaff	87.1	87.7	2.6	47.8	18	19.2	47.8	32.2	9.5	6.1	6.7	n.d.
Wheat straw	86.6	95.7	0.5	45.8	92	1.7	88.9	29.7	49.8	9.4	6.9	n.d.
Kiwi fruit	12.0	89.8	2.2	51.8	23	5.8	39.5	11.0	15.7	12.8	3.4	n.d.
Onion	9.1	93.6	1.7	36.6	21	1.3	10.1	3.3	6.5	0.3	3.2	n.d.
Dairy products	13.4	93.8	5.4	50.0	9	18.2	n.d.	n.d.	n.d.	n.d.	5.8	n.d.
Dry bread	87.5	96.4	2.2	43.9	20	0.8	6.0	4.71	0.7	0.6	5.5	n.d.

* NDF is the sum of H-CEL, CEL and ADL obtained by [14].

Table 1.

Biomass	DM	VS	pH	NH_4^+-N	Ntot
	(% FM)	(% FM)		(% FM)	(% FM)
Maize stalks	4.7	3.2	7.9	0.14	0.20
Rice chaff	4.5	3.0	8.2	0.20	0.25
Wheat straw	4.4	3.0	8.2	0.16	0.19
Kiwi fruit	5.1	3.4	7.8	0.19	0.27
Onion	6.2	4.1	7.8	0.17	0.25
Dairy products	5.2	3.7	7.7	0.23	0.28
Dry bread	6.4	4.2	8.4	0.17	0.20

Table 2.

Biomass	Availability of biomass in Italy (t of fresh matter/year)	Electrical energy potential (EEP) GWel/year	EEP/ EEP total %
Maize stalks	7713000	5057	67
Rice chaff	64384	66	1
Wheat straw	2514271	2374	31
Kiwi	17390	3	<1
Onion	11688	2	<1
Dairy products	9000	2	<1
Dry bread	33000	36	<1
Total		7540	

Table 3.

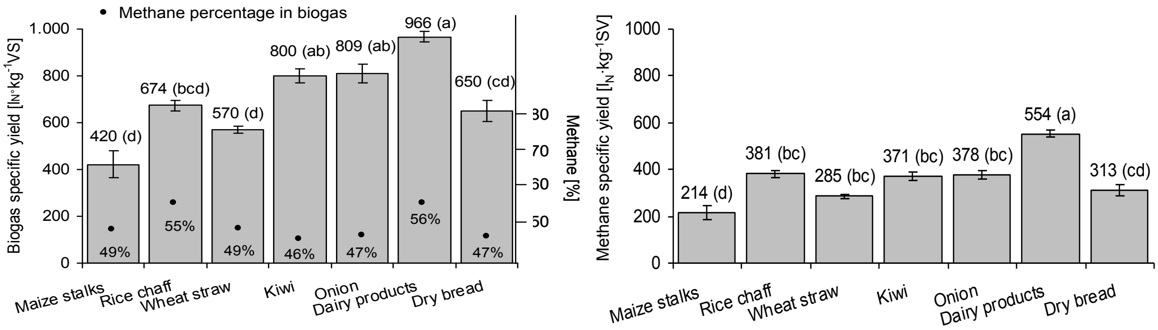
Figure captions

Figure 1. Biomass specific biogas and methane yields (biogas yield on left, methane yield on right). The bars indicate the standard deviation.

Figure 2. Specific cumulative methane yield and daily methane yield.

Figure 3. Correlation between organic matter degradation during anaerobic digestion batch trial and NDF. The value for dairy products was not showed, since NDF was not determined for this biomass.

Figure 4. Specific biogas and methane yields per ton of fresh biomass matter.



Means followed by the same letter are not statistically different using Tukey's test at 5% level.

Figure 1.

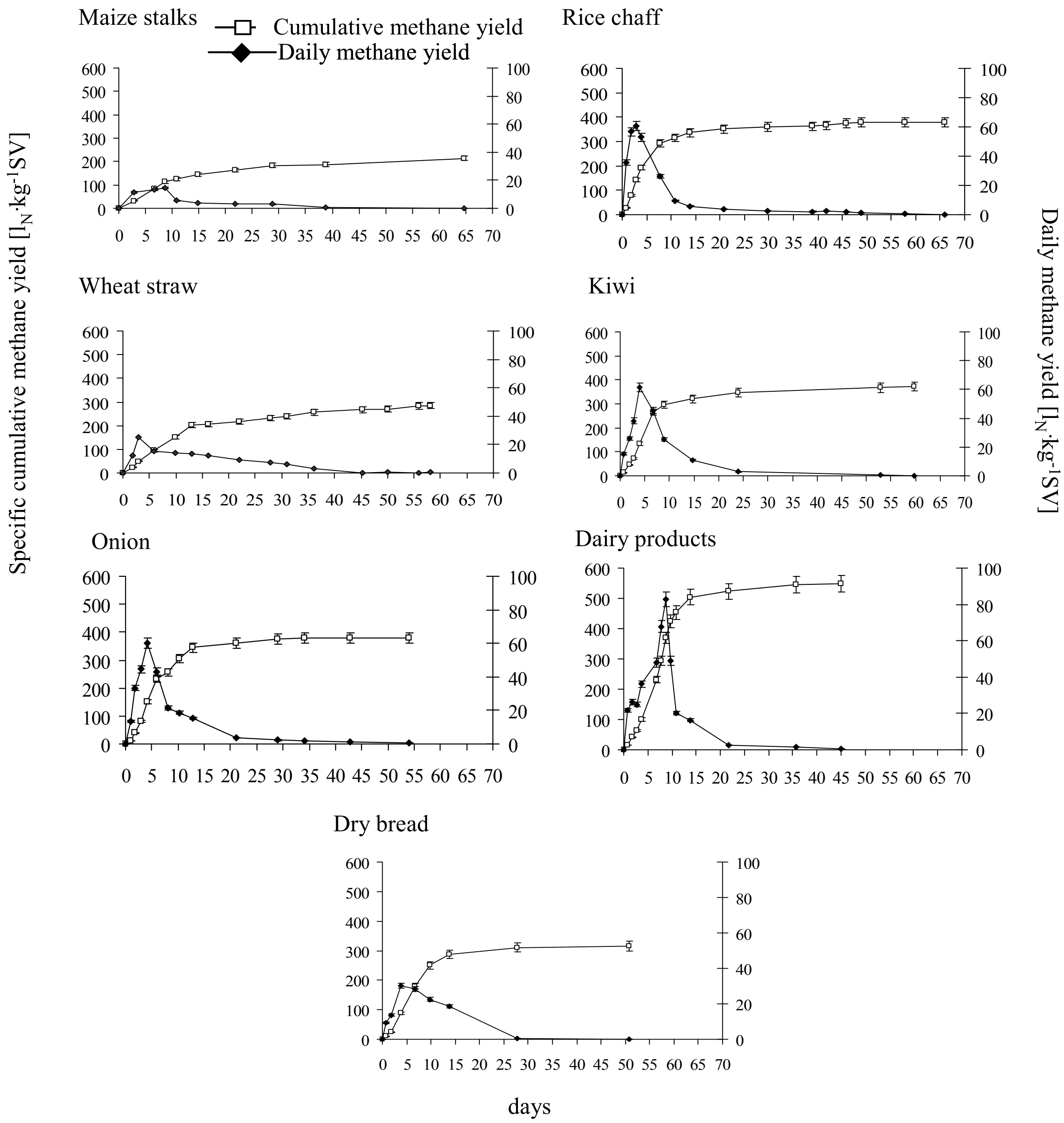

Maize stalks
Cumulative methane yield
Daily methane yield
Rice chaff
Wheat straw
Kiwi
Onion
Dairy products
Dry bread
Specific cumulative methane yield [$l_N \cdot kg^{-1}SV$]
Daily methane yield [$l_N \cdot kg^{-1}SV$]
days

Figure 2.

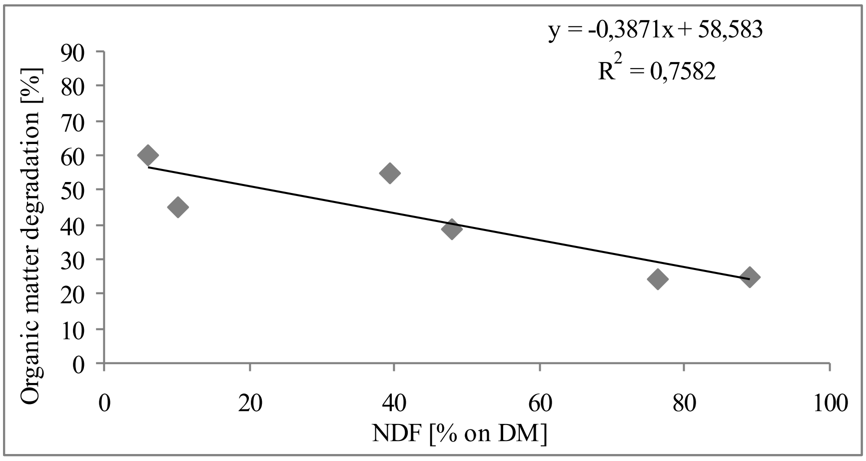
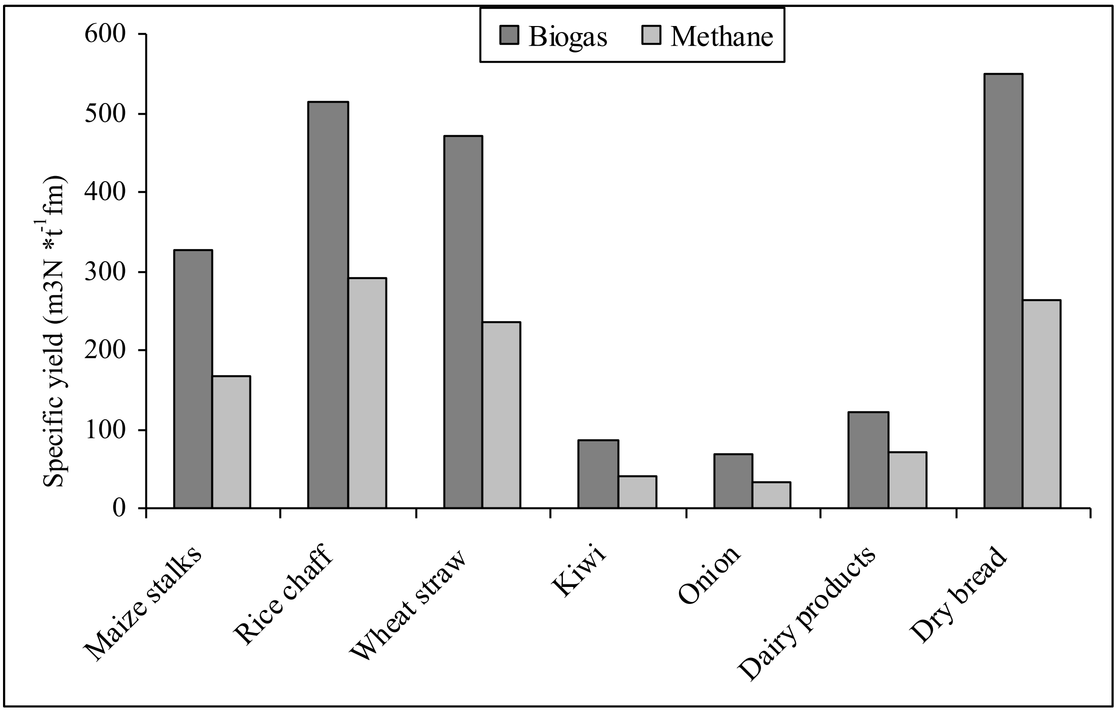

y = -0,3871x + 58,583
R2 = 0,7582
Organic matter degradation [%]
90
80
70
60
50
40
30
20
10
0
0
20
40
60
80
100
NDF [% on DM]

Figure 3.



Biogas
Methane
600
500
400
300
200
100
0
Specific yield (m3N *t-1 fm)
Maize stalks
Rice chaff
Wheat straw
Kiwi
Onion
Dairy products
Dry bread

Figure 4.