UNIVERSITÀ
DEGLI STUDI
DI PADOVA

<u>Administrative unit: University of Padova</u>

Department: **Land, Environment, Agriculture and Forestry (LEAF)**

PhD Program: **Land, Environment, Resources and Health (LERH)**

Batch: 30°

Energy valorisation of grass residues collected from non-cultivated areas

Thesis financially supported by

“Centro studi di economia e tecnica dell'energia Giorgio Levi Cases”

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ACKNOWLEDGEMENTS

I sincerely express my deepest gratitude to Prof. Luigi Sartori, my supervisor, who gave me the opportunity to attend this “adventure” and to learn many things related to agricultural technologies. Thanks for the guidance, for the encouragements, for the continuous support and for having had confidence in my skills.

I desire to thanks Francesco, Stefano, Alessandro for their support during the research activities.

A special thank also goes to my colleagues, Donato, Andrea, Franco and Roberto who contributed to improve my work and accompanied the PhD activities with funny moments.

A thank to Jacopo and Massimo for their accurate revision of the manuscript.

I wish to thanks my family and my friends for the support and the understanding.

Last but not least, I want to say thanks to Erica, for her support and for being close to me during the developing of this thesis.

ABSTRACT

Large amounts of grass residues derived from uncultivated areas are present in European regions. This biomass, which generally does not compete with food production and is partially recovered for animal feeding, represent an interesting feedstock for the supply of anaerobic digestion plants to produce renewable energy.

This thesis focused on the valorisation of grass from uncultivated areas in the anaerobic digestion supply chain, with particular attention on the Veneto region.

To achieve this objective, several research works have been performed in order to:

- Assess the potential areas and the biomass availability considering the situation of the Veneto region;
- Define the best technologies for grass mowing, harvesting, logistic and utilization in the economic, energy and environmental aspects;
- Determinate the energy and environmental balance that can derive from grass valorisation in the biogas supply chain.

In a first study, we demonstrated through a GIS based approach that large availability of residual grass is present in the Veneto Region, which it could be potentially utilized for anaerobic digestion. Grass from landscape management, such riverbanks, natural areas or parks, is of more interest for the energy generation in agricultural anaerobic digestion plants.

The harvesting of grass in these areas can be performed with different solutions. The total costs generally are high, however systems with better operative performances can reduce the economic and energy costs due to the specialized mechanization required.

Conceiving grass logistic, direct transport chain seems to be the most convenient solution under economical and energy aspects for the management of such material in short distances due to less mechanisations inputs requirement. Conversely, in longer distances, the best solution appears to be the interrupted transport chain due to the higher transport capacities.

The biochemical methane potential of grass is interesting, showing that a good amount of energy can be recovered.

Closing the whole energy and greenhouse gases balances is shown that the recovery of grass for energy purposes is sustainable.

As consequence, grass recovering represent and opportunity to reduce the dependency of anaerobic digestion sector on energy crops and obtain a positive return, in terms of energy and emissions saved, from the landscape management operations, creating interesting job opportunities.

RIASSUNTO

L'erba proveniente da aree non coltivate rappresenta un'interessante biomassa per l'alimentazione di impianti a digestione anaerobica. Tale biomassa generalmente non compete con la produzione alimentare e raramente viene recuperata per fini alimentari. L'obbiettivo di questa tesi riguarda la valorizzazione di erba da aree non coltivate per l'alimentazione di impianti a biogas, con particolare attenzione alla regione Veneto. Il raggiungimento di tale obiettivo è stato possibile attraverso diversi lavori di ricerca, con l'obbiettivo di:

- Valutare il potenziale quantitativo di biomassa nella regione Veneto;
- Definire le migliori tecnologie per il taglio, la raccolta, la logistica e l'utilizzazione dell'erba considerandone gli aspetti economici, energetici e ambientali;
- Determinare il bilancio energetico e ambientale derivante dalla valorizzazione nella filiera di produzione del biogas.

In un primo studio abbiamo dimostrato attraverso un approccio basato su GIS che in Veneto è presente una grande disponibilità di residui d'erba potenzialmente utilizzabili nella digestione anaerobica. In questo senso, l'erba derivante della gestione del paesaggio, come le banchine fluviali, le aree naturali, o i parchi, risulta essere di maggiore interesse per la produzione di energia negli impianti agricoli a digestione anaerobica. La raccolta di erba in queste aree può essere eseguita con diverse soluzioni. I costi complessivi sono generalmente elevati, tuttavia i sistemi con migliori capacità operative possono ridurre i costi economici e energetici. Considerando la logistica dell'erba, l'approccio a trasporto diretto risulta essere la soluzione più conveniente sotto gli aspetti economici e energetici per brevi distanze a causa di minori input di meccanizzazione. Viceversa, in lunghe distanze, la soluzione migliore risulta essere l'approccio di trasporto interrotto a causa delle maggiori capacità di trasporto.

Dagli studi si è potuto constatare inoltre che il potenziale metanigeno dell'erba è interessante, evidenziando una buona quantità di energia potenzialmente recuperabile. I bilanci energetici e dei gas serra dimostrano che il recupero dell'erba per scopi energetici è sostenibile.

Di conseguenza, il recupero dell'erba a fini energetici potrebbe costituire un'opportunità per il settore della produzione di biogas di ridurre la dipendenza da colture energetiche e ottenere un ritorno positivo, in termini di energia e di emissioni, dalla gestione del paesaggio, con la possibilità di creare interessanti opportunità di lavoro.

1. INTRODUCTION

In the last years, the production of biogas by anaerobic digestion (AD) of agricultural biomasses is notably augmented in Italy. As matter of fact, the number of plants is remarkably increased thanks to favourable incentives policies, passing from 16 in 2008 to 855 in 2012 (GSE, 2015).

Despite AD is a positive way to obtain energy with renewable resources and organic fertilizers, the main sources for AD plants feeding are energy crops (Di Maria et al. 2017; Lijó et al., 2015). Consequently, their cultivation compete with food production and exert strong pressures on the environment (Delbaere and Serradilla, 2004; Pick et al., 2012; Wilson et al., 2009). In fact, the intensive use of energy crops for biofuel and biogas production leads to higher climate gas emissions (Crutzen et al., 2007; Hensgen et al., 2011) and higher negative ecological impacts than the use of fossil fuels. This is due to the intensive use of inputs, such as fertilizers, pesticides, etc., for crops cultivation.

More sustainable scenarios can be achieved when biomasses that are in non-competition with food production are utilized in the AD supply chain (Buonocore and Franzese, 2012; Thompson and Meyer, 2013). By-products derived from landscape management, such as grass, could be of interest for AD since they present suitable bio-chemical characteristics for biogas production (Herrmann et al., 2014; Prochnow et al., 2005; Tsapekos et al., 2014).

In the Italian Padana plain, the number of biogas plants is consistent, especially in areas where there is a concentrated agricultural activity (Figure 1). In this optic, grass is an interesting feedstock for renewable bioenergy production because it is widely available and it can be used immediately or after silage. Many grassy areas are present in the territory, such as riverbanks, roadsides, parks, green areas or uncultivated agricultural areas (Pappalardo et al., 2014).

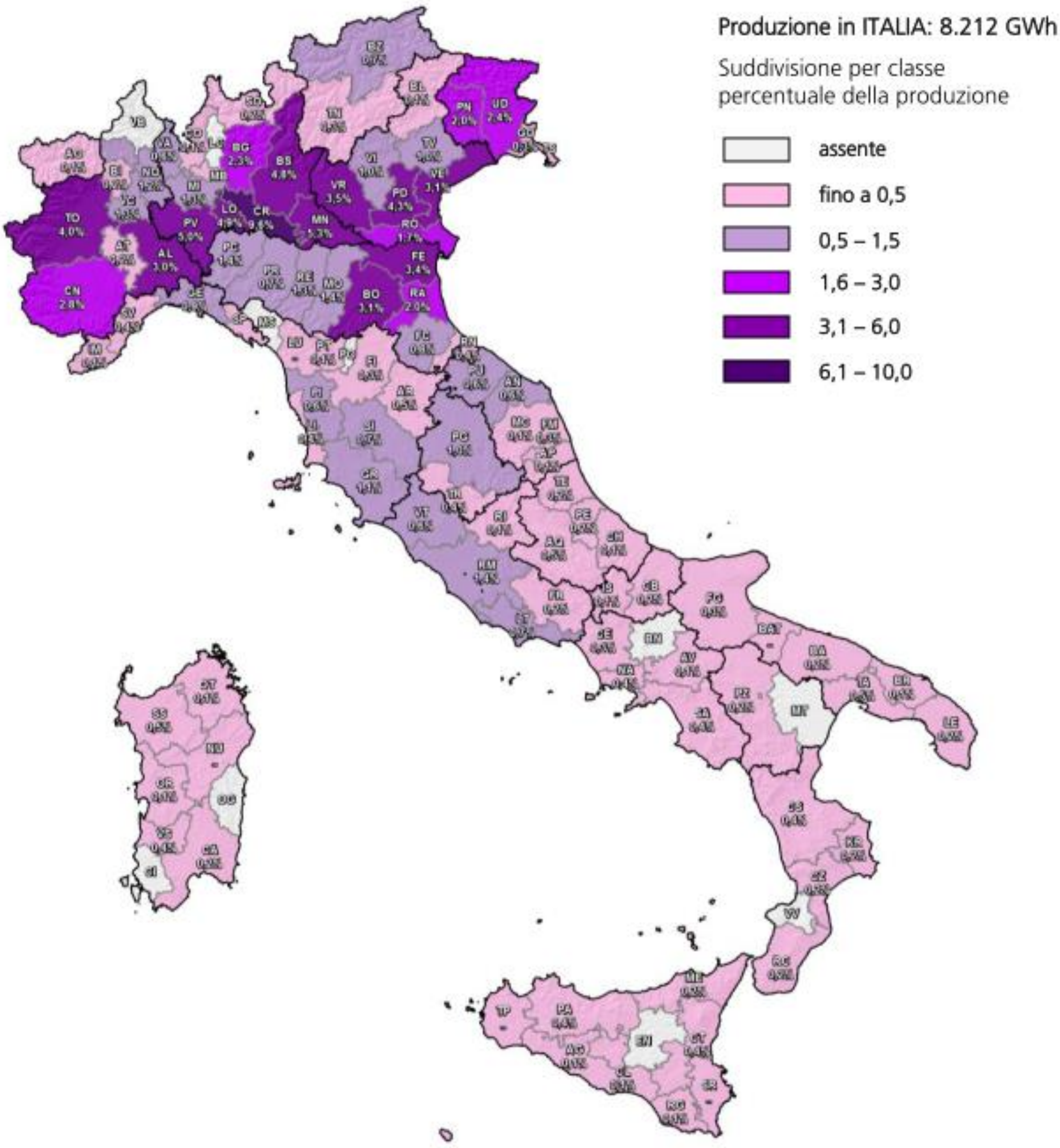

Figure 1: Subdivision per province of AD plants diffusion based on the electric power installed (GSE, 2015)

Although in the plain there are many hectares of those areas, not all are available for grass harvesting since several obstacles, legal constraints or unappropriated characteristics of grass can be founded. In fact, biogas process requires feedstock with a low contents of toxic compounds, ash, nutrients and pollution, to prevent possible inhibitions of the process (Gunaseelan 2007; Schievano et al. 2008; Gunaseelan 2009) and with appropriate quality requirements. Additionally, today there is a lack of information on the best technologies, systems and machines for the handling of this material in non-cultivated areas for energy purposes. Current knowledge about its utilization is poor and there are not specific technologies and machines, studies or researches available.

To encourage and promote the valorisation of these biomasses therefore more studies are necessaries to understand their potential. In fact, for instance the valorisation of grass could, in future, give an important contribution to produce energy sustainably and provide new renewable biomasses for AD creating new jobs possibilities.

The following thesis is aimed to provide a study about a potential energy valorisation chain of grass from non-cultivated areas with a particular focus on the Veneto region.

2. GRASS FROM UNCULTIVATED AREAS: RESOURCE FOR ANAEROBIC DIGESTION

Grass, considered as a mixture of herbaceous plants, is present in different uncultivated areas inside Veneto's territory. Although there are still no studies aimed to define its quantity and composition, the territory is evidently characterized by a large quantity of biomass (Colantoni et al., 2016; Pappalardo et al., 2014).

Largely, its botanical composition is categorized by *poaceae spp.*, *fabaceae spp.* or *asteracee spp.*, however other kind of species can be founded depending on the origin area (Figure 2).

Figure 2: Grass in uncultivated areas of the Veneto region

Potentially each area could be interesting for biomass recovery; however, several constrains can be founded, like:

- the presence of obstacles that restrict the access for the machineries;
- the presence of pollutants that ruin the quality of grass for the AD (e.g. litter, pollutants, wood residues);
- legal constrains that could prevent grass recovery in some areas;
- competition with other purposes (food for animals).

An analysis of the grassy areas that characterized the Veneto region territory is provided in the next sub-chapters.

2.1 Potential areas for grass harvesting

The potential areas for grass harvesting can be categorized in five groups:

- Roadsides;
- Riverbanks;
- Urban areas;
- Natural areas;
- Rural areas;

2.1.1 Roadsides

Roadsides are areas where uncultivated grassy lands are present (Figure 3).

Figure 3: Roadside grass area

Veneto region is characterized by a road network of about 9621 km (ACI, 2011), where grassy roadsides can be presented. Although the effective surface of green areas is still not quantified, the total amount of roads in Veneto shows that a good quantity of biomass could be recovered from these areas (Table 1).

Table 1: Classification of the road network of the Veneto by province

Province	Highways (km)	National ways (km)	Regional ways (km)	Provincial ways (km)	Total (km)
Belluno	16	217	205	709	1.147
Padua	74	87	167	1.093	1.421
Rovigo	25	82	124	546	777
Treviso	100	80	152	1.276	1.608
Venice	107	126	129	879	1.242
Verona	137	137	199	1.504	1.978
Vicenza	72	47	64	1.266	1.449
Total	530	777	1.041	7.273	9.621

Usually, grass is managed from one to four times per year, starting from March until October. The region takes charge of the maintenance of the area to provide traffic safety and road conservation.

Meyer et al. 2014 assessed in Denmark a biomass yield in roadsides variable between 4 to 6 tons of dry matter (DM) per year, depending on the number of cuttings. Although there are not studies in Italy, a similar or higher yield could be found also due to better climate conditions for grass growing. However, a problem related to the presence of litters that derives from the continuous transit of vehicles could ruin the biomass quality. For such reason, Italian legislation has classified this biomass as a waste (waste code 20.02.01).

On the other hand, according to recent studies conducted in some European countries, grass collected along roadsides has a low quantity of pollutants and AD of this feedstock is suitable (Heaven et al., 2007; Meyer et al., 2014). Hence, more studies in the Italian situation should be conducted before to consider these areas.

2.1.2 Riverbanks

A good amount of grass can be found along riverbanks. These kind of areas are generally present along river or watercourses to contain water streams (Figure 4).

Figure 4: Grassy area in riverbank in the Veneto Region

Currently, in the Veneto region, the management of these green areas is provided by ten public agencies called *“Consorzi di Bonifica”*. They generally run two/three cuts per year of grass without collect this material. As consequence, a recovery of this material could be interesting thanks to the possibility to reduce the management costs due to energy recover. As matter of fact, as shown in the Table 2, according to the data of two public agencies, the potential energy output from the recovery of grass could be interesting.

Table 2: Assessment of the quantity of biomass and electric power obtainable from two public agencies in the Veneto region

	Consorzio di bonifica Dese-Sile (2009)	**Consorzio di bonifica AdigEuganeo**
Grassy surfaces (ha)	1,113	600
N° of cuts per year	2	2
Hypothetical biomass amount (t_{DM})	≈ 7,500	≈ 4,000
Methane obtainable (m^3)	≈ 1,660,000	≈ 890,000
Electrical power generable (GWh/y)	≈ 4.5	≈2.5

2.1.3 Urban Areas

Urban areas are individuated as grassy surfaces, such as parks, gardens or airports (Figure 5).

Figure 5: An example of grass present in airports

Veneto territory is composed by 579 different towns where private and public green spaces are present (ISTAT, 2014).

According to recent surveys conducted by ISTAT, in some of the most important Italian cities there is a good presence of grass (Table 3). Considering only the Veneto Region, from the recycling of urban waste about 200,000 t/y of grass can be provided.

The potential biogas achievably could be interesting because grass is not utilized in AD, but usually it is utilized in the composting plants. However, it is necessary to consider that, as in case of roadsides, grass in urban areas could present problems due to the presence of pollutants or other undesirable materials that could ruin its quality.

Table 3: Available grassy areas and energy recovery potential of some of the most important Italian cities

City	Green areas (ha)	Biomass productivity (t/y)	Biogas (m^3/y)	Electric power (MWh/y)
Trento	5,006	15,018	3,303,960	5,947
Turin	2,101	6,303	1,386,660	2,496
Potenza	2,436	7,308	1,607,760	2,894
Milan	2,167	6,501	1,430,220	2,574
Florence	932	2,796	615,120	1,107
Bologna	1,154	3,462	761,640	1,371
Cagliari	616	1,848	406,560	732
Naples	645	1,935	425,700	766
Trieste	397	1,191	262,020	472
Aosta	96	288	63,360	114
Rome	4,499	13,497	2,969,340	5,345
Genova	1,047	3,141	691,020	1,244
Palermo	620	1,860	409,200	737
Catanzaro	334	1,002	220,440	397
Venice	908	2,724	599,280	1,079
Bari	244	732	161,040	290
Ancona	210	630	138,600	249
Campobasso	83	249	54,780	99
Perugia	585	1,755	386,100	695
L'Aquila	47	141	31020	56
TOTALE	24,127	72,381	15,923,820	28,663

2.1.4 Natural areas

Veneto region is characterized by natural areas identified as natural parks, pastures or mountain valleys (Figure 6).

Figure 6: Natural area present in the North part of the Veneto region

Grass from nature management or natural fields generally is mowed for biodiversity purposes once or twice a year depending on the necessity. These areas are ideal for the recovering of biomass compatible with AD because grasslands are larger and there is (almost) no contamination from pollutants, reducing the need for additional cleaning (GR3, 2016).

However, grass in these areas could be in competition with cattle feeding (Sturaro et al., 2009). Therefore, the consumption as fodder should be prioritised to using grass for AD. Nevertheless, a problem of land abandonment, especially in mountainous areas, is characterizing the region due to the low economical convenience of breeding (Giupponi et al., 2006; MacDonald et al., 2000). Consequently, the recovery of grass for biogas production could be an interesting opportunity for the valorisation of these areas.

2.1.5 Rural areas

In rural areas, the presence of grass is relevant. Indeed, marginal grassy parts can be present inside agricultural lands (for example headlands or drains).

In Veneto region is estimated that there is a surface of 31,000 ha of marginal areas (Censimento dell’agricoltura, 2010). Moreover, the region is characterized also by many vineyards or orchards where there could be a presence of grass in the inter-rows between the plants (Figure 7).

Figure 7: Grassy surfaces in vineyards

The potential energy recovery could be interesting (Table 4). However, a contamination risk in vineyards or orchards due to the drift of pesticides and fungicides should be taken into account for the biomass quality (Puig-Montserrat et al., 2017).

Table 4: Estimated energy potential from vineyards and orchards in the Veneto region

	Vineyards	**Orchards**
N° of Hectares (ha)	77,000	23,100
Biomass yield (t_{DM}/ha)	6	6
Biomass (t_{DM}/y)	462,000	138,600
Biogas (m^3/y)	101,640,000	30,492,000
Electric power (MWh/y)	182,952	54,886

3. TECHNOLOGIES FOR GRASS VALORISATION

3.1 Grass mowing and harvesting

To mow and harvest grasslands, different machineries can be deployed.

Relief, obstacles, vegetation and soil type are the most important factors herein. Moreover, because of its tendency of accumulate hemicelluloses and lignin during the maturation phase (Lindsey et al., 2013), it is necessary also to consider an appropriate period for harvesting.

According to some authors, the technologies for grassland would consider the use of mowers or shredders for cutting, self-loader wagons or round balers for harvesting, or machines like self-propelled forage harvesters for both combined operations (Berg et al., 2006; Hogan, 2007; Prochnow et al., 2009). All these kinds of machines can also provide a mechanical pre-treatment that reduces the size of grass (Tsapekos et al., 2017), which is a fundamental parameter for an enhanced methane production or for the ensiling process (Sharma et al., 1988).

Riverbanks or roadsides can be characterized by physical obstacles that can restrict the access for machineries reducing the efficiency of the whole system. For this kind of areas, solutions provided by an arm brush cutter with a sucking equipment (Figure 8A, 8B), mowers (Figure 8C, 8D, 8E, 8F), wrappers, shredders, and round balers (Figure 8G) or self-loaders wagons (Figure 8H) for the harvesting could be more appropriate. All these kind of machineries could mow and harvest grass in a single operation or separately, depending on their technical characteristics (Heaven et al., 2007).

Figure 8: Machineries utilized for riverbank grass mowing and harvesting

In the urban areas, grass mowing and harvesting can be performed by self-propelled lawnmowers (Piccarolo, 2000). They, thanks to their characteristics, are adapted to work in conditions with a high number of obstacles that could affect the accessibility of other machineries (Figure 9A).

In rural and natural areas instead, the appropriate solutions for mowing and harvesting differs than the roadsides, riverbanks and urban areas. In fact, in these areas generally less accessibility constrains can be founded allowing to obtain a better performance. Machineries can involve in shredders with a cargo trailers (Figure 9B). This system mow and collect grass in a single operation reducing operative times, but requiring an appropriate solution for logistic due to the necessities of download the material constantly. On the other hand, in larger areas, common technologies used in the haymaking supply chain could be an appropriate solution (Figure 9C, 9D).

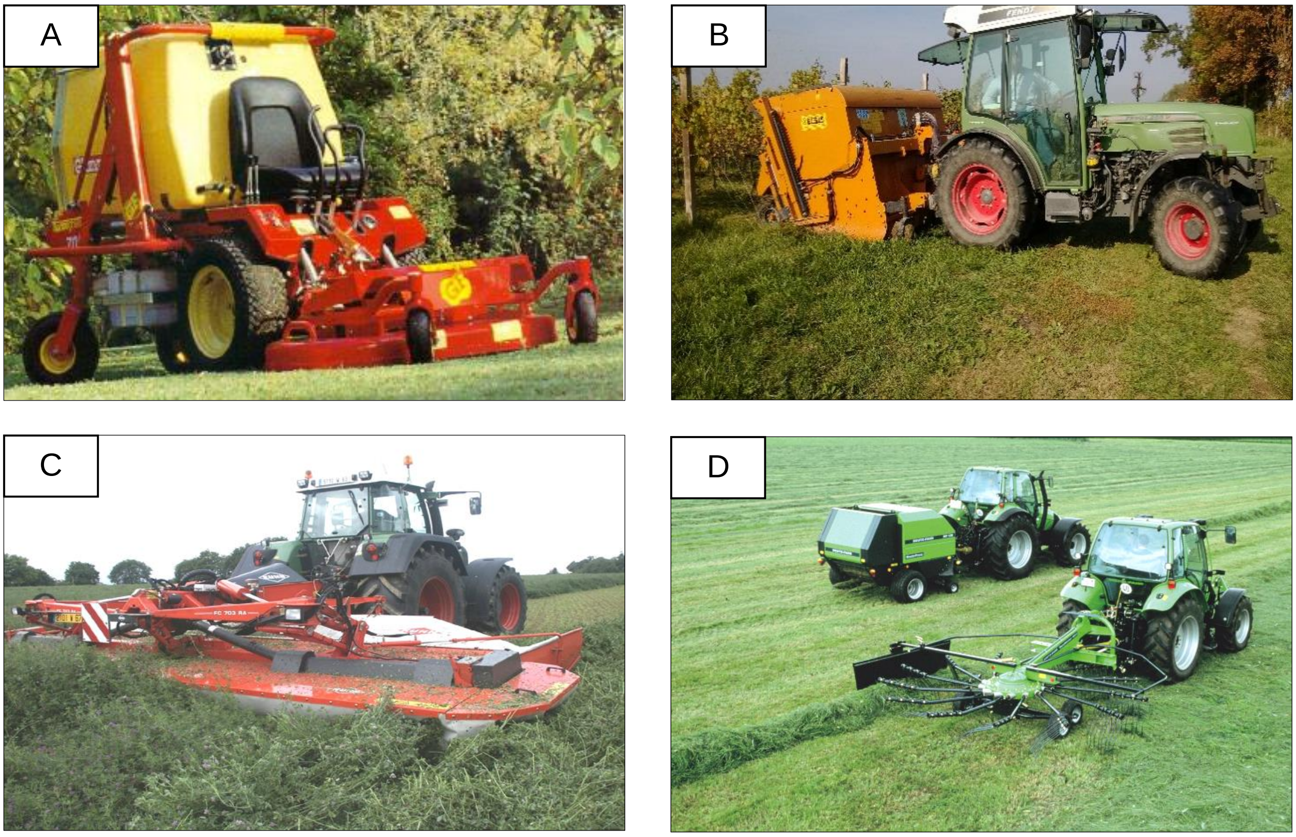

Figure 9: Machineries utilized for urban and rural areas grass mowing and harvesting

3.2 Grass logistics

Logistics is the part of the supply chain that plan, implement and control the effective flow and storage of goods, services and information related to them from the point of origin to the point of consumption to meet customer requirements. Therefore, logistics not only includes a transportation from production to use location but also includes a process of planning, organizing and control of activities aimed at making available the right thing at the right time and in the right location (Bodria and Berruto, 2011).

Grass logistics for biogas plants supply must be adapted to the characteristics that this kind of biomass has. According to Karampinis and Grammelis (2012), grass presents the following characteristics:

- harvesting can be typically performed in a very narrow time span due to weather conditions that can make impractical or not possible an operative application;
- it is available only for a specific period during the year; therefore, a storage intermediate step should be planned to extend its availability;
- it has a low density and this is an important factor because it influences the transport volumes increasing the overall costs and, thus, limiting potential applications.

For these reasons, in order to minimize possible concerns that could be present, the transport distance should be limited and the energy plants should be as close as possible to the biomass location.

The mowing and harvesting systems influence directly the transport system (Larson et al., 2010). In fact, these operations can be performed through one passage or two or more passages (Heaven et al., 2007). In the first case, the work of the system is interrupted when the harvesting system is full for the downloading of the product. In the second case, the harvesting system could work continually (without the necessity of downloading).

An optimal logistic of harvester and post-harvester chain, therefore, is a key figure in the minimising time required for harvesting and the resulting costs (Gunnarsson et al., 2008). In order to perform an optimal supply chain of grass for AD, the choice of technique for the logistic is essential. There are two basic concepts of supply chain, which can be adopted for grass:

- direct transport chain
- interrupted transport chain

3.2.1 Direct transport chain

The direct transport supply chain implies that mowing, harvesting and transport to the final digestion plant are performed without interruption of the harvesting operations.

The advantage of this approach depends mainly by the transport distance (generally not more than 40-50 km) and by the transport configuration (longer is the distance, more payload capacity of the transportation system would be required for an improved performance).

In the direct supply chain, mowing, harvesting and transportation can be performed by the same machine (Figure 10), such as a mower with a self-loader trailer (transportation capacity changes from 10 to 40 m^3 or more depending on the axle number of the trailer) or can be alternatively performed by different machines (AA.VV., 2014). In this case, for instance a self-loader wagon can be used for the harvesting of the biomass and transport.

The strengths of this system is the possibility to reduce the logistic costs for short distances and the easy management of grass that is located in areas with a difficult access. The respect of the harvesting timeless is fundamental; for this reason, in case of long distances, a higher number of vehicles should be utilized.

Figure 10: An example of a direct transport chain

3.2.2 Interrupted transport chain

The interrupted transport supply chains are defined by those where the ensilage activity and the transportation to the digester are separated and function independently of each other (AA.VV., 2014).

This solution is advantageous when there is a high quantity of biomass that has to be supplied to AD plants and the transport system is not able to transport the product in a reasonable time due to high distances (AA.VV., 2014). In this case, the transport capacity of the combined mower and self-loader trailer could be not necessary high as the distance to the intermediate storage location. A tractor with trailer with higher payload capacity can perform the successive long distance transportation from the intermediate storage to the digestion plant.

3.3 Grass storing

Grass can be utilized as a fresh feedstock to feed directly AD plants or, alternatively, it can be ensiled in a temporary place (Figure 11).

The first solution deals with problems related to high contents of liquids that increase the cost for the handling of this biomass during AD and for the difficulty to follow a precise diet in the plant.

The second way results more suitable in management terms. In fact, since grass is accumulated seasonally, biogas plants need to be fed continuously, and for these reasons grass has to be available constantly (AA.VV., 2014). Moreover, ensiling provides a biological treatment able to enhance grass degradability (Ambye-Jensen et al., 2013; Herrmann et al., 2012). Ensiling is based on solid-state lactic acid fermentation under anaerobic conditions whereby lactic acid bacteria (LAB) convert water-soluble sugars into organic acids, mainly to lactic acid (Weinberg and Ashbell, 2003). As a result, the pH decreases, and the biomass moisture is preserved. Air is detrimental to this process because it enables plant respiration and the activity of aerobic spoilage microorganisms such as yeasts and moulds (Woolford, 1990).

Figure 11: Grass ensiling in a bunker silo

A traditional process for biomass ensiling consists in the filling of bunker silos where to store the biomass (AA.VV., 2014). This kind of structure is generally made in concrete and it has to be accurately designed depending on the amount of biomass to store. The optimal moment for grass ensiling is when dry matter content is between 30 and 35% (Martin et al., 2004). Additionally, an appropriate cut length of the feedstock is necessary to facilitate the compression of the biomass in order to avoid air penetration (Prochnow et al., 2009). To achieve this, generally heavy machines are used during the silo filling operations (more than 15 tons) for the biomass packing. During the filling operations, also, soil contamination should be avoided. For these reasons, the supply track of silos structures should be preferably in concrete in order to limit soil contamination and make sure the surface area of the silo is swept clean before ensiling. When the biomass is ensiled in the silo is necessary to cover the silo surface with two layers of plastic foil and a canvas against birds. The silo should be closed for 6 weeks to let it stabilize (Elsen et al., 2009). Application of silage additives is recommended to improve the ensiling process, avoid excessive fermentation losses and ensure high methane yield recovery. For instance, addition of homofermentative LAB succeeds in improving acidification and silage quality as long as sufficient fermentable sugars are available. Besides its supportive impact on silage fermentation, molasses also increases methane production; however, additional costs of molasses have to be considered (Herrmann et al., 2014).

Besides the bunker silo, other techniques are available for ensiling, as silobags or silage bales (Figure 12). These ensiling techniques are possible with the utilization of dedicated machineries that can put the product inside a long plastic bags in the case of silobags or wrap the biomass in bales with a plastic bandage. According to some authors, these kinds of ensiling could reduce dry matter loses that occurs during filling operations (Bacenetti & Fusi 2015; Rony et al. 1984; Martin et al. 2000; R. E. Muck 2004) because biomass is put in anaerobic condition quickly. However, these techniques usually present higher costs than the bunker silos due to the higher utilization of plastic.

Figure 12: alternative techniques for the ensiling: silobag (At) and silage bales (B)

3.4 Grass pre-treatments

Grass residues are chemically composed by a complex of ligno-carbohydrate matrix made of cellulose, hemicellulose and lignin (de Wild et al., 2009; Li et al., 2015). Cellulose and hemicellulose are biodegradable due to their chemical properties and hence, easily available for several biological processes, such as AD for biogas production (Triolo et al., 2012; Tsapekos et al., 2017) or fermentation for bio-ethanol production (Taherzadeh and Karimi, 2008), while lignin presents a difficult bio-degradability (Beckham et al., 2016).

In order to make these compounds more available for AD, the lignocellulose complex needs to be torn down by the bacteria. This can be facilitated by introducing a pre-treatment step before the digestion (Kumar et al., 2009; P. F. H. Harmsen, 2010; Taherzadeh and Karimi, 2008).

In the last decades, many pre-treatments for biomass have been developed in order to make biomass-streams more digestible and get a higher methane yield. Their aims are to change the characteristics of the biomass and/or increasing the efficiency of the enzymes (Taherzadeh and Karimi, 2008).

Pre-treatment techniques are usually subdivided according to typology of products and methods that are involved. According to this, it is possible to subdivide three kind of pre-treatments: biological, chemical and mechanical.

Biological pre-treatments consist in the adding of bio-compounds or microorganism like enzymes and additive into the biomass to facilitate degradation processes. Several studies revealed that biological pre-treatment can improve the hydrolysis efficiency with the advantage of limited energy consumption and less damage to the environment (Chen et al., 2010; Shi et al., 2009). However, in the current scenario, there are limitations using this strategy for pilot scale process. The first and foremost one is the long incubation time for effective delignification by the bacteria. This can be minimized using suitable microbial consortium. However, there is an urgent need for research and development activities and fine tuning of the process for the development of an economically viable process (Sindhu et al., 2015).

The chemical treatments, instead, consist in treatment of biomass using chemical reactions for disruption of the biomass structure (P. F. H. Harmsen, 2010). Some of the most common chemical treatments consist in the:

- Use of alkaline or acid substances to favour the hydrolysis of the biomass;

- Use of organic solvent with water (Organosolv);
- Oxidant agents to remove lignin.

According to some authors, these kind of processes usually required a high value of energy for their application, so they have to be assessed warmly depending on the type of biomass to treat (Antonopoulou et al., 2015; Michalska and Ledakowicz, 2016). Mechanical treatments consist in the reduction of particle size. The reduction is often needed to make material handling easier and to increase surface/volume ratio. This can be done by chipping, milling or grinding. Recent studies have demonstrated as mechanical treatments can be a good strategy for biogas enhancing, increasing the methane production in an order of magnitude between 15-20% (Popelier, 2011; Tsapekos et al., 2015).

3.5 Grass purification

Grass from litter polluted areas should be cleaned in order to avoid problems inside AD digesters.

Several techniques for the purification of biomasses from metal, plastic and heavy objects are available nowadays (AA.VV., 2014). These derived specially from the composting sector (Figure 13).

Figure 13: Ballistic separator used to purify biomasses

A first solution for the purification is represented by sieves. Two kinds of these machineries are available: rotary and star. Rotary sieves are usually used in composting plants. It consists in a cylindrical sieve that rotates in a drum (Figure 14). Here the heavy fraction does not go through the sieve and comes out at the end of the cylinder while the fine fraction is sieved and goes into the drum where it is intercepted. Conversely, a star sieve consists of parallel placed axles; on every axis, some disks in a star shape are placed. They are mounted so that a star rotates between its two neighbours. All axles rotate in the same direction. The fine fraction falls between the star disks. The star disks to the edge of the sieve transport the coarse fraction. A medium fraction can be separated between the last and the next-to-last axles.

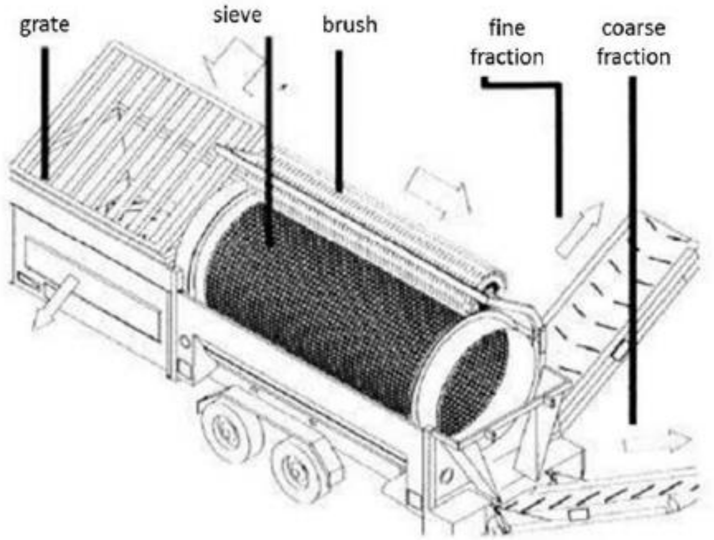

Figure 14 Sieve separator

A second solution consists in the utilization of ballistic separators (Figure 13). This kind of machine separates heavy objects like stones and glass from biomass. Its functioning is based on the difference in weight and hardness of the fractions (Figure 15). When introduced the material collides with a special bouncing plate. The heavy fraction bounces up more and is separated from the light fraction, which falls to the bottom. These machines can be equipped with magnets to separate the iron part of the biomass.

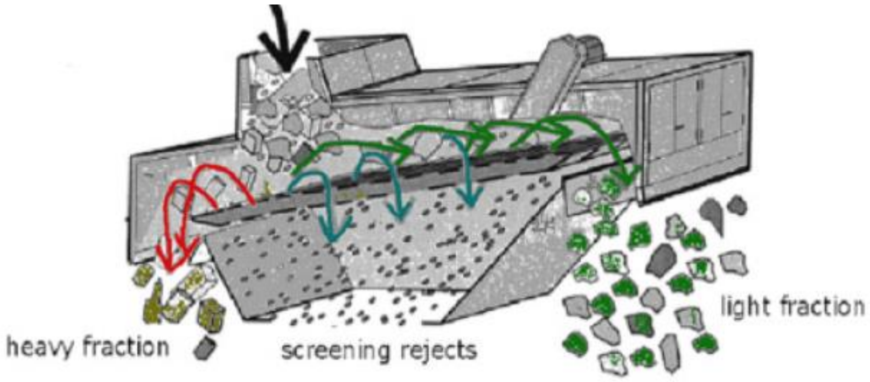

Figure 12: Ballistic separator

Although purification techniques are available when grass quality is ruined by the presence of pollutants, the harvest of grass from non-cultivated lands should interest areas where there is a low presence of pollutants and where can be collected a good quality biomass for AD. However, the integration of a purification phase could increase the overall costs of the process, making the grass unfeasibility from the economic point of view.

3.6 Anaerobic digestion of grass

Grass, thanks to its characteristics, is an interesting feedstock that can be used in the biogas supply-chain (Prochnow et al., 2009).

According to several authors, the potential biogas yield of this biomass is extremely variable, depending on the cutting period, type of grass, geographical position, number of cuttings per month (Table 5). In addition, grass biochemical methane potential (BMP) is influenced by the particle size, use of ensiling additives, and ensiling duration (Nizami and Murphy, 2010; Prochnow et al., 2009; Tsapekos et al., 2015).

Table 5 shows the variability of the biogas yield according some experimental studies conducted in North Europe.

Table 5: Grass BMP depending on the number of cuts

Grass-cuttings	Biogas yield, range (m^3/t_{FM})	Biogas yield, typical (m^3/t_{FM})	References
1-cut	150-220	185	Öchsner, 2005 Prochnow, 2007 Lemmer and Ochsner, 2002
2-3 cut	440-480	460	Öchsner, 2005 Prochnow, 2007 Lemmer and Ochsner, 2002
4-5 cut	330-400	365	Öchsner, 2005 Lemmer and Ochsner, 2002
Golf course	750-790	770	Öchsner, 2003
Public lawns	644		Heintschel, 2012
Public lawns/sport fields (high intensity)	676		Heintschel, 2012

Considering Italian situation, University of Verona conducted some batch biogas trials, showing that typical grass cut and mown in the urban areas the Veneto Region, gave a biogas yield as high as 0.63 m^3/kg_{VS} (equivalent to 150-160 m^3/ton of fresh matter) with a methane content of about 50% (AA.VV., 2014). Other studies conducted in batch trials by the project ProBiTec in Lombardia region, show that grass collected in soccer fields have a biogas yield of about 0,35 m^3/kg_{VS} (equivalent to 80 m^3/t of fresh matter) with a methane content of 45%. Although these data are discordant, considering the expected dry matter content of grass, these values correspond to a biogas productivity in the range of 80 – 150 m^3 of biogas per ton of fresh material. These values could be considered equals half of the 200 m^3 biogas obtained from 1 ton of maize silage (Amon et al., 2007). Therefore, 2 or 3 tons of grass silage can produce the same amount of biogas (and methane) of 1 ton of maize silage. However, to obtain the complete potential yield it is important to consider a long retention time for grass. For this reason, a right configuration of the biogas plant is extremely important in order to obtain the highest energy potential from grass (Nizami and Murphy, 2010).

In this sense, Nizami & Murphy, 2010 compared two different kind of biogas plants for the conversion of grass into biogas, a two stage continuously stirred tank reactor (CSTR) and a sequentially fed leach bed reactor connected to an up flow anaerobic sludge blanket (SLBR–UASB). They found that the first system achieved 451 l_{CH4}/kg_{VS} with a 50-day retention period while the SLBR–UASB achieved 341 l_{CH4}/kg_{VS} with a 30-day retention time. However, several problems on AD plants could be implied when grass is utilized. For instance, grass tends to float upon the fluid surface of the digester, leading an increase of stirring energy. In addition, wrapping of longer grass particles around moving devices can cause failures in operating the biogas plant and an abrasion intensification (Prochnow et al., 2009). To avoid these concerns, grass should be digested in combination with other feedstock that could minimize these problems inside the digesters (Thamsiriroj and Murphy, 2010). A right strategy could involve in the combination of grass with, for example, slurries or other by-products (De Moor et al., 2013).

4. RESEARCH QUESTIONS AND OBJECTIVES

4.1 General objective

The general objective of the research is to valorise grass from uncultivated areas in the anaerobic digestion supply chain.

4.2 Specific objective

From the general objective, specific objectives have been formulated to achieve the main purpose of the thesis. Specifically, they are:

- To assess the potential areas and the biomass availability considering the situation of the Veneto region;
- To define the best technologies for grass mowing, harvesting, logistic and utilization in the economic, energy and environmental aspects;
- To determinate the energy and environmental balance that can derive from grass valorisation in the biogas supply chain.

4.3 Questions

The specifics questions that the research work will try to solve are:

- Which are the best areas and the quantity of this material in the Veneto region?
- Which are the best technologies to manage grass from uncultivated areas?
- Which are the energy and environmental profile of grass valorisation?

In order to fulfil the literature gap and answer to the research questions, the thesis was performed in four different research. The following chapters present the scientific work already published in peer-reviewed journals. Each research aimed to answer the formulated research questions.

In more detail, the references of the chapters are:

Chapter 5) Mattioli, A., Boscaro, D., Dalla Venezia, F., Correale Santacroce, F., Pezzuolo, A., Sartori, L., Bolzonella, D., 2017. Biogas from Residual Grass: A

Territorial Approach for Sustainable Bioenergy Production. Waste and Biomass Valorization 1–10.

Chapter 6) Boscaro, D., Pezzuolo, A., Grigolato, S., Cavalli, R., Marinello, F., Sartori, L., 2015. Preliminary analysis on mowing and harvesting grass along riverbanks for the supply of anaerobic digestion plants in north-eastern Italy. Journal of agricultural engineering. 46(3):100-104.

Chapter 7) Boscaro, D., Sartori, L., Correale Santacroce, F., Marinello, F., Grigolato, S., Pezzuolo, A. 2017. Grass supply chains for biogas production. Comm. Apl. Biol. Scie. 82(4):64.

Chapter 8) Boscaro, D., Pezzuolo, A., Sartori, L., Marinello, F., Mattioli, A., Bolzonella, D., Grigolato, S., 2017. Evaluation of the energy and greenhouse gases impacts of grass harvested on riverbanks for feeding anaerobic digestion plants. Journal of Cleaner Production. In press.

Additionally, two research works focused on the improvement of grass valorisation chain have been added as annex to the thesis. In particular, the references are:

Chapter 11) Brambilla, M., Boscaro, D., Pezzuolo, A., Trabacchin, F., Berti, F., Bisaglia, C., Sartori, L. 2017. Preliminary evaluation of the performances of a purpose designed machine for grass harvesting and pre-processing in orchards, vineyards and uncultivated areas. EUBCE, Stockholm, 12-15 June 2017.

Chapter 12) Boscaro, D., Chiumenti, A., Da Borso, F., Brambilla, M., Bisaglia, C., Sartori, L., Pezzuolo, A. 2017. Composting of different agricultural by-products with raw digestate: preliminary considerations about technical feasibility. EUBCE, Stockholm, 12-15 June 2017.

5. BIOGAS FROM RESIDUAL GRASS: A TERRITORIAL APPROACH FOR SUSTAINABLE BIOENERGY PRODUCTION

Large amounts of residual grass originating from the management of landscape and natural areas are produced in Europe. This material, which is not competing for land use like energy crops, and is only partially recovered for animal feeding, can be profitably used for sustainable bioenergy production. In this study we demonstrated through a GIS based approach that this feedstock can be of some interest for the production of biogas in the Veneto Region, north east Italy, where more than 150 anaerobic digesters are in operation and feedstock availability can be sometime problematic. Specific field trials showed that costs for grass management are around 30 €/t $_{FM}$ while corresponding CO_2 emission for grass handling (cutting, wrapping and harvesting) are 25 kg CO_2/t of grass processed. On the other hand, average biogas productions of some 500–600 m^3 of biogas/t of volatile solids (52–56% methane) should be expected from this residual material. Both treatment costs and biogas yields of residual grass are in line with similar data for some energy crops. The technical, environmental, and economic sustainability for the production of bioenergy through the proposed approach was demonstrated.

5.1 Introduction

Global warming and the necessity to reduce dependency from fossil fuels force society to look for alternative sources for renewable energy production. AD because of its flexibility and capability of producing electric and thermal energy, biofuels (biomethane) and a renewable fertilizer (digestate) can play a major role in the energetic scenario especially in the rural context.

According to the European Biogas Association (EBA, 2015), there are currently more than 14,000 AD plants running in Europe, 80% of which are treating agricultural feedstocks. AD can be a valuable tool for turning waste and residual material into resources at local level, provided that enough biomass is available for running the plants at reasonable economic and environmental costs.

Landscape and waste grass, because of its interesting biomass productivity, in the range 4–8 t dry matter/ha/year (Meyer et al., 2014; Pick et al., 2012; Singh et al., 2010) and because it is not competing with food and feed chains, can be a valid source for feeding AD plants and recovery energy (Singh et al., 2010). Several studies demonstrated the possibility to use grass of different origin for energetic purposes via AD: in particular, those studies focused on grass from landscape management (Pick et al., 2012), meadow grass from nature conservation areas (Meyer et al., 2015; Tsapekos et al., 2015), grassland (Melts and Heinsoo, 2015; Prochnow et al., 2009), grass from urban roadside verges (Meyer et al., 2014; Piepenschneider et al., 2016), riverbanks (Boscaro et al., 2015). Grass biomass, depending on its origin and nature, can be co-treated in farm AD plants together with manure, energy crops and other agricultural residual material (Frigon et al., 2012) or together with biowaste and sludge in industrial AD plants (Hidaka et al., 2013; Kosse et al., 2015). These two situations, namely, agricultural and urban, are clearly distinguished at legislation level in several European Countries, namely Germany, Austria, Italy, and Spain.

Most of these studies focused on the anaerobic conversion of this biomass into methane but only a few considered a territorial approach so to define the available biomass on a given territory and the environmental, energetic, and economic sustainability of the proposed approach (i.e., Melts and Heinsoo, 2015; Pick et al., 2012).

According to literature, use of grass as co-substrate in farm based biogas seems to be particularly favourable. Prochnow et al. (2009) reported about the benefits of using grassland as energy biomass. In fact, grass can be easily harvested and processed for storage (ensilaging) and its biogas yield is in the range 490–540 m^3/kg_{VS}. In this sense it is absolutely similar to some energy crops (triticale, wheat, barley…) but it not requires for fertilization and phytosanitary treatments. Moreover, because of the capability of grassland to act as a carbon storage (70–90 t_C/ha), the use of digestate originated from grass digestion show great environmental benefits. Meyer et al. (2014) showed that the energy returns on energy invested (EROI) for meadow grass treatment in the Danish scenario was in the range 1.7–3.3 and was 2.1–2.8 in the case of roadside grass, demonstrating the sustainability of the approach.

Clearly, when considering the grass originating from roads and railways management, the feedstock quality varies a lot (Meyer et al., 2014; Pick et al., 2012; Piepenschneider et al., 2016). This material generally shows high levels of litter material and needs to be processed before ensilaging or feeding the digesters. Moreover, the presence of heavy metals and other micro pollutants can affect the quality of the final digestate obtained (Meyer et al., 2014; Piepenschneider et al., 2016).

In this study we considered the specific situation of the Veneto Region, north-east of Italy, and calculated the biomass available for biogas generation at a Regional level. Moreover, the territorial distribution of anaerobic digesters and the costs for transportation of mowed grass were taken into account so to verify both the economic and environmental sustainability of the approach.

5.2 Materials and Methods

5.2.1 Experimental Design

In the first part of the study we identified the grass available at territorial level for the Veneto Region, north east Italy, considering both grass coming from the waste sector (roadside verge, urban parks) and grass potentially recoverable in natural areas, grassland, meadows, riverbanks that undergoes to the regulation for agricultural by-products. This distinction it is not only valid for Italy but also in other European Countries like Germany, Austria, and Spain among the others as it derives directly from the EU Directive 2008/98 on waste. Information on wasted grass were directly collected from Regional databanks while the grass potentially recoverable from landscape was calculated considering the territorial specificity (use of land) of the Region. The biomass globally available was therefore determined. At the same time, anaerobic trials were carried out on grass samples of different origin (public parks and natural areas) to define the biogas potential for the two streams.

These information were then combined and a map indicating the biomass availability at territorial level was defined and compared with the territorial distribution of AD plants. The costs for logistic as well as their environmental impact were also considered so to define the global sustainability of the proposed approach.

5.2.2 Grass Samples and Biogas Potential

Grass samples were grabbed both in public parks in Verona (45.40N, 10.99E) and natural areas in Valle Vecchia, Caorle, Venice (45.63N, 12.95E) an experimental farm managed by Veneto Agricoltura. The average rainfall for Verona is 783 mm/year, while the average temperature is 13.5 °C. With specific reference to ValleVecchia the average rainfall is 893 mm/year while the average temperature is 11.4 °C. Samples considered in this study were collected in early summer (June) when grass in landscape, riverbanks, roads verge as well parks and gardens is mowed. Grass mowed in Vallevecchia was cut at a size of 0.1 and 1 m before balling it. As a normal procedure, this material was left in place for 48 h before collection so to reduce the water content, thus mass and volume to be transported. Samples of grass in all the different conditions, namely, fresh, dried and cut at different size (0.1 and 1 m), were taken. The same material underwent also to an ensilaging process without enzymes addition (constipation in anaerobic conditions) so to verify the effect of ensilaging on biogas production. Also in this case the different samples were taken and characterized in terms of chemical–physical characteristics and biogas potential.

Analysis for dry and volatile matter, COD, nitrogen and phosphorus content were carried out according to the Standard Methods for Analysis. Anaerobic batch tests for the evaluation of biogas production (BMP test) were carried out following the methodology suggested in Angelidaki et al. (2009). Biogas was determined in batch trials carried out in triplicate using 1 L reactors, 0.5 L working volume, sealed with chlorobutyl caps after nitrogen injection for anaerobic conditions.

The inoculum used in these trials was obtained from a farm anaerobic digester working in mesophilic conditions (37 °C) fed with cow and chicken manure, and mix of energy crops (maize silage, sorghum silage, triticale silage) and straw. The inoculum was filtered at 2 mm in order to remove coarse material and left at 37 °C for 1 week to reach endogenous conditions. The solids content after acclimation was 24.3 g/kg, 73% of volatile solids .

The volume of generated biogas was determined by water displacement while its composition was determined using a Geotech Biogas 5000 (Geotechnical Instruments®, United Kingdom) determining methane percentage and H_2S concentration.

5.2.3 Data Collection on Grass Availability

The global quantity of available biomass was calculated taking into account both the quantity of grass produced in urban areas and along roads and rails, which is classified as a waste, and the grass coming from rural areas and landscape and water courses management which is considered a residual material available for feeding purposes.

With specific reference to wasted grass coming from urban areas all companies involved in waste management are obliged to upload the data regarding the collection of different waste streams into a Regional portal managed by the Environmental Protection Agency of the Veneto Region (ARPAV). On the website of ARPAV (http://www.arpa.veneto.it/rifiuti/htm/banca_dati_ru.asp) it is possible to find data of different types of collected urban waste, reported in tonnes per year and per municipality. With specific reference to grass, this is collected together with clippings, branches, and catalogued under the European Waste Code 20.02.01. The data with code 20.02.01 for the year 2012, referred to the 581 municipalities of the Veneto Region, were collected and then processed. As a first step the data on green waste were transformed into “grass”, removing the mass referred to clippings, branches and other lignocellulosic materials. Based on the information passed by waste management companies, it was roughly estimated that grass represented 90% of the waste with code 20.02.01.

As for the grass potentially recoverable in rural areas or deriving from landscape and water courses management, this was estimated by use of regional maps defining the use of land. The number of hectares covered of grass was determined and a specific yield of 6.5 tons of dry matter/hectare/year was determined (see below). In particular, the grass potentially recoverable in rural areas or deriving from landscape and water courses management, was estimated by use of GIS. The Veneto Region has one of the most detailed map regarding the use of land: starting from the database G.S.E. Land—Urban Atlas then improved by using satellite imagines SPOT 5 (multispectral band 10 m, panchromatic band 2.5 m) and integrating the data with several different databases (TeleAtlas, Roads Map, Numerical Regional Chart, DEM, and forestry maps), a detailed map for the “Land Use” for the Veneto Region was defined. This is a 1:10.000 map with a thematic area with detail of 0.25 ha and 5 levels of “land use” based on the Corine Land Cover nomenclature. The map can be found at http://idt.regione.veneto.it/app/metacatalog/getMetadata/?id=551&isIe=false.

Through this exercise we have therefore individuated the areas (in hectares) dedicated to natural areas, meadows, water courses banks and the associated grass production. This approach is similar to that used in similar studies carried out in Germany (Pick et al., 2012; Piepenschneider et al., 2016). In order to consider a reliable amount of usable grass we then applied a 25% capture rate of this grass available for AD (the rest is normally left in place because of handling costs) (Pick et al., 2012; Piepenschneider et al., 2016).

5.2.4 Energy Efficiency of Grass Valorisation

The energy balance of grass use for AD was calculated using the gross energy requirement method (Pezzuolo et al., 2014; Sartori et al., 2005). In this approach the energy inputs for grass moving, transportation, AD, and digestate spreading and treatment, were accounted (see Table 6). In addition, the energy produced over energy input, a ratio that estimates the energy return on energy invested (EROEI) (Arodudu et al., 2013), was calculated according to Eq.:

$$\text{EROEI} = \text{output energy} / \text{input energy} \qquad (1)$$

The energy output was estimated considering the conversion of grass into methane. It was assumed that methane has an average energy content of 39 MJ/m^3 (Meyer et al., 2015; Prade et al., 2012) while the grass methane yield was obtained by the BMP trials.

On the other hand, the energy inputs include both the direct, e.g. fuel consumptions, and indirect, e.g. machineries manufacturing, inputs required for the grass recovering and digesting operations (Berglund and Börjesson, 2006; Beatrice M. Smyth et al., 2009). The operations that are required to recovery and convert grass into biogas were divided in three phases: grass recovery (mowing, harvesting, logistic operations and grass storing), biogas conversion (grass purification, plant feeding and AD process) and digestate management (treatment and spreading)

Concerning the first-phase, for the mowing and harvesting processes, three operative scenarios were considered:

1. if grass came from the urban waste management, no inputs was taken into account because these operations are performed independently and often they are accomplished at a household level;

2. if grass came from riverbanks or roadsides a combined mowing-harvesting system was considered as proposed by Boscaro et al., 2015;

3. if grass came from natural and rural areas a separate mowing and harvesting system with a higher field capacity than the previous scenario was set.

For each scenario, two different logistic distances were computed: a shorter distance of about 5 km and a higher distance of about 30 km, the limit distance to collect biomass for bioenergy purposes. The energy values were calculated according to those proposed by Boscaro et al. (2014).

When calculating the recovery of grass it was also considered if grass comes from riverbanks, roadsides, natural and rural areas because while grass from waste management is available on a daily base for the AD plants, grass from these areas is collectable only in some specific periods during the year. Therefore, a silo is required in order to make grass available for AD plants during the year. The energy inputs required for these operations were calculated according to those proposed by Pezzuolo et al. (2016).

The direct and indirect energy requirement for biogas conversion of grass was analysed considering that grass is typically only 10% of the feedstock in a 1 MW plant. The value of 10% was chosen because of the experiences of some digesters treating grass (Boscaro et al., 2015; Clemens et al., 2006). Moreover, a cleaning process was considered for grass from urban waste management, roadsides and riverbanks because grass could be polluted by materials that can damage pumps and mixers of the AD plants such as plastics residues, cans, wood, etc.

The energy amounts for the construction of digesters and storage tanks, and the energy required for the heating, pumping and mixing of the digesters were assumed as described by other researchers (Berglund and Börjesson, 2006; Pöschl et al., 2010; Prade et al., 2012).

An energy value was also computed for the management of the digestate that is produced as resulting material of the AD process. If grass comes from the waste management and areas such as roadsides a further treatment operation (composting) is necessary because digestate of waste is still a waste according to the Italian laws.

Again, the spreading distance of the resulting product of the process has been assumed close to the AD plant.

Table 6 reports the energy input for the different operations regarding grass mowing and the relative logistic, AD, and digestate treatment.

Table 6: Energy inputs required for the three operational phases

Operations	Energy input	Unit	Sources
Grass recovery phase			
Mowing and harvesting [b]	799	MJ/t	Boscaro et al. (2015)
Mowing and harvesting [c]	435	MJ/t	Boscaro et al. (2015)
Logistic	35	MJ/t · km	Beatrice M Smyth et al. (2009)
Storing (ensiling in horizontal silos) [bc]	135	MJ/t	Arodudu et al. (2013)
Biogas conversion phase			
Cleaning of grass [ab]	28	MJ/t	Own calculations
Plant feeding and biogas conversion (electricity and heating)	200	MJ/t	Clemens et al. (2006); Triolo et al. (2012)
Construction of AD plant and digestate storage tanks	135	MJ/t	Prade et al. (2012)
Digestate management phase			
Waste treatment: composting [ab]	510	MJ/t	Micolucci et al. (2016)
Loading, transport and spreading	75	MJ/t	Gerin et al., (2008)

[a] Grass from urban waste management

[b] Roadsides and riverbanks

[c] Natural and rural areas

5.3 Results and Discussion

5.3.1 Grass Characteristics and Biogas Potential

The basic chemical–physical characteristics of collected grass samples from public parks and natural areas and their biogas potential were determined.

Grass from public parks is mowed often so grass is fresh and the lignin content is low. As a consequence, the corresponding biogas production was some 0.60–0.65 m^3/kg_{VS} (see Table 7). However, values up to 0.7 m^3/kg_{VS} were also observed in similar studies (Triolo et al., 2012).

As for the samples coming from natural areas (Vallevecchia, Caorle) also ensilaging was considered in this study.

As described in the “Materials and Methods” section, grass after mowing was cut at different size (0.1 m and some 1 m) and left in place for 48 h. After that time, grass was harvested and balled. The same samples underwent ensilaging in anaerobic conditions so to verify the effect of this process on the main properties and energy content of grass. The complete set of samples was analysed and the main results are shown in Table 7. The dry and volatile matter content was similar for grass samples of no ensiled grass of size of 0.1 or 1 m. Similar results were also observed for ensiled samples. The dry matter content was around 390 g/kg for samples of 1 m and some 460 g/kg for samples of 0.1 m. Volatile matter was 90% in all cases. On the other hand, when considering samples left in place for 48 h after mowing, the dry matter content rose up to 900 g/kg because of water evaporation. This is a fundamental parameter for transportation since the amount of grass to be transported and its energy density are largely improved. The COD content is in line with the dry matter content being carbohydrates the main constituent. Nitrogen and phosphorus were at levels of 3–4 g_N/kg and 0.4–0.5 g_P/kg, respectively. These values are similar to those of other vegetable substrates like energy crops (Frigon et al., 2012; Prochnow et al., 2009) and can be limiting for the anaerobic process. That is why grass can be only a co-substrate where other substrates like manure are present in the feedstock so to balance the presence of macro- and micro-nutrients (Micolucci et al., 2016).

The biogas potential values increased in the trials with dried grass samples after 48 h on fields. With specific reference to biogas production the levels were in the range 0.52–0.58 m^3/kg_{VS}, with a methane concentration of 53–55%. When considering ensiled samples of 0.1 and 1 m the dry matter content was very similar: concentrations of 382 and 462 g/kg were observed, 90% volatile matter. The samples left in place for 48 h showed dry matter levels of 916 g/kg. Also in this case COD showed a similar level compared to dry matter. Values for biogas potential were slightly higher compared to those observed from no ensiled samples exceeding levels of 0.6 m^3/kg_{VS} in all cases methane being at 55% on average.

All these results are in line with data reported in literature which are however quite broad. Prochnow et al. (2009) reported a considerable number of data for biogas production from grass species collected in different seasons in some European countries. Reported biogas values were in the range 0.299–1.080 m^3/kg_{VS}. It was emphasized in that study that grass biogas potential can be influenced by climate, latitude, environmental conditions as well as seasonal variations.

The profiles of the BMP tests (Figure 16) showed that trials on “fresh” samples (Figure 16a) gave similar results (between 0.5 and 0.6 m^3/kg_{VS}) no matter the cut size, drying and the ensilaging process. The biogas production rate was however quite variable given that material of different length maintains and protects the liquor material in a different manner: material cut at 0.1 m, because of its larger specific surface for enzymatic attack (Mansfield et al., 1999), gave a faster response compared to material cut at 1 m (higher specific gas production (SGP) after 30–40 days) but with a lower ultimate SGP (90 days). On the other hand, when considering ensiled material differences were smoothed and the SGP values were similar on all the tested conditions and around 0.6 m^3/kg_{VS} (Figure 16b).

So, despite the number of variables to be taken into account (latitude, climate, chemical composition…), it turned out that results were quite similar in all trials. This is also because in our study samples originated in the same Region, with similar climate conditions. Comparable results can be easily found in literature: Dandikas et al. (2015) presented the data regarding the SGP of more than 40 different grass species collected in different seasons. The average SGP reported in the study gave a value of 659 l/kg_{VS} with 54% methane content, values very similar to those reported in our study.

Also Nizami et al. (2012), who performed biogas potential trials for different grass species, reported that the average biogas potential was similar for each grass specie. They argued that the more easily biodegradable part is the one associated to liquor and humor and this is quite conservative in different grass species. For this reason, the biogas potential was often similar for the different samples. Overall, considering our results and the literature, it turned out clear that the biogas potential for grass can be considered similar to the one of other vegetable materials and crops with an average value in the range 0.5–0.6 m^3/kg_{VS}. On the other hand, compared to other substrates rich in sugars, like maize silage, the time requested for the recovery of biogas, thus energy, from grass can be as high as 50–60 days.

Noticeably, the average value observed in our study for grass from natural areas, some 0.560 ± 0.021 m^3/kg_{VS}, was similar to the one reported in the study of Kosse et al., (2015), where the authors reported an average SGP of 0.544 m^3_{biogas}/kg_{VS} with a methane percentage of 59%.

In that study a number of different grass samples coming from different environments like forest, pastures and green urban areas were considered.

These results are however in contrast with those reported in Triolo et al. (2012) where the SGP was associated with the lignin content and average predicted values were considerably higher (up to 740 l/kg_{VS}) than those reported in this study and other cited papers where data derived from experimental trials.

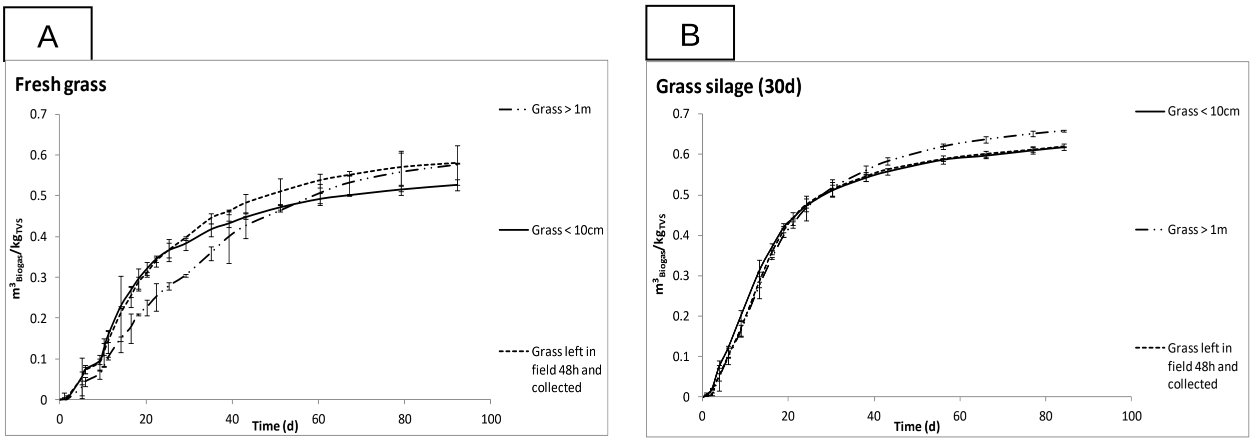

Figure 16: Biogas production of different samples of grass of different size, fresh (A) and after 30-day ensilaging (B)

5.3.2 Biomass Availability and Potential Energy Recovery

As described in "Data Collection on Grass Availability" section, we considered an average production of grass equivalent to 6.5 ton dry matter/ha/year, a value very robust for the Veneto Region and similar to other data present in literature also for other European Regions with similar climate conditions (Kosse et al., 2015; Pick et al., 2012). Considering the hectares of land classified as landscape, natural area or river banks, we determined the total grass production. The potentially recoverable grass (urban and rural) in ton DM per year was calculated as described in the material and methods section. In particular, a 25% capture yield was considered for this material. These values were associated with the shapefiles of the municipalities of the Veneto Region. The resulting map of grass availability is shown in Figure 17. The productivity is divided into seven levels: to give an example, a productivity of 1,000 ton $_{DM}$/year corresponds to some 3,000 ton fresh matter/year, or 9 ton/day of available grass biomass. This quantity can be considered available for AD in a given municipality. Therefore, in the same map, also the location of the anaerobic digester is geo-referenced so to identify the match between high productivity areas and presence of anaerobic digesters. There are currently 13 AD plants for biowaste treatment and 140 agricultural AD plants running in the Veneto Region. In this sense, and considering that the average size of anaerobic digesters in the Veneto Region is larger than 600 kW, only a grass production >1.800 ton DM/year (pale green) can be of some interest for reasonable bioenergy production.

It turns out clear from the reported map that recoverable grass is extremely low in mountain areas in the northern part of the Region but also in the flat central and southern part of the Region where most of the digesters are located. This is in fact a rural area where land is used for crops cultivation or livestock husbandry, therefore land with different uses is very limited. In these specific cases the amount of collected grass is typically lower than 500 ton $_{DM}$/year and therefore of scarce interest for sustainable bioenergy production. On the other hand, the main cities in the central flat area, namely Venice, Padua, Vicenza, Treviso, Rovigo and Verona, show the greatest collection yields for wasted grass: typical values of collection of grass are >500 tons dry matter (DM)/year. This result is related to the presence of parks and gardens in these cities. Moreover, in Venice, Treviso and Villafranca (Verona) international airports are present which can partially contribute to grass generation.

Other areas with relatively high yields (generally >500 tons DM/year) are touristic areas located along the Adriatic coast (Venice and Rovigo provinces) and the Garda lake (Verona province) where a number of camping places are present.

Overall, Figure 17 shows that there is only a limited number of situations where a relatively high presence of grass is near an anaerobic digester (green dots). However, in some cases digester are located at distances lower than 30 km from high productivity areas and can be of some interest for sustainable biogas production.

We carried out a series of interviews with operators of the sector and found out that there is a limited interest for grass originating from urban areas and roads which should be accepted in the digesters for organic waste treatment: in this material, in fact, the presence of inert material (stones, plastic, cans…) can be important and a dedicated preparation step should be implemented in the plant. Moreover, the biogas potential of the fresh material is not very interesting of compared with that one of municipal organic waste (Palmowski and Müller, 2003).

On the other hand, there is a strong interest for such material in the agricultural sector: the grass originating from rural areas is in fact clean and, after ensilaging, can be used in the same way of dedicated energy crops. Moreover, its biogas potential, although lower than the one for maize, is at least of comparable magnitude.

Grass can be therefore an interesting feedstock in substitution of energy crops provided it comes from relatively low distance and could be recovered at costs lower than those determined by energy crops production. Grass should be not considered as an additional feedstock for farm based anaerobic digesters but as a partial substitute of other biomasses like energy crops in the co-digestion with manure: the operational conditions in terms of organic loading and retention time remain therefore similar, and the same is for the nutrients balance.

In general terms, grass is not thought as the single feedstock for AD but, on the contrary, if after mowing and harvesting it is ensiled, it can be used daily like any other energy crop but avoiding any competition for land use. Clearly, the distance of the closest digester is the limiting step, but in such a Region, and given the high presence of AD plants, this is not the main bottleneck.

Considering the grass potentially collectable in the landscape management in rural areas or in water courses management, equivalent to 495,000 ton wet weight or 198,999 ton dry matter/year, which can be used in the 140 AD farm plants, and considering a specific biogas production of 500 m^3/ton_{DM} it can be calculated that some

100.000.000 m^3 biogas/annum can be generated. This is equivalent to some 220.000 MWh of electric energy (33% yield in CHP). This can cover the energy use of some 68.000 families (calculated on the basis of an average use of 3.200 kWh/annum per a 3-people family). On the other hand, some 50 million m^3 of biomethane for the automotive sector can be generated with more than 90% reduction in CO_2 emissions (4–5 g_{CO2eq}/MJ fuel).

Table 7 – Chemical physical characteristics and biogas potential of grass samples of different size

Fresh grass			
	Fiber > 1 m	**Fiber > 10 cm**	**48h left in place**
Biogas, m^3/kg_{VS}	0.576 ± 0.049	0.526 ± 0.014	0.580 ± 0.001
Dry matter, g_{DM}/kg_{FM}	394 ± 28	468 ± 33	906±63
Volatile matter, g_{VS}/kg_{FM}	363±25	418±29	829±58
Organic matter, g_{COD}/kg_{FM}	382 ± 26	453 ± 31	878 ± 64
Nitrogen, g_N/kg_{FM}	3.86 ± 0.23	4.59 ± 0.32	8.88 ± 0.56
Phosphorus, g_P/kg_{FM}	0.43 ± 0.03	0.51 ± 0.03	0.99 ± 0.07
Grass silage (30 days)			
	Fiber > 1 m	**Fiber < 10 cm**	**48 h left in place**
Biogas, m^3/kg_{VS}	0.659 ± 0.002	0.618 ± 0.008	0.619 ± 0.002
Dry matter, g_{DM}/kg_{FM}	382 ± 27	462 ± 32	916 ± 64
Volatile matter, g_{VS}/kg_{FM}	354 ± 25	417 ± 29	833 ± 58
Organic matter, g_{COD}/kg_{FM}	371 ± 31	448 ± 28	888 ± 65
Nitrogen, g_N/kg_{FM}	3.75 ± 0.32	4.53 ± 0.25	8.98 ± 0.57
Phosphorus, g_P/kg_{FM}	0.42 ± 0.03	0.50 ± 0.03	1.00 ± 0.06

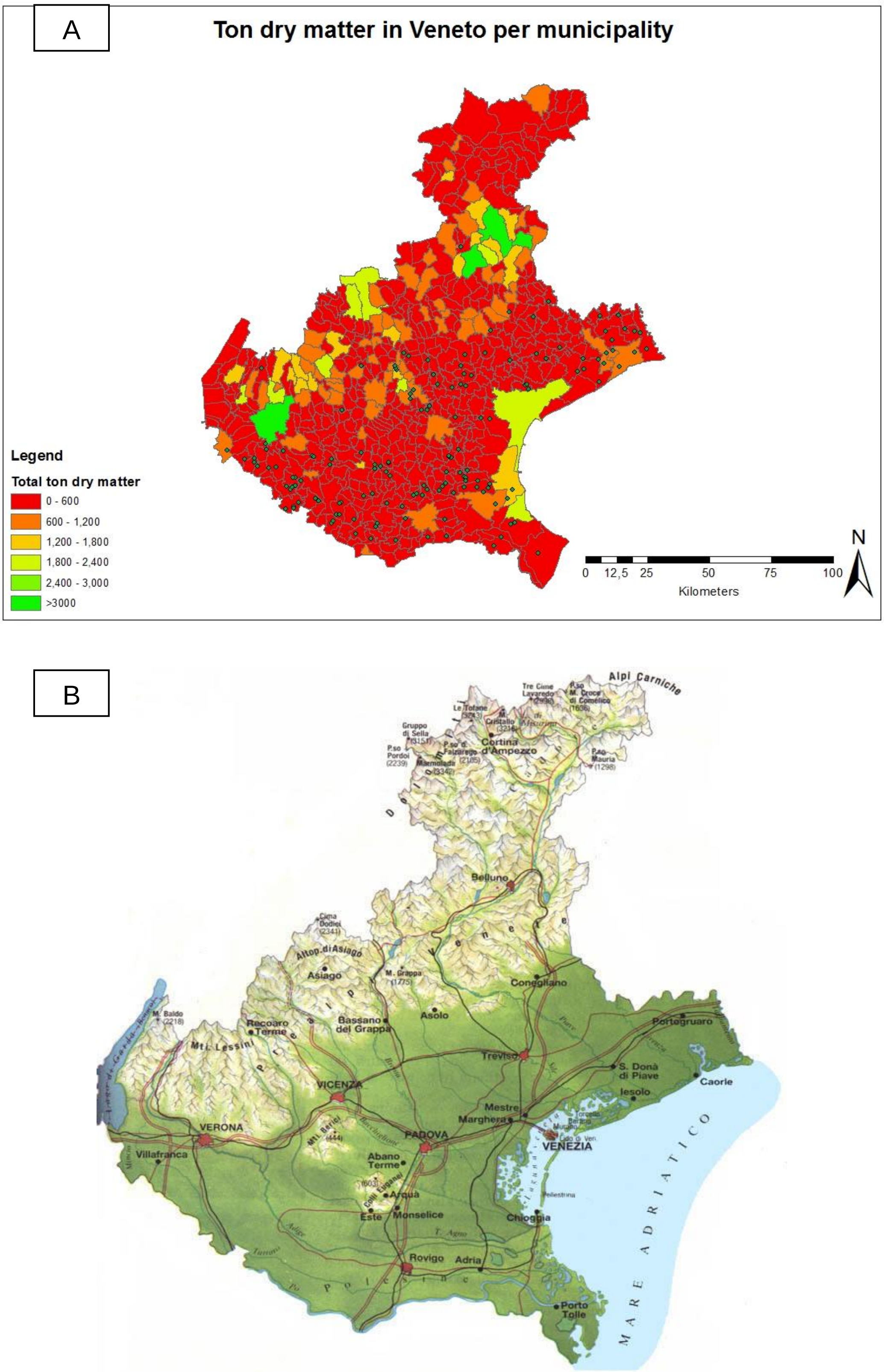

Figure 17: Dry matter distribution and AD plants location in the Veneto Region (A) and physical map (B)

5.3.3 Energy Efficiency of Grass Valorisation

Table 8 and Figure 18 report the energy balance and the influence of each operation over the total energy input. In all the considered scenarios, grass presents a positive net energy gain, highlighting also a positive energy return on energy invested. Although EROEI index was not particularly high considering other biomasses such as maize (Boscaro et al., 2017), greater results were achieved in the scenarios where waste grass and grass from natural and rural areas were treated. In this case, when the grass was collected at short distance from the biogas plants, the EROEI ratio was about 4 proving an interesting convenience for collecting grass. On the other hand, the EROEI in the other scenarios was approximately about 2, anyway positive.

With the exception of the scenario where waste grass collected at short distance was treated, as shown in the picture of Figure 18, grass recovery operations were the input factor that most affected the total energy efficiency. In fact, more than 50% of energy input was influenced by these operations. In particular, the transport distance seemed to be the parameter that more impacted the grass recovery inputs. Therefore, the transport distance should be as low as possible in order to reduce the energy inputs.

Systems that can reduce the transport volumes like round baling or trailers that push-off the product could improve the energy efficiency of the logistic operations. This issue was also confirmed by an energetic and economic evaluation of grass handling performed by Boscaro et al. (2014).

The study showed average energetic requests of 450 MJ/t of handled material (cutting, wrapping and harvesting) for a corresponding CO_2 emission of 25 kg_{CO_2}/t and an average cost of 33 €/t of collected material, confirming the feasibility of the proposed approach when limited distance from anaerobic digesters should be covered, confirming the interest for such a solution (Schattauer et al., 2011).

Another important parameter that affected the energy efficiency of grass was digestate management. The composting treatment, which is necessary when treated grass is considered as a waste, clearly caused an increase of energy requirements. As consequence, no-polluted areas should be preferably considered and could be more interesting under the energy aspects.

However, a clear legislation that establish when grass is considered as a by-product rather than a waste should solve definitely this problem, giving the possibility to identify which areas of the territory should be utilized for the grass recovery.

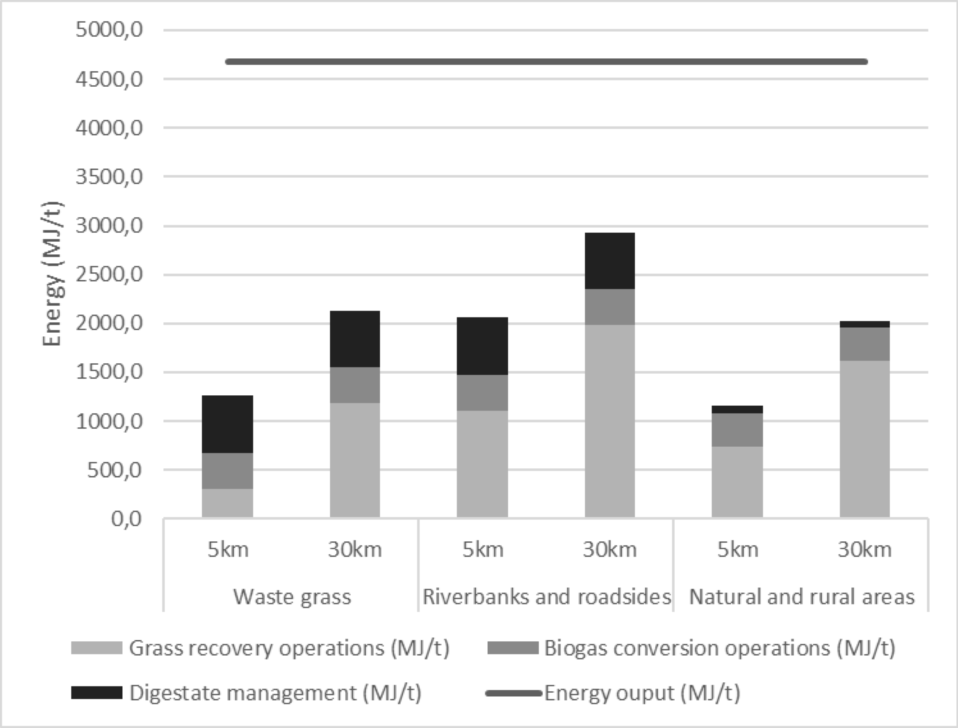

Figure 18: Influence of the several operations over the total energy input

Table 8 - Energy balance of grass energy valorisation

	Urban Waste management		**Riverbanks and Roadsides**		**Natural and Rural Areas**	
	5 km	**30 km**	**5 km**	**30 km**	**5 km**	**30 km**
Energy output (MJ/t)	4,680	4,680	4,680	4,680	4,680	4,680
Energy input (MJ/t)	1,258	2,133	2,057	2,932	1,155	2,030
NEG (MJ/t)	3,422	2,547	2,623	1,748	3,525	2,650
EROEI	3.7	2.2	2.3	1.6	4.1	2.3

5.4 Conclusions

The study showed the potential of using part of the grass produced in natural conservation areas, landscape and riverbanks management and in the waste management sector within the Veneto Region for bioenergy production. It was shown that this can be of interest for the agricultural sector in farm based digesters. Results revealed that a good biogas production, typically in the range 500–600 m^3/ton of volatile solids, can be reached: these yields when associated with a large availability of biomass and the presence of digesters at relatively low distance (<30 km), open the opportunity for a really sustainable bioenergy production both from an economic and environmental point of view.

As for the energy recovered on energy input (EROI), this figure resulted > 1 in all the tested scenarios showing the potential of this approach.

6. PRELIMINARY ANALYSIS ON MOWING AND HARVESTING GRASS ALONG RIVERBANKS FOR THE SUPPLY OF ANAEROBIC DIGESTION PLANTS IN NORTH-EASTERN ITALY

The increasing demand of vegetal biomass for biogas production is causing competition with food production. To reduce this problem and to provide new opportunities it is necessary to take into consideration different kinds of vegetable biomass that are more sustainable. Grass from the maintenance of non-cultivated areas such as riverbanks has not yet been fully studied as a potential biomass for biogas production.

Although grass has lower methane potential, it could be interesting because it does not compete with food production. However, there is a lack of appropriate technologies and working system adapted to these areas. In this paper, different systems that could be available for the mowing and harvesting of grass along riverbanks have been preliminarily assessed through the evaluation of the field capacity, labour requirement, economic and energy aspects. The splitting of the cutting and harvesting phases into operations with different machinery seems to be the best system for handling this biomass. However, these solutions have to take into consideration the presence of obstacles or accessibility problems in the harvesting areas that could limit the operational feasibility and subsequent correct sizing.

6.1 Introduction

The intensification of biogas plants is arousing concern about the sustainability of their supply chain (Crutzen et al., 2007). The recent interest in cultivating energy crops on arable lands (Amon et al., 2007) has increased the competition between food and non-food products (De Moor et al., 2013; Müller et al., 2008; Tilman et al., 2006; Timilsina et al., 2011; Triolo et al., 2012). As a consequence, there is the necessity to verify the possibility of using alternative biomass sources for the production of methane by AD (Thompson and Meyer, 2013).

The competition with food could be reduced through the exploitation of feedstock from non-cultivated areas. In this respect, grass from marginal lands could be an important source in order to produce more sustainable energy (McKendry, 2002; Molari et al., 2014). According to different authors (Blokhina et al., 2011; Hensgen et al., 2011; Shi et al., 2013; Thompson and Meyer, 2013), the main reasons for using grass as biomass source for methane production are: i) no direct production costs; ii) no competition with food production; and iii) reduction of landscape management costs. Nonetheless, the short harvesting period, the physical limitations and the storage and energy conversion sites location are critical constraints (Gunnarsson and Va, 2010; Rentizelas et al., 2009). In particular, grass as biomass source for methane production needs to be mowed and harvested at the appropriate maturation phase because of the later accumulation of lignin and hemicelluloses (Lindsey et al., 2013). These compounds have a strong influence on the degradation process during AD (P. F. H. Harmsen, 2010; Taherzadeh and Karimi, 2008).

These concerns can be minimised by identifying suitable technological solutions for the mowing and harvesting. According to some authors, the technologies for grassland would consider the use of mowers or shredders for the cutting, and self-loader wagons or round balers for the successive harvesting, or machines like self-propelled forage harvesters (Berg et al., 2006; Hogan, 2007; Prochnow et al., 2009). All these kinds of machines can provide a mechanical pre-treatment that reduces the size of the grass, which is a fundamental parameter for methane production and for the ensiling process (Sharma et al., 1988). However, it is important to consider that in other areas like riverbanks or roadsides, it is fundamental to assess appropriate mowing and harvesting technologies because of the presence of physical obstacles that can restrict the access for the machineries and reduce the efficiency of the whole system. To achieve this, a preliminary evaluation of some available mowing and harvesting systems in non-cultivated areas could help to identify the most appropriate technologies and working systems.

Again, the economic and energy advantage of exploiting grass as biomass source in Italy has not been carefully assessed compared to Central Europe where grass for methane production is already seen as a viable option (Gunaseelan, 2007; Pick et al., 2012; Prochnow et al., 2009; DLG, 2012; Weiland, 2010), even its potential can only be achieved when the harvesting, transport and processing are cost-effective (Blokhina et al., 2011).

This paper presents a preliminary analysis on the available technologies for the mowing and harvesting of grass in non-cultivated areas such as along riverbanks in north-eastern Italy, in order to compare different mowing and harvesting systems from an operative, economic and energetic point of view.

6.2 Materials and methods

6.2.1 Machines and working systems

By preliminary surveys of operators working in north-eastern Italy and of national mowing and harvesting machinery manufacturers, different types of machinery were identified as adapted for use in grass mowing and harvesting along riverbanks (Tables 9 and 10). For each machine, the hourly costs were calculated according to the methods proposed by ASABE (ASABE, 2011, 2007). The number of working-hours per year were computed taking into account that the number of working days per year amounts to about 80 days/year, assuming other uses for the tractors during the rest of the year. The lubricants and fuel consumptions were assessed according to the ASABE standards (ASABE, 2011). Fuel cost was fixed at 0.90 €/L (subsidized price).

According to a questionnaire in the north-eastern Italy in 2014, the average value of interest rate for these type of machines was approximately 3% whereas the labour costs was 14.5 € /h.

The number of passages was used to classify the mowing and harvesting systems for grass on riverbanks (Table 11). According to the different types of machines reported in Tables 1 and 2, the likely systems can be classified according to the number of operations and as a consequence the number of machine passages for mowing and harvesting the grass, as also proposed by Salter et al. (2007). The mowing and harvesting systems identify 4 types of combined mowing equipment (shredding-vacuum self-loader; shredding-wrapping; mowing; chopping-wrapping); for systems 2, 3 and 4, two types of harvesting equipment (a and b) are selected. Systems 3a and 3b require the grass to be wrapped after mowing for the following harvesting phase. Each mowing and harvesting system differs on the working width and its flexibility under different operative conditions. When the arm brush cutter is used (systems 1 and 2) the grass can be more easily managed than with the use of single mowers or shredders, also when there are physical obstacles on the riverbanks such as linear barriers. When after the mowing operation the grass is stockpiled along the riverbanks, systems 2b, 3b and 4b seem to be the most appropriate; instead the use of the round-baler in systems 2a, 3a and 4a considerably reduces the harvested volume in pressed bales and therefore increases the efficiency of the logistics (Cundiff, 1996). However, it is necessary to take into account that the utilisation of round balers is possible only when the accessibility along riverbank is adequate to the machine width.

Table 9: Main characteristics and economic values of the most common tractors currently used for mowing and harvesting grass on riverbanks

n.	Tractors	Mass	Estimated life	Annual usage	Purchase value	Hourly cost
		(kg)	(h)	(h)	(€)	(€/h)
1	Tractor (110-120 kW)	6,370	8,000	600-800	75,000	53
2	Tractor (85-95 kW)	5,200	8,000	600-800	60,000	45
3	Tractor (70-80 kW)	4,347	8,000	600	45,000	39
4	Tractor (40-50 kW)	3,200	6,000	400	28,000	32

Table 10: Main characteristics and economic values of equipment considered for mowing and harvesting grass

n.	Equipment	Work length	Mass	Estimated life	Annual usage	Purchase value	Hourly cost
		(mm)	(kg)	(h)	(h)	(€)	(€/h)
5	Arm brush cutter with vacuum self-loader equipment	1,250	2,500	2,000	300	30,000	24
6	Front disc mower	2,000	550	2,000	200	6,000	10
7	Rear disc mower	2,200	650	2,000	300	7,000	10
8	Front flail mower	1,800	700	2,000	200	4,500	4
9	Rear flail mower with tedder	2,200	900	2,000	300	15,000	15
10	Rotary rake for levees	2,600	500	2,000	200	4,000	8
11	Round baler with wrapping system	2,000	3,500	2,000	300	50,000	38
12	Self-loader wagon (load capacity 40 m^3)	2,000	5,000	2,000	300	40,000	33
13	Trailer (load capacity 18 m^3)		4,100	3,000	300	20,000	10

Table 11: Potential mowing and harvesting systems for grass on riverbanks

	1st Passage		2nd Passage		3rd Passage	
Mowing and harvesting systems	**Operation**	**Machines used ***	**Operation**	**Machines used ***	**Operation**	**Machines used ***
1	Shredding-vacuum self-loader	2 – 5 – 13				
2a	Shredding - wrapping	1 – 5 – 8	Baling with wrapping	2 - 11		
2b	Shredding - wrapping	1 – 5 – 8	Harvesting	3 - 12		
3a	Mowing	2 – 6 – 7	Wrapping	4-10	Shredding - Baling with wrapping	2 - 11
3b	Mowing	2 – 6 – 7	Wrapping	4-10	Harvesting - Shredding	3 - 12
4a	Chopping - wrapping	1 – 8 – 9	Baling with wrapping	2 - 11		
4b	Chopping - wrapping	1 – 8 – 9	Harvesting	3 - 12		

*The types of the machinery are numbered according to the listing in Tables 1 and 2

Therefore, larger riverbanks without obstacles that restrict the access can be the best condition for the harvesting operation with round balers.

6.2.2 Costs balance

To calculate the unit costs of the grass, the following equation was used:

$$C = \frac{\sum Su}{Co \times p}$$

C= Unit cost of the operation (€/t) *(2)*

∑Su= Sum of the hourly costs of the tractors and equipment involved in the system (€/h)

Co= Field capacity (ha/h)

p= Grass yield (t/ha)

The field capacity of each mowing and harvesting system (reported as time unit hour) was obtained through field surveys on working time and the idle time of the single operations. Grass yield was assumed, on the basis of previous experiments (Elsäßer, 2001, 2003), at 6 t/ha (fresh matter) per cut, with moisture content ranging between 75 and 80%.

6.2.3 Energetic and CO_2 analysis of mowing and harvesting operations

The energetic analysis was evaluated by using the gross energy demand method (Pezzuolo et al., 2014; Slesser and Wallace, 1981), also including the energy value related to labour (Balimunsi et al., 2012; Sartori et al., 2005). Table 12 summarises the coefficients used, while the values of the mass, fuel consumption, and labour were based on those reported in Tables 9, 10 and 13.

The direct CO_2 emissions were computed from the average fuel consumption of the tractors and an emission coefficient of 3.106 CO_2/kg, which reports the amount of carbon dioxide released in the atmosphere by the combustion of one kilogram of Diesel fuel.

Table 12: Average energy content of the inputs required for the cutting and harvesting of grass

Inputs	(MJ/kg)	References
Fuel	50.23	Biondi et al. (1989)
Lubricant	78.13	Carillon (1979)
Labour	1.93	Pimentel & Pimentel, (1979)
Tractor	80.23	Hornacek (1979)

6.3 Results

6.3.1 Field capacities and labour requirements

The operative analysis of the mowing and harvesting systems shows that there are some differences in the field capacity, productivity and labour requirement (Table 13). The mowing and harvesting system 1 (shredding-vacuum self-loader) is the system with the least field cutting capacity and harvesting productivity. It amounts to about 0.3 ha/h with a harvesting productivity of 1.5 t/h. This system shows the highest labour requirement. In fact, the small working width of the arm brush cutter and the necessity to pull a trailer for the contemporary loading limit the productivity of the system. Instead, the system that can manage the grass in more passages presents a higher field capacity and harvesting productivity with less labour requirement due to the greater working width and the possibility to work without interruptions for off-loading the product when the trailer is full. In particular, mowing and harvesting systems 3 and 4 report an average field capacity that is threefold if compared with system 1 and a labour requirement that is half of the systems 4a and 4b.

Table 13: Field capacity and productivity, and labour requirement of the different systems

Mowing and harvesting systems	Field cutting capacity	Harvesting productivity	Labour requirement
	(ha/h)	(t/h)	(h/ha)
1	0.3	1.5	4.0
2a	0.7	6.6	2.4
2b	0.7	6.8	2.3
3a	1.1	6.6	2.9
3b	1.1	6.8	2.8
4a	0.9	6.6	2.0
4b	0.9	6.8	1.9

6.3.2 Economic analysis

From the economic point of view, the use of mowing and harvesting systems in different passages (2 or more) seems to be the best solution for the management of grass (Figure 19; Table 14). In fact, system 1 shows the highest costs for processing the grass (53 € /t). In particular, the systems with lower total costs are 3b and 4b; the system 4b results as the most cost-effective, being 15% less than system 3b.

Taking into consideration just the mowing phase, the use of the disc mowers seems to decrease the cutting costs (mowing and harvesting systems 3a and 3b) than the use of flail mowers (systems 4a and 4b).

However, the system 3 requires one more passage for the collection of the grass, increasing the total costs.

For the harvesting phase, the adoption of the self-loader wagon decreases the costs by about 45% with respect to the use of round balers. However, it is important to consider that the use of round balers allows the logistic and storage costs to be reduced.

Table 14: Economic balance of mowing and harvesting systems

Mowing and harvesting systems	**Cutting and harvesting costs**	**Cutting costs**	**Wrapping costs**	**Harvesting costs**	**Total**
	€/t	**€/t**	**€/t**	**€/t**	**€/t**
1	53				53
2a		21		19	40
2b		21		11	32
3a		10	7	19	36
3b		10	7	11	28
4a		13		19	32
4b		13		11	24

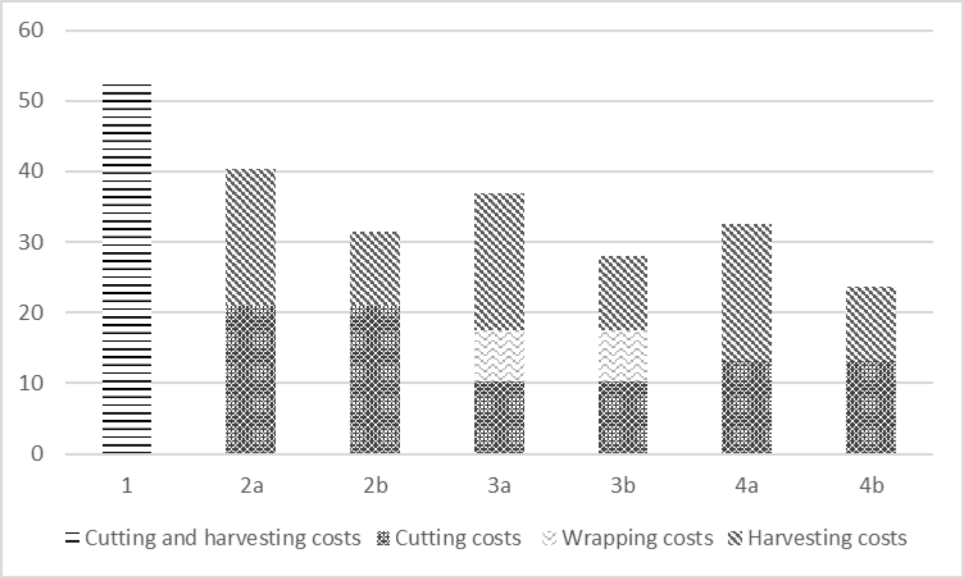

Figure 19: Economic comparison between mowing and harvesting systems

6.3.3 Energetic and CO_2 analysis

The energetic analysis highlights differences between the mowing and harvesting systems (Table 14). System 1 requires the highest energy input, about 799 MJ/t. Instead, the systems 2a and 2b show a lower energy requirement. In addition, the systems 3a and 3b allow a reduction of the inputs compared to system 1. Systems 4a and 4b report less energy requirement than all the others, with an average diminution of the inputs of 51% compared to system 1.

Considering the CO_2 emissions, it is possible to underline a fairly similar trend between the mowing and harvesting systems that use round balers and those that are equipped with a self-loader wagon.

Table 15: Energy balance of the systems and CO_2 emissions

Mowing and harvesting systems	Energy Input	Energy Input	CO_2 Emissions	CO_2 Emissions
	(MJ/ha)	(MJ/t)	(kg CO_2/ha)	(kg CO_2/t)
1	4,796	799	229	38
2a	3,028	505	157	26
2b	2,894	482	147	24
3a	2,682	447	144	24
3b	2,547	424	134	22
4a	2,405	401	128	21
4b	2,271	378	118	19

6.4 Conclusions

This preliminary analysis points out some aspects of the mowing and harvesting of grass for energy purposes along riverbanks in north-eastern Italy.

First of all, the mowing and harvesting system 1 (shredding- vacuum self-loader) differs from the others due to a low field capacity, high costs and high-energy requirement.

The best mowing machinery could be flail mowers or disc mowers, whereas the more appropriate solutions for harvesting could be the self-loader wagons thanks to slightly lower economic and energy costs.

However, even though this study has not taken into account the logistics and storage phases of grass, the harvesting with round balers, due to the pressing of the grass, would seem to involve lower costs for these successive phases.

In conclusion, it is necessary to focus on the notable variability of the working sites found in north-eastern Italy, where the mowing and harvesting are not always easily adapted to the conditions because of the presence of obstacles such as a linear barrier along the riverbanks. The operational feasibility and the subsequent correct sizing of the mowing and harvesting system is of fundamental importance for the exploitation of grass along riverbanks to supply AD plants.

7. GRASS SUPPLY CHAINS FOR BIOGAS PRODUCTION

The aim of this study is to evaluate different possible approaches to the logistic supply chain of grass harvested in riverbanks, focusing into its economic and energy aspects. Three different logistic approaches for the supply of AD plants have been proposed and evaluated at four different supply distances from the biogas plant (5, 10, 20, 30 km).

The results show that, under economic aspects, the direct transport chain seems to be the most convenient solution for the management of such material in short distances; conversely, for longer distances, the best solution appears to be the interrupted transport chain. The transport of grass in round bales always appears disadvantageous under economic aspects with respect to the interrupted transport chain.

On the other hand, the energy balance clearly highlights the higher efficiency of the interrupted and round bales transport scenarios while the direct transport system noticeably requires higher energy inputs.

7.1 Introduction and objective of the research

The utilisation of energy crops for biogas production by AD can compete with food production and exerts a strong pressure on the environment (Basso et al., 2016). Consequently, alternative biomass sources, such as grass from non-cultivated areas, should be taken into consideration as an integrative feedstock for the biogas supply chain.

Although today grass is not a common feedstock in the AD process, according to some authors (Prochnow et al. 2009; De Moor et al. 2013), it has good characteristics and it could be an integrative biomass in the biogas process.

However, one of the main problems that prevent its exploitation is the lack of appropriate technologies that could make its recovery sustainable under economic and energy aspects (Boscaro et al., 2015). In particular, due to its low energy content, the logistic operations of grass seem to be one of the most important factors to solve for an energetic valorisation of such biomass (Athanasios et al., 2009).

The aim of this study is to evaluate different possible approaches to the logistic supply chain of grass harvested in riverbanks, focusing into its economic and energy aspects.

7.2 Materials and methods

7.2.1 Logistic systems

Three different logistic approaches for the supply of AD plants have been proposed and evaluated at four different supply distances from the biogas plant (5, 10, 20, 30 km), according to the mowing and harvesting systems proposed by Boscaro et al. (2015) (Figure 20).

In the scenario “a” (direct transport chain) and “b” (interrupted transport chain) the grass is managed as loose product. For this reason, a low transport density (assumed of 180 kg/m^3) characterizes the grass.

On the other hand, in the scenario “c” (transport in round bales), thanks to the compression action of the round-baler, grass presents a higher density (assumed of 330 kg/m^3) with, as consequence, a reduction of the transport volumes.

For the scenario “b”, the distance to the temporary storage place was assumed to be of 1 km on average. A following loading operation in a trailer with a higher transport capacity is planned.

Each system, agreeing to surveys among Italian operators, involves one or more tractors in order to complete different operations. In the present study, the following assumptions have been formulated:

- Scenario “a”: Tractor 88 kW + Self Loading Wagon (25 m^3)
- Scenario “b”: Tractor 88 kW + Self Loading Wagon (25 m^3); Tractor 60 kW + Hayfork loader; Tractor 100 kW + Trailer (40 m^3)
- Scenario “c”: Telehandler 73 kW; Tractor 100 kW + Trailer (40 m^3)

The average transport speed was assumed, considering the Italian roads conditions and legislation, of 13 km/h.

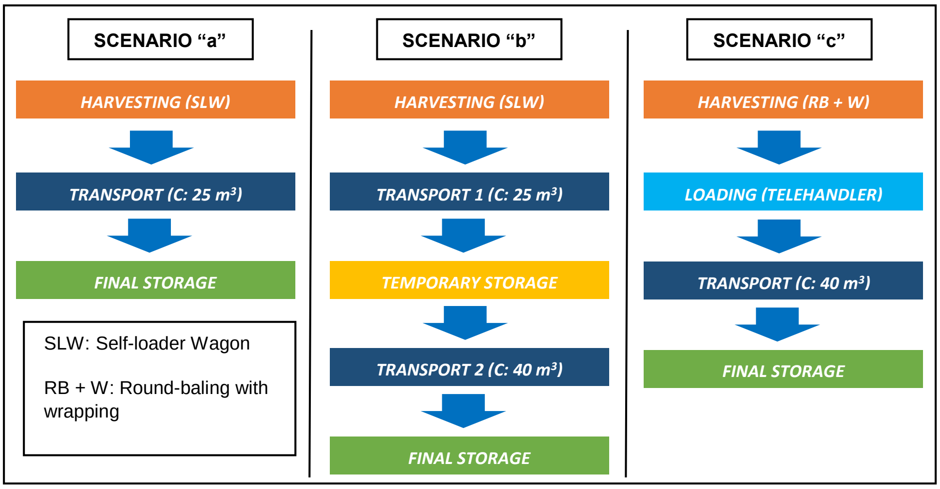

Figure 20: Logistic scenarios

7.2.2 Economic analysis

The economic analysis has been performed providing an economic value for each operation executed in every system.

The unit costs per tons of fresh matter (FM) of the logistic process for the grass was calculated according the following equation:

$$C = \sum Su / C_t \qquad (3)$$

C= Unit cost of the operation (€/t $_{FM}$)

$\sum Su$= Sum of the hourly costs of the tractors and equipment involved in the operation (€/h)

C_t= Transport capacity (t/h)

The hourly costs of machineries were computed according to the ASABE procedures (ASABE 2011), considering the purchase costs of the Italian price lists.

On the basis of previous experiments carried out in Germany (Pick et al., 2012), grass yield was assumed to be 6 t/ha (FM) per cut, with a 25% dry matter content.

7.2.3 Energy balance

The energy comparison was evaluated based on the gross energy demand method (Slesser and Wallace 1981; Pezzuolo et al. 2014), also including the energy value related to labour of the field operations, as described in Sartori et al. 2005 (Table 16).

Table 16: Average energy content of the inputs required

Inputs	Energy required	Sources
Fuels (MJ/kg)	50.23	Biondi et al. (1989)
Oils (MJ/kg)	78.13	Carillon (1979)
Labour (MJ/h)	1.93	Pimentel & Pimentel, (1979)
Tractor (MJ/kg)	80.23	Hornacek (1979)

7.3 Results and Discussion

7.3.1 Economic analysis

According to the economic analysis, the direct transport allows a reduction of transport costs in the case of short distances (Figure 21). However, the scenario “a” costs tend significantly to increase for long distances.

Conversely, the interrupted transport chain appears to be more convenient in the case of distances higher than about 6 km, with a tendency to keep the costs more stable than in the case of direct transport chain.

On the other hand, the scenario “c” (transport in round bales) is never energetically advantageous compared to interrupted transport chain. In fact, the major costs due to the recovery of the product by telehandler negatively influence its economic balance.

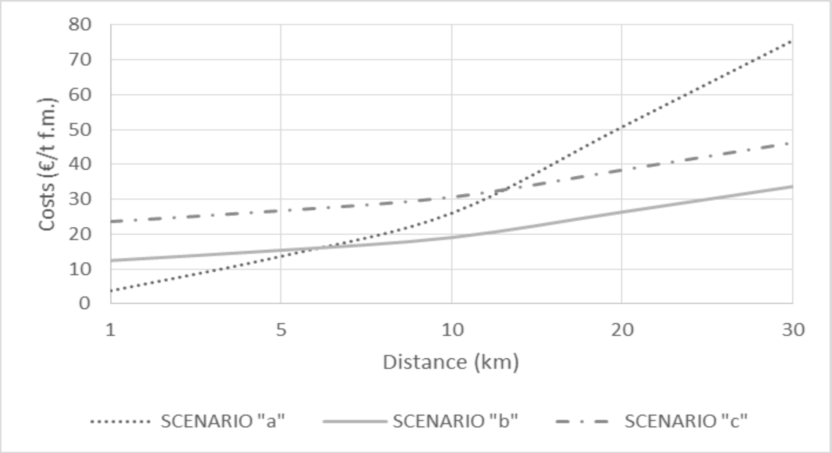

Figure 21: Economic analysis of different logistic scenarios

7.3.2 Energy Balance

According to the energy balance, the direct transport chain requires the highest energy inputs (Figure 22). Indeed, the lower transport capacity negatively impacts on energetic efficiency.

Conversely, the interrupted transport chain and the transport in round bales are the systems with a higher energy efficiency: their energy requirements are almost equal, and markedly lower than the direct transport chain.

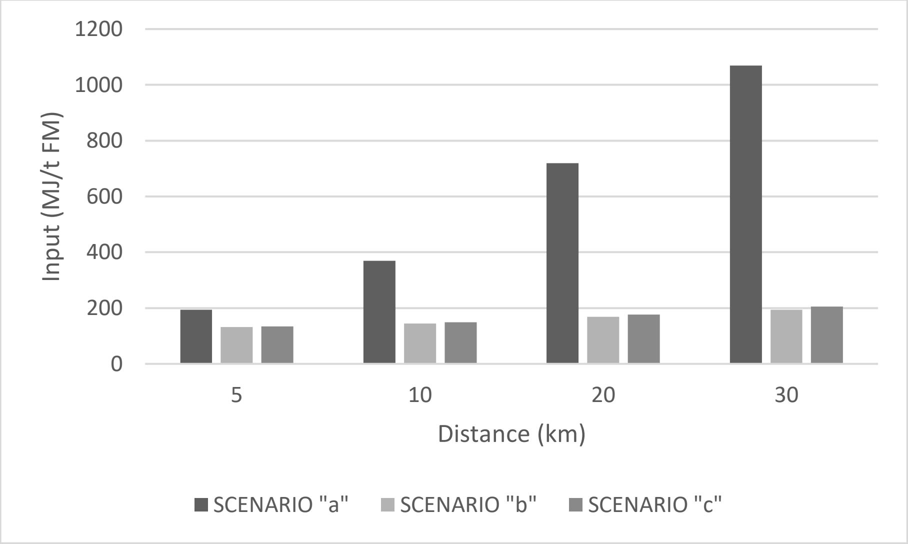

Figure 22: Energy balance of different logistic scenarios

7.4 Conclusion

Three different approaches of the logistic of grass for the feeding of AD plants have been evaluated under economic and energy aspects.

The results show that, under economic aspects, the direct transport chain seems to be the most convenient solution for the management of such material in short distances; conversely, for longer distances, the best solution appears to be the interrupted transport chain. The transport of grass in round bales always appears disadvantageous under economic aspects with respect to the interrupted transport chain.

On the other hand, the energy balance clearly highlights the higher efficiency of the interrupted and round bales transport scenarios while the direct transport system noticeably requires higher energy inputs.

In order to improve the performances of the interrupted transport chain, further investigations could be carried out to reduce the transport volumes in this system. Indeed, from preliminaries examines the reduction of volumes could reduce costs by nearly 30%.

8. EVALUATION OF THE ENERGY AND GREENHOUSE GASES IMPACTS OF GRASS HARVESTED ON RIVERBANKS FOR FEEDING ANAEROBIC DIGESTION PLANTS

More sustainable scenarios in the bioenergy sector can be achieved when biomass exploitation is based on eco-efficient supply chains. Regarding this, grass as a by-product obtained from landscape management could provide a large quantity of biomass potentially utilizable in the AD supply chain.

This study assessed the energy and greenhouse gases (GHG) impacts of grass obtained from the landscape management of riverbanks.

A study area of a land reclamation authority was investigated by interpreting high resolution spatial data and determination of the biomass yield. In addition, an inventory was made of the grass production chain. An energy analysis was performed using the Cumulative Energy Demand method (CED), while the GHG balance of grass AD was calculated based on CO_2 equivalents. Special attention was also given to the logistic approaches: two different supply systems were evaluated in order to determine the best supply chain for this feedstock.

The results show that the biomass yield of riverbank grass amounts to 13 t_{FM}/ha (4.8 $t_{d.m}$/ha) while the energy utilization of grass determines a saving on fossil energy of about 2.6 – 2.4 GJ/t_{FM} (7.0 – 6.4 GJ/t_{DM}) and on GHG equivalent emissions of about 86 – 67 kg_{CO2eq}/t_{FM} (233 – 181 kg_{CO2eq}/t_{DM}) depending on supply distance and logistic approach. In this regard, the Indirect Logistic Approach (ILA) achieves the best performance in terms of the reduction of fossil energy and GHG emissions.

The results suggest positive prospects for the integration of grass from non-cultivated areas into the AD supply chain in order to mitigate the requirement for agricultural feedstock and obtain a positive return, in terms of energy and emissions saved, from landscape management operations.

8.1 Introduction

The exploitation of biomasses from non-food agricultural annual crops in the AD supply chain implies a strong pressure on the environment as well as competition in terms of land use (Pick et al., 2012; Timilsina et al., 2011). This problem, especially in Europe, has become more accentuated in the last years due to a rapid development of AD that mainly exploits agricultural biomasses (EBA, 2015). As a consequence, the agricultural framework is changing rapidly with negative impacts on the local economies (Ingrao et al., 2016).

By-products from agricultural processes or biomasses derived from still not exploited resources, could represent an important sustainable source able to satisfy the environmental needs and reduce the dependence on fossil fuels of society and the requirement for agricultural biomasses (Martínez-Blanco et al., 2010; Menardo et al., 2015; Triolo et al., 2012). Regarding this, landscape management could provide a large quantity of biomasses potentially utilizable in an AD supply chain, like grass cuttings (Piepenschneider et al., 2016).

The potential contribution that landscape management could make to the AD supply chain could be interesting, especially in a region with an extensive system of non-cultivated green areas composed of linear elements such as riverbanks or roadsides, and wide open areas of grasslands or marginal lands (Colantoni et al., 2016; Dandikas et al., 2015; Herrmann et al., 2014; Meyer et al., 2014; Voinov et al., 2015). In fact, all these elements produce a relevant quantity of biomass, generally not exploited today, that could potentially reduce the requirement for energy crops for the AD sector and exert a positive impact on the environment and society (Ingrao et al., 2015; Weiland, 2006).

Several studies have pointed out how grass can be a reliable feedstock for biogas production (De Moor et al., 2013; McEniry et al., 2014; Nizami et al., 2012; Prochnow et al., 2009b). However, a number of issues should be taken into account when considering the use of grass instead of energy crops in AD. The main ones are: the intrinsic lower energy density of grass; the lower hydrolysis rate and consequent need for prolonged retention time in the reactor; the presence of inert material like sand or stones, but also plastic and cans depending on the grass origin. Because of these, grass has so far only been partially exploited as feedstock.

The energy and environmental impacts of biogas production systems from renewable resources have been a topic in many studies (Bacenetti et al., 2016; Dressler et al., 2012; Lijó et al., 2015). Nevertheless, when considering the entire grass value chain, it turns out that only a few studies have investigated the effective energy and GHG impacts related to the use of this kind of biomass. As demonstrated by Gerin et al. (2008), Meyer et al. (2015), Pöschl et al. (2010), and Smyth et al. (2009), the gain and the return on invested energy seems to be positive. However, the main limit is the poor energy efficiency and reduction of GHG with respect to energy crops such as maize (Gerin et al., 2008). In particular, the main issues concerning this biomass are the high recovery costs correlated with low energy returns. These costs are particularly high because of constraints associated with harvesting operations (machinery accessibility along linear systems such as riverbanks and roadside areas) (Boscaro et al., 2015) and, mainly, the high logistic inputs necessary due to the low energy density of the biomass (Blokhina et al., 2011; Gerin et al., 2008; Gunnarsson et al., 2008). In fact, a proper logistic approach could mitigate these energy and GHG problems, enhancing the benefits associated with the use of these biomasses (Boscaro et al., 2016; Pavlou et al., 2016).

The aim of this study is to assess the sustainability, in terms of energy return and GHG balance, of grass harvested in non-cultivated areas in the AD supply chain. The study investigates: i) the individuation and analysis of non-cultivated areas for grass harvesting; ii) the grass biomass yield obtainable from these areas, iii) the most appropriate production chain in order to solve the energy and GHG impacts issues related to the harvesting and logistic operations; iv) the energy yield of AD from this kind of biomass.

8.2 Materials and methods

8.2.1 Description of the study-area

The study area corresponds to the area of the *Consorzio di Bonifica Veronese* that manages a hydrographic basin of more than 160,000 ha in the province of Verona (Northeastern Italy). The total hydrographic network amounts to about 3,000 km and usually has grassy riverbanks for the control of water. The *Consorzio* manages these riverbanks by mowing grass twice per year without harvesting it.

The area was chosen as representative because of this large amount of grass and also the presence of a number of biogas plants with different power potential. Although the biogas plants are mainly fed with energy crops, such as maize (*Zea mays L.*) or triticale (*Triticosecale*), local authorities are interested in integrating the current supply with grass from non-cultivated areas.

8.2.2 Spatial analysis

The spatial analysis of the territory conformation was performed by the interpretation of high resolution spatial data such as high quality aerial orthophotos (0.5 m resolution) and a high-resolution Digital Elevation Model (DEM) with 0.5 m resolution derived from Aerial Laser Scanner data (Pappalardo et al., 2014). This allowed a potential territory suitable for grass collection to be estimated and to identify the technical constraints that may arise during the harvesting operations in order to choose appropriate solutions.

8.2.3 Determination of biomass yield

The grass biomass yield was determined by studying two sites that were chosen as representative after an inspection of the *Consorzio di Bonifica Veronese* territory.

The potential grass yield (t_{FM}/ha) was determined by the collection and weighing of grass samples in ten 0.16 m^2 random areas within each site. The average value obtained was assumed as grass yield. The dry matter content of grass samples was also determined according to standard procedures (APHA 2005).

In order to define the types of grass that accounted for the biomass yield estimation, a species identification was conducted for each sample. The two sites were identified within the study area. Both sites were suitable for the access of grass harvesting machinery with appropriate manoeuvring spaces and few obstacles.

8.2.4 Inventory analysis of grass production chain

The production of agricultural biomasses, such as maize or autumn cereals, is possible with a standardized process that starts with the seeding and fertilization of the fields and ends with the harvesting of the crop, whereas the landscape grass production chain for AD has not yet been well developed and optimized (Boscaro et al., 2015). For this reason, a viable production chain was assumed considering the investigations and studies on the best practices for grass cuttings collection and valorisation reported by Gruwez et al. (2016).

The operations needed for grass collection and utilisation involve i) mowing and harvesting, ii) logistics, iii) storage, iv) digestion and v) digestate management. An inventory of the grass production chain was made in order to obtain data for the determination of the energy and GHG impacts that these operations imply.

8.2.4.1 Mowing and Harvesting

The best technologies adaptable for grass mowing and harvesting were considered depending on the spatial characteristics of the harvesting area of the *Consorzio di Bonifica Veronese* computed as described in section 8.2.2. In more detail, the riverbank surfaces are often difficult to access by the conventional machinery utilized in the biomass production chain due to the presence of obstacles or insufficient working space. As a consequence, alternative technologies have to be defined, also considering the qualitative characteristics required for an optimal AD: an appropriate particle size and harvesting time (Herrmann et al., 2012; Prochnow et al., 2005; Sharma et al., 1988). In fact, these are of fundamental importance in order to improve the degradation and preservability of grass and avoid biomass quality losses caused by the accumulation of lignin and hemicelluloses during grass maturation (P. F. H. Harmsen, 2010; Tsapekos et al., 2015).

The best system that could mow and harvest grass within the study area, according to the solutions proposed by Boscaro et al. (2015), could be a gathering mowing and harvesting system, composed of an arm brush cutter equipped with a vacuum unit that blows the grass through a pipe into a trailer towed by a 95 kW tractor. This system generally shows a good adaptability to obstacles guaranteeing an appropriate grass particle size. However, it does not present high working performances in comparison with other haymaking systems due its narrow mowing width (1,2 m) (Boscaro et al., 2015).

The performance data of the system was collected by monitoring the mowing machinery owned by the *Consorzio*, which have quite similar mechanical characteristics to the proposed mowing and harvesting system. The monitoring was conducted by a commercial GPS/GSM data logger for continuous real-time collection of position data and machine parameters, such as working time or machine transferring time. Data collected by the GPS/GSM data logger allowed the average harvesting speed of the mowing system (about 3 km/h) and the working times to be defined.

8.2.4.2 Logistics

Evaluation of the grass logistic operations was performed through Discrete Event Simulation (DES) analysis as proposed in similar studies by Mobini et al. (2011) and Tako and Robinson (2012). The advantage of utilizing DES modelling for the logistic determination is the creation of a defined system (Banks et al., 2005), with the following characteristics: i) a dynamic and a temporal dimension (the variables evolve over time); ii) a stochastic setting, hence inputs are described by statistical distributions; iii) the state of the system can only change instantaneously at a discrete set of points in time (events), not continuously (Cavalli et al., 2012; Grigolato et al., 2011). The DES analysis was designed and performed by Witness® (Lanner, UK) software. The logical process of work sequences was tested by running the model step by step and observing the interaction between all the elements from graphic and value outputs, in an interactive building and verification activity as suggested by Bank et al. (2005). Each model considered two different scenarios, which involved the two logistic approaches described in Figure 23.

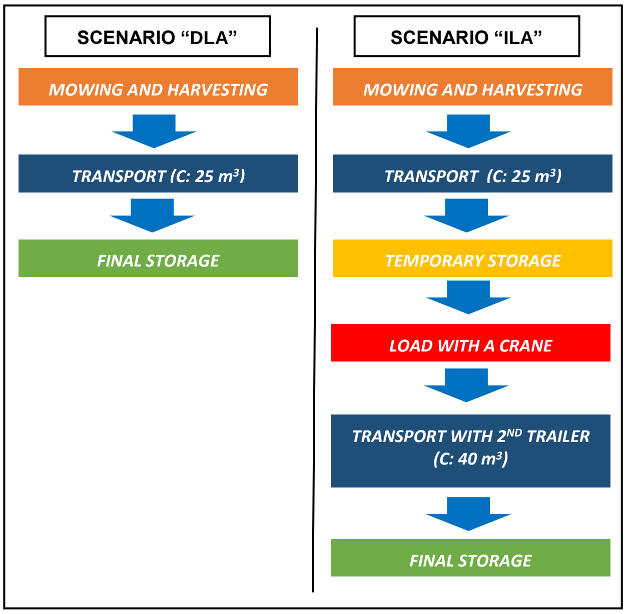

Figure 23: Schematic representation of the two logistic approaches evaluated

Specifically, the logistic system consisted of:

- Direct Logistic Approach (DLA): when the mowing and harvesting system transports the biomass directly to the biogas plant,

- Interrupted Logistic Approach (ILA): when the mowing and harvesting system transports the product to a temporary storage place near the harvesting area (assumed as 1 km on average). Successively, a loading operation performed by a 60 kW tractor equipped with a crane allows a bigger trailer, pulled by a 110 kW tractor, to be loaded.

Each logistic approach was tested for two supply distances from the harvesting location to the biogas plants, 5 and 10 km. These distances were fixed after the spatial analysis performed in section 8.2.2. Each model was run five times.

The parameters that were used for the DLA and ILA simulation models are summarized in Tables 17 and 18.

Table 17: Parameters of the DLA utilized for the simulation model

Parameter	Value	Unit	Reference
Simulation time	200	h	------------
Tractor	95	kW	Boscaro et al. (2015)
Cutting width	1.2	m	Boscaro et al. (2015)
Trailer load capacity	20	m^3	Farm operators*
Grass transport density	220	kg/m^3	Farm operators*
Average harvesting speed	3	km/h	GPS tracking
Average transport speed when trailer is full	15	km/h	Farm operators*
Average transport speed when trailer is empty	20	km/h	Farm operators*
Download time of a trailer	0.08	h	Farm operators*
Grass yield	----	t_{FM}/ha	Assumed in section 8.2.4

*Data provided by surveys of Farm operators

Table 18: Parameters of the ILA utilized to create the simulation model

Parameter	Value	Unit	Reference
Simulation time	200	h	------------
1st tractor	95	kW	Boscaro et al. (2015)
Mowing width	1.2	m	Boscaro et al. (2015)
Load capacity of 1st trailer	20	m^3	Machine characteristic
Grass transport density	220	kg/m^3	Farm operators*
Average harvesting speed	3	km/h	GPS tracking
Average transport speed when the trailer is full	15	km/h	Pezzuolo et al. (2016)
Average transport speed when trailer is empty	20	km/h	Pezzuolo et al. (2016)
Download time of a trailer	0.08	h	Farm operators*
Distance between harvesting area and intermediate storage area	1	km	------------
Crane load capacity	15	t/h	Farm operators*
2nd tractor	110	kW	Farm operators*
Load capacity of 2nd trailer	40	m^3	Farm operators*
Average transport speed when 2nd trailer is full	15	km/h	Pezzuolo et al. (2016)
Average transport speed when 2nd trailer is empty	20	km/h	Pezzuolo et al. (2016)
Download time of 2nd trailer	0.08	h	Farm operators*
Grass yield	----	t_{FM}/ha	Assumed in section 8.2.4

*Data provided by surveys of Farm operators that are involved in the management of grassy riverbanks

The simulation model delivers several data, such as the working or idle time of the machinery and the quantity of grass that was harvested, transported and downloaded at the plant.

Starting from the obtained data, the working capacity and productivity of the machinery were computed according to the ASABE procedures (ASABE 2011, 2007).

8.2.4.3 Storage

The storage process of grass is of fundamental importance in order to make this feedstock available during the year in the biogas plant. The best practice to guarantee good storage of this biomass is ensiling, as reported by Ambye-Jensen et al. (2013), Egg et al. (1993) and McEniry et al. (2014).

This is usually performed in a bunker silo, a structure composed of a rectangular concrete pad with two reinforced concrete walls on the long sides where the biomass is pressed by a tractor and then covered by a plastic film.

In this study, the filling operations of the silo were assumed to be performed by a 150 kW tractor equipped with a shovel. This takes place once grass has been transported and downloaded at the storage site through pressing into the bunker. The obtained density of grass is typically 600 kg/m^3 (Muck and Holmes, 2000).

The volume of the bunker and amount of plastic film was calculated considering the quantity of grass necessary in order to feed an AD plant of 1,000 kW$_{el}$, which is typical in the Italian situation (Chinese et al., 2014; Riva et al. 2014). In addition, a value for the dry matter losses that could occur during the ensiling phase was assumed. This amounts to 10% of the ensiling Mass. (Bacenetti and Fusi 2015; Köhler et al. 2013; Martin et al., 2004)

8.2.4.4 Digestion

To digest and convert grass into biogas a continued stirred tank reactor plant was considered as applicable (Nizami and Murphy, 2010). This kind of plant generally works in wet conditions (average dry matter content of biomass 10%) and is the most widespread option in the Italian scenario.

Because of its characteristics, grass should be no more than 10-15% of the feedstock due its tendency to float and create occlusive layers inside the digesters (Dinuccio et al., 2010; Thamsiriroj and Murphy, 2010).

To compute the bio methane potential (BMP) the grass harvested on the riverbanks was characterized considering total and volatile solids. Analyses followed the standard methods (APHA, 2015).

Anaerobic batch trials for the evaluation of biogas production (BMP test) were conducted following the methodology suggested in Angelidaki et al. (2009). Biogas was determined in triplicate using 1 L reactors, 0.5 L working volume, sealed with chloro-butyl caps after nitrogen injection for anaerobic conditions. The inoculum used in these trials was obtained from a farm anaerobic mesophilic (37 °C) digester usually fed with cattle and chicken manure, and a mix of energy crops (maize) silage, sorghum (*Sorghum* spp.) silage, triticale silage) and straw. The inoculum was filtered at 2 mm in order to remove coarse material and left at 37 °C for one week to reach endogenous conditions. The solids content after acclimation was 24.3 g/kg, 73% volatile. The volume of generated biogas was determined by water displacement, while its composition was determined using a Geotech Biogas 5000 (Geotechnical Instruments®, United Kingdom) determining methane percentage and H_2S concentration (Mattioli et al., 2016).

8.2.4.5 Digestate management

Digestate obtained by AD of grass amounts to 90% of the initial mass (Bacenetti and Fusi, 2015). Once produced, it is stored in a reinforced concrete slurry tank for a maximum of 180 days, and is then distributed on the fields. The tank was assumed uncovered, which is typical in the Italian situation (Gioelli et al., 2011). The disposal of the material is performed by a 150 kW tractor equipped with a 20 m^3 slurry tank, while the disposal distances from the AD plant were assumed according to the logistics scenarios evaluated previously: when the distance between the harvesting site and biogas plant was set at 5 km, the distance for the disposal of the digestate is 5 km; the same procedures were applied when the distance between the harvesting site and biogas plant is 10 km.

The operative capacity of the digestate disposal system was assumed as 0.6 ha/h at shorter distances and 0,3 ha/h at longer distances (Bacenetti and Fiala, 2015)

8.2.5 Energy and Greenhouse gases balance

8.2.5.1 Energy balance

The energy balance of grass harvested in non-cultivated areas was assessed according to the Cumulative Energy Demand (CED) methodology (Bacenetti et al., 2013). The CED is an indicator that reports the entire energy demand needed for the production, use and disposal of an economic good, minus the saved energy that the production of this good implies.

To perform the analysis, the primary and secondary fossil fuel sources and the energy saved by the production of renewable energy were assessed, first, in terms of energy equivalent expressed in MJ/t_{FM}, and then converted into $MJ/t_{\text{dry matter (DM)}}$, according to the dry matter content of grass.

The CED was computed according to the equation:

$$CED = (DE + IE) - (ESel + ESth + ESf)$$

Where:

CED is the Cumulative Energy Demand, which is the difference between required and saved fossil energy;

DE is the Direct Energy, and it accounts for the fuel consumption of the grass production chain, as described in the previous section. They were assumed depending on the consumption of diesel multiplied by an energy coefficient (Table 20). The diesel and the oil consumptions of the machinery were computed according to the equations:

$$DC = (SDC * EL * P) / (FC) \tag{5}$$

$$OC = (SOC * EL * P) / (FC) \tag{6}$$

Where DC and OC are diesel and oil consumption (kg/ha) respectively; SDC is specific diesel consumption that corresponds to 0.3 kg_{diesel}/kW (Borin et al., 1997); SOC is the specific oil consumption that corresponds to 0.001 kg_{oil}/kW (Borin et al., 1997); EL is the engine load of the tractor (assumed as 0.7 for heavy load operations, e.g. mowing and harvesting, and 0.5 for soft load operations, e.g. transport); P is the power of the machine (kW); FC is the field capacity (ha/h). Other direct energy inputs are the heating energy (e.g. heating of the biogas digester) and electricity (e.g. pumping and mixing of digesters). They were accounted from reference data considering a 1,000 kW_{el} power energy biogas plant (Table 20);

IE is the Indirect Energy, accounting the energy utilized in the manufacturing of machinery, digesters, storage tanks or other structures that could be required. The energy contained in machinery was calculated based on energy used for production of raw material. The mass of the machinery and equipment was converted into manufacturing energy values using reference coefficients (Table 19) and was then divided by the estimated technical and economic life, to allow calculation of the hourly energy costs. Table 20 reports the mass, economic life and annual usage of the tractors and equipment considered in this study.

Table 19: Main characteristics of the tractors and equipment involved in the grass production chain (P: Power (kW), LC: Load Capacity (m^3))

Type	Operation	Weight (kg)	Estimated life (y)	Annual usage (h)
Tractor (P: 95 kW)	Mowing and harvesting	5,000	8,000	800
Tractor (P: 60 kW)	Load	3,500	8,000	800
Tractor (P: 110 kW)	Transport	6,000	8,000	800
Tractor (P: 150 kW)	Ensiling	8,000	8,000	800
Tractor (P: 150 kW)	Digestate management	8,000	8,000	800
Arm brush cutter with vacuum self-loader equipment	Mowing and harvesting	2,500	2,000	400
Trailer (LC: 20 m^3)	Transport	4,000	3,000	300
Trailer (LC: 40 m^3)	Transport	6,000	3,000	300
Crane	Load	800	1,500	100
Shovel	Ensiling	600	2,000	200
Slurry tank	Digestate management	8,000	3,000	400

ESel is the Electrical Energy Saved, i.e. the energy recovered through the production of electricity by biogas conversion. This value was obtained by multiplying the grass BMP by the energy content of methane (assumed as 39 MJ/m^3) (Meyer et al., 2015) and by the electrical efficiency of the combined heat and power of the biogas engine (assumed as 0.38) (Bacenetti et al., 2013; Berglund and Börjesson, 2006).

ESth is the Thermal Energy Saved, which accounts the heating energy. It was computed by multiplying the energy content of grass BMP by the thermal energy efficiency of the combined heat and power of the biogas engine (assumed as 0.50) (Bacenetti et al., 2013; Berglund and Börjesson, 2006).

ESf is the Energy Saved by reducing the production of chemical fertilizers thanks to the production of digestate. It was computed considering that an organic fertilizer (the digestate) can be obtained from the AD of grass, which has a relevant content of fertilizing elements such as nitrogen (6% on DM), phosphorus (1.5% on DM) and potassium (3% on DM) (Möller and Müller, 2012). The energy content of such elements was computed as the surrogate value of fertilizer, considering the coefficients reported by Šarauskis et al. (2015).

Table 20: Average direct energy content of the inputs required in the biogas production chain

Input	Coefficient	Unit	Reference
Diesel	53.87	MJ/kg	Piringer and Steinberg (2008)
Oil	78.13	MJ/kg	Piringer and Steinberg (2008)
Direct energy for biogas plant feeding (electricity)	25	MJ/t FM of grass	Meyer et al., (2015)
Direct energy for biogas plant mixing and pumping (electricity)	70	MJ/t FM of grass	Berglund and Börjesson, (2006)
Direct energy for heating the digesters (heat)	110	MJ/t FM of grass	Berglund and Börjesson, (2006)

Table 21: Average indirect energy content of the inputs required in the biogas production chain

Input	Coefficient	Unit	Reference
Tractors manufacturing and materials	80.25	MJ/kg	Kitani (2009); Franzese et al. (2009); Pezzuolo et al. (2016); Piringer & Steinberg (2008)
Machinery manufacturing and materials	8	MJ/kg y	Kitani (2009)
Concrete	4	MJ/kg	Canakci and Akinci (2006)
Plastic film	90	MJ/kg	Canakci and Akinci (2006)
Digesters construction	39	MJ/t FM of grass	Prade et al. (2012)
Storage tank construction	13	MJ/t FM of grass	Prade et al. (2012)
Combined Heat and Power Unit	11	MJ/t FM of grass	Mattioli et al. (2016)

8.2.5.2 GHG balance

The GHG emitted during the AD production chain of the grass was evaluated indicating a CO_2 equivalent value (CO_2eq) as defined by the IPCC (2006).

The CO_2 released during the biogas combustion in AD plants was not computed in this balance because it was assumed that the CO_2 fixed during the photosynthesis of grass compensates for the CO_2 emitted (Bacenetti et al., 2013).

The equation used for computation of the GHG is:

$$GHG = (DE_{CO2} + IE_{CO2} + FE_{CO2}) - (ES_{CO2}\,el + ES_{CO2}\,th + ES_{CO2}\,f) \qquad (7)$$

Where:

GHG: is the balance between the GHG emitted and the GHG emission saved from the atmosphere. It was expressed in $kg_{CO2eq}/t_{grass\ FM}$ and then converted into kg_{CO2eq}/t_{DM} considering the dry matter of grass computed in section 8.2.3;

DE_{CO2}: Direct Emission, are the CO_2eq emissions due to the combustion of fossil fuels, such as diesel and oil, during the grass production chain. To compute these emissions, the fuel consumption of machinery considered was multiplied by an emission coefficient set at 3.12 kg_{CO2eq}/kg_{diesel} for diesel and 2.94 kg_{CO2eq}/kg_{oil} for oil (Borin et al., 1997; Manzone and Calvo, 2016; Sartori et al., 2005);

IE_{CO2}: Indirect Emission, are the emissions realised during the manufacturing of the inputs such as machinery (e.g. tractors), materials or structures (e.g. digestate tanks). The coefficient used for the computation of IE_{CO2} for tractors and equipment is 0.159 kg_{CO2eq}/MJ_{ie} (West and Marland, 2002), while for the concrete of the structures it is 0.148 kg_{CO2eq}/MJ_{ie} (Friedrich et al., 2007)

FE_{CO2}: Fugitive Emissions, are the emissions related to the methane leaks caused by open digestate storage, losses from pipes or valves of digesters, CHP unit inefficiencies. The fugitive emissions were accounted as 3.8% of grass BMP (Flesch et al., 2011; Groth et al., 2015; Hrad et al., 2015; Reinelt et al., 2016). The methane loss was converted into CO_2eq considering the global warming potential (GWP) of methane (IPCC, 2006). The assumed GWP for methane is 25 (Gioelli et al., 2011).

$ES_{CO2}\,el$: are the fossil emissions saved thanks to the renewable electricity produced by the AD plant. The equivalent CO_2 value was calculated considering that a fossil kWh_{el} of electrical energy produced in Italy currently corresponds to 0.35 kg_{CO2eq}/kWh_{el}, as reported by Ang and Su (2016). The kWh_{el} of electrical energy that are produced by grass are equivalent to the product of its energy potential, as described in section 8.2.4.4, and a conversion value of 3.2 kWh_{el}/m^3_{CH4}.

ES_{CO2} th: are the fossil emissions saved thanks to the production of heat by the AD plant. A fossil kWh_{th} of electrical energy is equivalent to 0.23 kg_{CO2eq}/kWh_{th} (Bacenetti et al., 2013; Capponi et al., 2012; West and Marland, 2002). Instead, the thermal energy that is produced by grass is equal to the product of its energy potential, as calculated in section 8.2.4.4, and a conversion value of 4.2 kWh_{th}/m^3_{CH4}.

ES_{CO2} f: are the fossil emissions saved thanks to the production of digestate, i.e. fertilizer, by the AD plant. The equivalent CO_2 value was calculated considering the saving of chemical fertilizers that a ton of digestate gives. It was assumed as 7.8 kg of CO_2eq (Poeschl et al., 2012; West and Marland, 2002).

8.2.6 Statistical analysis of data

In order to compare the results of the simulation model for the Direct Logistic Approach (DLA) and the Interrupted Logistic Approach (ILA) (see section 8.2.4.2), the CED and GHG balances were calculated for each run of the DES models. As a consequence, the difference among scenarios (ILA - 5 km, ILA - 10 km, DLA - 5 km and DLA - 10 km) was checked by a one-way analysis of variance and by previously checking for the normality of the data and the homogeneity of variance. In the case of significant difference between the groups, the LSD test was applied to explore the differences among means and to provide which means are significantly different from each other. The analysis was considered at a confidence level of 95%. The statistical analysis was performed by Statgraphichs 17.2® (Statpoint Technologies Inc., Warrenton, Virginia).

8.3 Results

8.3.1 Spatial analysis

From the case study analysis, it emerged that the most favorable areas for grass valorization are located in the southeast of the *Consorzio di Bonifica Veronese* territory, in an area that extends for about 10 km^2 within the municipalities area of Castagnaro, Cerea, Legnago and Villa Bartolomea. The total area is about 19,400 ha.

The territory is rural with the grassy riverbanks usually bordering farmland. This is of fundamental importance considering the Italian situation because, according to the national law (D.lgs 152/2006), grass can be classified as a byproduct if it comes from a rural framework and it thus is available for agricultural AD plants. However, it is important to note that the laws regulating to the utilization of landscape residues could change depending on EU country. Nevertheless, recent Directives issued by the EU, such as the Renewable Energy Directive (2009/28/EC), defined grass cuttings eligible and accountable in the national renewable energy share calculation used to quantify the country specific climate targets (Gruwez et al., 2016).

Concerning the spatial data from the analysis of high quality aerial orthophotos and DTM, the surfaces that could be utilized for grass collection are summarized in Table 22.

Table 22: Dimensional data of the Consorzio di Bonifica Veronese district. The hydrological network in this district is categorized, according to the Consorzio classification, as "primary", "secondary" and "tertiary" depending on the importance and width of the rivers.

	Primary hydrographic network	**Secondary hydrographic network**	**Tertiary hydrographic network**	**TOT**
Width of riverbanks (m)	9.1 ± 2,8	3.5 ± 1,5	3.2 ± 1,7	-------
Total river length (m)	50.5	19.5	222.0	467.0
Total grassy surfaces (ha)	92	140	144	376

8.3.2 Determination of biomass yield

In terms of grass species, the common grasses that grow on the riverbanks of the *Consorzio di Bonifica Veronese* belong to the *Poacacee* spp. family. The most widespread are *Sorghum* spp., *Phraghmites* spp., *Poa* spp. and *Festuca* spp. Apart from these, other plant families can be found with a lesser distribution, such as *Asteracee* spp., *Equisetaceae* spp. and *Polygonaceae* spp.

The average grass yield computed was 13±5 t $_{FM}$/ha per cut. The dry matter content was 37% while moisture content was 63%; so this corresponds to a yield of 4.8±1.8 t $_{DM}$/ha in terms of dry matter. Conceivably, considering the total amount of surfaces computed in section 8.3.1, the biomass quantity available on the entire surface is about 4,887 tons of fresh matter per cut (1.808 t $_{DM}$).

Cutting is usually performed two or three times per year, and during the investigations it emerged that, according to the North-East Italian climate, two grass cuts are potentially usable for the AD. The first cut could be performed in the late spring or early summer while the second could be in autumn.

8.3.3 Inventory analysis of grass production chain

By the simulation of the models for grass logistic operations it emerged that:

The field capacity of the DLA – 5 km system is about 0.16 ha/h with a productivity of 2.1 t_{FM}/h. Instead, for the scenario DLA – 10 km the field capacity is about 0.12 ha/h and productivity is about 1.5 t_{FM}/h.

Considering both the ILA – 5 km system and the ILA -10 km, their field capacity is 0.19 ha/h with a productivity of 2.4 t_{FM}/h. The effective transport capacity is 0.9 ha/h for the 5 km scenario and 0.5 ha/h for the 10 km scenario.

These results reveal that in the ILA the harvesting and mowing operations are not influenced by the transport distance because they are performed separately. However, in the DLA the mowing and harvesting operation are influenced by the logistic operations because the tractor has to transport and download the biomass into the AD plant when the trailer is full.

The quantity of grass that could be harvested daily with both systems would range between 12-20 t_{FM}/d depending on the harvesting distance and logistic approach adopted.

BMP trials showed an average biogas production in the range 500-600 m^3 per ton TVS, 53-54% as methane, resulting in a specific yield of 300 m^3_{CH4} per ton TVS (on average). The TVS content of grass was 91.5%. These figures are in line with the results of the GR3 project (2014) and other studies in the literature (Nizami et al., 2012; Seppala et al., 2009), which reported yields in the range 300-350 m^3_{CH4}/t_{VS}.

According to our results and the literature data, an average value of 300 m^3_{CH4}/t_{VS} was assumed for the energy calculations.

Considering the grass characteristics and the average BMP, 9 t_{FM} of grass per day was calculated in order to feed a 1,000 kW_{el} AD plant. Therefore, the daily harvested quantity would be enough to feed an AD plant with the fresh product. Considering this value, the surface area required to supply one plant for a year is about 126 ha with two cuts/y.

However, in order to maintain a good harvesting timeliness, two harvesting units should be used to supply one AD plant in the harvesting area. This entails doubling the grass harvested daily. The surplus daily quantity could then be ensiled in a bunker silo that has to have a volume of about 4,500 m^3 in order to stock a quantity of grass for one year, and a plastic cover of about 1,350 m^2.

8.3.4 Energy analysis

8.3.4.1 Indirect and direct energy

The indirect and direct energy inputs required for the grass production chain are reported in Table 23.

Table 23: Average indirect and direct energy inputs required for each grass production chain scenario

	DLA - 5 km		**DLA - 10 km**		**ILA - 5 km**		**ILA - 10 km**	
Operation	**IE**	**DE**	**IE**	**DE**	**IE**	**DE**	**IE**	**DE**
Mowing and harvesting (MJ/t $_{FM}$)	60	267	60	267	90	403	90	403
Logistics (MJ/t $_{FM}$)	45	203	83	375	21	103	39	176
Storage (MJ/t $_{FM}$)	67	70	67	70	67	70	67	70
Digestion (MJ/t $_{FM}$)	63	205	63	205	63	205	63	205
Digestate management (MJ/t $_{FM}$)	5	31	8	50	5	31	8	50
TOTAL (MJ/t $_{FM}$)	240	776	281	967	246	812	267	904
IE + DE (MJ/t $_{FM}$)	1,016		1,248		1,058		1,171	

The DLA presents a lower energy requirement on average than the ILA for the 5 km scenario while the ILA presents a better profile for the 10 km scenario. Although the difference between the two approaches is only slight at 5 km, with the increasing of the transport distance the ILA tends to be better under the energy profile.

Again, computing the influence of the moving and harvesting operations and logistic operations in respect to the whole energy demand it emerged that:

-in the DLA - 5 km the mowing and harvesting operation influence is 32%, while for the logistic operations it is 24%. For the scenario DLA – 10 km the mowing and harvesting operations have an influence of 26%, while the logistic operations 36%;

-in the ILA - 5 km the mowing and harvesting operations have an impact of 46% on the total energy costs and the logistic operations 12%. Instead, in the 10 km scenario the mowing and harvesting operations have an influence of 42% and the logistic operations 18% on the entire energy costs.

This reveals that, with the increasing of transport distance, in the DLA the influence of the logistic operations on the total energy costs becomes more conspicuous. Conversely, in the ILA, the logistic operations influence is generally lower, even when distances increase.

Considering the other operations of the grass production chain, their influence on the total energy demand are generally constant because these operations are not influenced by the transporting distance.

8.3.4.2 Energy saved

The biogas plant generally produces electrical and thermal energy and, as a result of the AD process, digestate.

The energy saved by the production of electrical energy amounts to 1,507 MJ/t $_{FM}$. This value, if only the electricity output is considered, can largely compensate the sum of the IE and DE costs of every scenario.

However, the highest energy output is thermal energy that amounts to 1,983 MJ/t $_{FM}$. Although this kind of energy is generally not fully utilized, biogas plants should valorize this energy source, for instance, by giving it to local authorities, such as the *Consorzio di Bonifica Veronese,* or to the community.

Finally, the digestate has the lowest output (165 MJ/t $_{FM}$). Although the energy content of this product is not evident, thanks to its intrinsic characteristic, digestate could provide an interesting opportunity for the improvement of soil fertility reducing the requirement for chemical fertilizers.

8.3.4.3 Cumulative energy demand

The Figure 24 illustrates the CED in each of the evaluated scenarios.

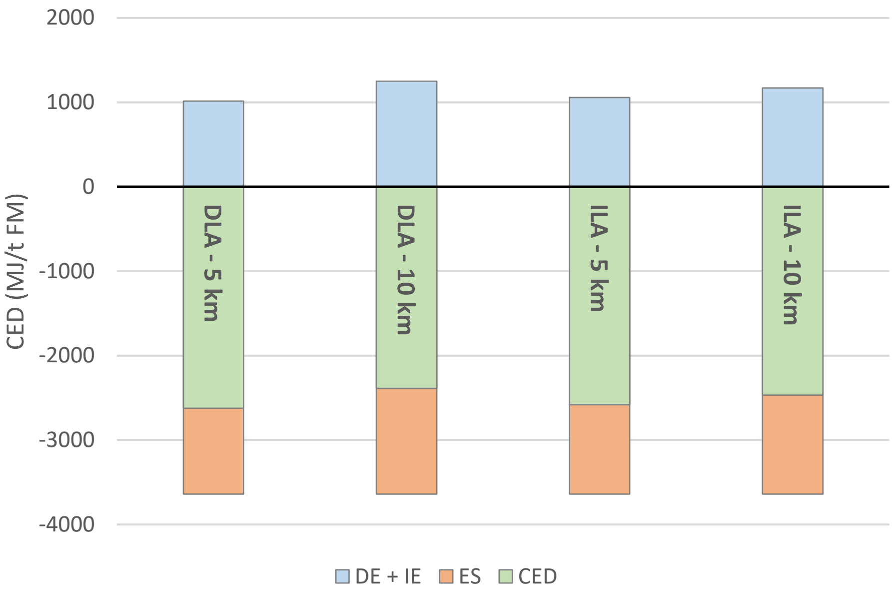

Figure 24: Representation of the CED computed for each of the logistic approaches

The average CED of DLA – 5 km and ILA – 5 km are quite similar and amount to -2,622 MJ/t $_{FM}$ (7,087 MJ/t $_{DM}$) and -2,581 MJ/t $_{FM}$ (6,976 MJ/t $_{DM}$) respectively, with a standard deviation of, ±12 and ±3 MJ/t $_{FM}$ (32 and 8 MJ/t $_{DM}$). Instead, the CED for ILA - 10km is -2,468 MJ/t $_{FM}$ (6,671 MJ/t $_{DM}$) and DLA – 10 km is -2,389 MJ/t $_{FM}$ (6,457 MJ/t $_{DM}$) with a standard deviation of ±24 and ±4 MJ/t $_{FM}$ (65 and 11 MJ/t $_{DM}$) respectively.
According to the multiple range test it emerged that there is a significant difference between the mean of each CED calculated for each logistic approach with a LSD of 95%.
Thus, when the supply distances are short, a DLA would be most appropriate solution because it allows more energy to be saved; an ILA results as being the best solution in terms of energy saving, when the supply distances are longer.

8.3.5 GHG analysis

8.3.5.1 Direct, indirect and fugitive GHG emissions

The direct and indirect emissions computed for grass recovery are reported in Table 24.

Table 24: Direct and indirect CO_2eq emissions emitted during the grass production chain

Operation	DLA - 5 km		DLA - 10 km		ILA - 5 km		ILA - 10 km	
	IE_{CO2}	DE_{CO2}	IE_{CO2}	DE_{CO2}	IE_{CO2}	DE_{CO2}	IE_{CO2}	DE_{CO2}
Mowing and harvesting (kg_{CO2eq}/t_{FM})	9.5	15.4	9.5	15.4	14.2	23.0	14.2	23.0
Logistics (kg_{CO2eq}/t_{FM})	7.2	11.7	13.3	21.5	3.3	6.0	6.1	10.1
Storage (kg_{CO2eq}/t_{FM})	3.0	0.8	3	0.8	3.0	0.8	3	0.8
Digestion (kg_{CO2eq}/t_{FM})	9.4	-------	9.4	-------	9 .4	-------	9.4	-------
Digestate management (kg_{CO2eq}/t_{FM})	1.9	3.5	3.1	5.7	1.9	3.5	3.1	5 .7
TOT (kg_{CO2eq}/t_{FM})	31.0	31.5	38.2	43.4	31.8	33.4	35.9	39.7
IE_{CO2} + DE_{CO2} (kg_{CO2eq}/t_{FM})	62.5		81.7		65.3		75.6	

The DLA allows a CO_2eq reduction of 3% on average in the 5 km scenario compared to the ILA while, for the 10 km scenario, the CO_2eq emissions increase on average by 9% over the ILA.

Computing the influence of the mowing and harvesting operations and logistic operations with respect to the whole direct and indirect CO_2eq emissions it emerged that:

-in the DLA at the distance of 5 km, the mowing and harvesting operations influence the entire emissions by 40% while the logistic operations affect the CO_2eq emissions by 30%. In the DLA – 10 km scenario the mowing and harvesting operations have an influence of 30% while the logistic operations 43%;

-in the ILA 5 km scenario the mowing and harvesting operations have an influence of 57% and the logistic operations 14%, while in the 10 km scenario the mowing and harvesting operations have an influence of 49% and the logistic operations 22%.

These aspects highlight similar trends of the energy balance: the logistic operations impact in DLA are dependent on the distance while in the ILA the logistic operations have less impact on both the direct and indirect CO_2eq emissions than the mowing and harvesting operations.

The fugitive emissions due to methane leaks amounted to 71 kg_{CO2eq}/t_{FM} for every scenario.

8.3.5.2 GHG emissions saved

One ton of fresh matter of grass has an electricity production potential of 325 kWh_e. Considering the fossil coefficient for the production of electricity assumed in this study, it corresponds to about 114 kg_{CO2eq}/t_{FM} of fossil emissions saved. This means that with the production of energy alone it is not possible to compensate the direct, indirect and fugitive kg_{CO2eq} emissions that were calculated in the previous section. Indeed, the advantage of these scenarios is achieved only when there is the possibility to exploit the additional thermal energy. The thermal energy of one ton of grass is 427 kWh_{th}, which corresponds to 98.3 kg_{CO2eq}/t_{FM} saved. This value, summed with the ES_{CO2} el, allows the total emissions calculated to be compensated.

Finally, the emissions saved by the digestate, assumed as 7.8 $kg_{CO2eq}/t_{f.m}$ are somewhat lower than the others.

8.3.5.3 GHG balance

The GHG balance is reported in Figure 25.

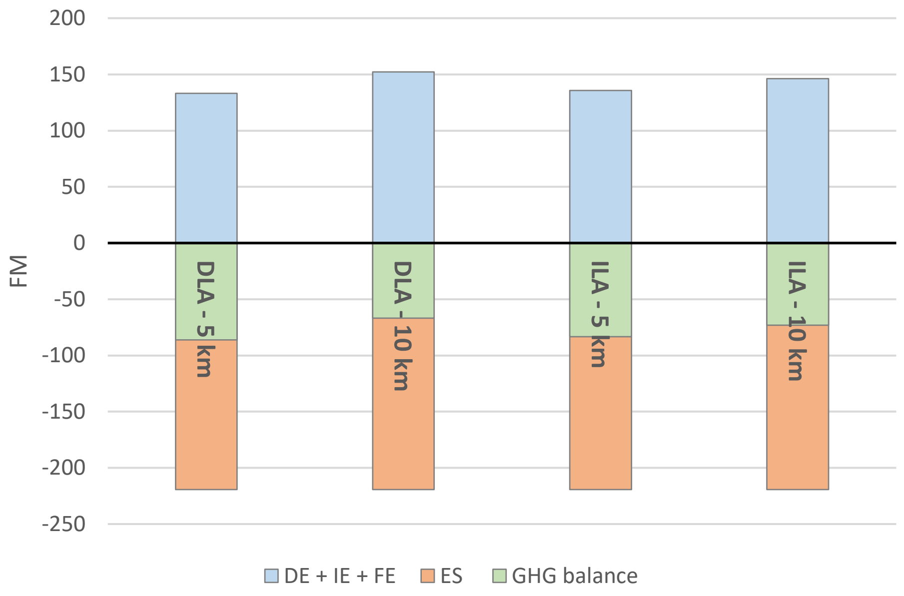

Figure 25: Representation of the GHG balance for each logistic approach

The DLA - 5 km allows 86.1 kg_{CO2eq}/t_{FM} (232.8 kg_{CO2eq}/t_{DM}) to be saved on average with a standard deviation of ±1.0 kg_{CO2eq}/t_{FM} (2.7 kg_{CO2eq}/t_{DM}), while the DLA-10 km GHG balance is 67.0 kg_{CO2eq}/t_{FM} (181.0 kg_{CO2eq}/t_{DM}) and a standard deviation of ±2.0 kg_{CO2eq}/t_{FM} (5.4 kg_{CO2eq}/t_{DM}). Conversely, for the ILA – 5 km the GHG balance is 83.4

kg_{CO2eq}/t_{FM} (225.3 kg_{CO2eq}/t_{DM}) while for the ILA – 10 km it is 73.0 kg_{CO2eq}/t_{FM} (197.3 kg_{CO2eq}/t_{DM}). Their standard deviation is ±0.2 and ±0.3 kg_{CO2eq}/t_{FM} (0.5 and 0.8 kg_{CO2eq}/t_{DM}) respectively.

According to the multiple range test it emerged that there is a significant difference between the mean of each GHG balance calculated for every logistic approach with a confidence level of 95%.

Anyway, although there are no notable differences among scenarios, according to the results obtained the DLA results as being the better solution for short distances. On the other hand, an ILA is more appropriate for longer distances.

8.4 Discussion

The utilization of grass collected within a local authority district for AD supply generally provides an interesting CED and GHG profile according to the balances computed in this study. Indeed, if all the grassy surface of the study area was converted into energy by AD, the energy and GHG savings from fossil sources could amount to about 24,880 GJ/y and 826 t_{CO2eq}/y respectively. Again, as emerged in the study, the DLA allows the energy and GHG impacts to be contained more accurately for short supply distances while the ILA results as better when the supply distances are longer.

Although this positive return would justify the utilization of such biomass in the AD supply chain, a comparison of this biomass with other common agricultural biomasses, such as maize silage, could define the energy and GHG efficiency of this biomass more accurately. Maize silage is the most widespread agricultural feedstock in Italian AD plants because of its highest achievable yield in terms of methane per hectare (Amon et al., 2007; Bacenetti and Fiala, 2015). Although its characteristics are favourable for AD, it competes with food production and requires high amounts of inputs for its cultivation, such as fertilizers, herbicides, pesticides and mechanization (Basso et al., 2016; Borin et al., 1997; Pezzuolo et al., 2014). Actually, a common AD plant in Italy requires from 220 to 350 ha cultivated with agricultural crops per year (Bartoli et al., 2016).

The integration of grass that comes from, for e.g., local authorities such as the *Consorzio di Bonifica Veronese* could alleviate these problems with a positive impact from the energy point of view. Indeed, while the CED for the production of 1 ton of maize, computing both the direct and indirect energy, corresponds to a value of between -5,500 MJ/t $_{DM}$ and -9,000 MJ/t $_{DM}$ depending on the biomass yield per ha (Manzone and Calvo, 2016; Sartori et al., 2005), the CED of grass from marginal lands computed in this study is between -7,000 MJ/t $_{DM}$ and -6,800 MJ/t $_{DM}$.

However, according to the GHG balance, the CO_2eq saved by maize silage AD amounts to about 450 - 260 kg$_{CO2eq}$/t $_{DM}$ (Felten et al., 2013; Manzone and Calvo, 2016) while the CO_2eq saved by grass amounts to 230 – 180 kg$_{CO2eq}$/t $_{DM}$.

Although the GHG profile of grass is lower than maize, this result could offer positive prospects for the integration of feedstocks, such as grass, from non-cultivated areas or landscape management into the AD supply chain. In fact, although these biomasses present lower energy and GHG performances than energy crops, they do not compete with food production and their management today represents a negative cost for the community.

8.5 Conclusions

The aim of this study was to assess the energy and greenhouse gases impacts of grass harvested in non-cultivated areas as integrative biomass for an AD supply chain. The results show that the recovery of grass for energy purposes is sustainable under energy and GHG aspects. However, in order to obtain the highest energy and GHG balance outcomes, the logistic approach in the grass production chain should be planned properly. In fact, while a direct logistic approach generally presents a less inputs in terms of energy and GHG when transport distances are short, an interrupted logistic approach gives the possibility of slightly reducing the energy and GHG impacts for longer supply distances.

Comparing grass with other agricultural biomasses such as maize silage, grass biomass presents a lower cumulative energy demand and greenhouse gases balances. Anyway, these points suggest that the recovery of this kind of biomass could provide an interesting energy source and opportunity that should be implemented in the future in the AD supply chain in order to reduce the dependency of this sector on energy crops and obtain a positive return, in terms of energy and emissions saved, from the landscape management operations.

9. CONCLUSIVE CONSIDERATIONS

This thesis focused on the valorisation of grass from uncultivated areas in the AD supply chain.

This biomass, which is still poor utilized in the AD supply chain, if recovered from uncultivated areas could be of interested due to non-competition with food production. In a first study, we demonstrated through a GIS based approach that large availability of residual grass is present in the Veneto Region, which it could be potentially utilized for AD. As matter of fact, more than 150 anaerobic digesters are in operation and feedstock availability can be sometime problematic due to competition of local land grabbing.

Although uncultivated grassy areas are scarcely centralized and grass residues can be often categorized as a waste, grass originating from riverbanks, natural parks or rural areas is clean and, therefore, it can be used in the same way of dedicated energy crops. However, in order to valorise these areas, a proper strategy for grass recovery is required. Generally, the main problems on grass harvesting in these areas are related to the terrain conditions. Difficulty of access, small spaces for manoeuvrability, relief and obstacles limit the harvesting operations to only a specific mechanisation that implies high mowing and harvesting costs, both under economic and energy aspects, making the biomass valorisation unfeasible. As matter of fact, due to accessibility and manoeuvrability problems not all the systems can be proper for grass mowing and harvesting. The right choice of the system should be based on the area characteristics. However, systems with better operative performances can reduce the economic and energy costs.

In this optic, we have seen that the cheapest mowing machineries could be flail mowers or disc mowers, whereas the more appropriate solutions for harvesting could be self-loader wagons. However, in difficulty areas arm brush cutters equipped with a sucking system could be a viable solution.

Conceiving grass logistic, direct transport chain seems to be the most convenient solution under economical and energy aspects for the management of such material in short distances due to less mechanisations inputs requirement; conversely, in longer distances, the best solution appears to be the interrupted transport chain due to the higher transport capacities. Nevertheless, problems related to low energy density of grass biomass should be solved in order to reduce overall costs. As matter of fact, a development of machineries more adaptable to the working conditions would improve grass management. In this sense, we have tested a designed purposed machinery aimed at increasing the energetic exploitation of the herbaceous biomass from grass-planted vineyards, orchards and riverbanks, finding that a reduction of grass harvesting costs is possible with a more suitable technology (Chapter 11), opening interesting opportunities for overall costs reduction.

Investigations about grass BMP show that the energy potential that can be recovered from this biomass is interesting, quite comparable with the used energy crops. Some problems related to the AD of this feedstock should be solved due to the tendency of float inside the digesters. In this optic, future scenarios could consider the possibility of pre-treat grass before to be digested inside the digesters in order to solve this problem.

Closing the whole energy and greenhouse gases balances, the results show that there is a positive energy and GHG return from grass valorisation. Comparing grass with other agricultural biomasses such as maize silage, grass biomass presents a lower cumulative energy demand and GHG balances. However, in order to obtain the highest energy and GHG saving, the distance from the AD plants should be as lower as possible.

These points suggest that the recovery of this kind of biomass could provide an interesting energy source and opportunity to reduce the dependency of this sector on energy crops and obtain a positive return, in terms of energy and emissions saved, from the landscape management operations, creating also job opportunities. In this sense, and considering that the average size of anaerobic digesters in Veneto is larger than 600 kW, grass could be a partial substitute of other biomasses like energy crops in co-digestion with manure. Indeed, only considering grass potentially collectable in landscape management in rural areas or in water courses management, equivalent to 495,000 t wet weight or 198,999 t DM/year, which can be used in the 140 AD farm plants, 100,000,000 m^3 biogas/annum can be generated. This is equivalent to about 220,000 MWh of electric energy which can cover the energy use of approximately 68,000 families. Alternatively, some 50 million m^3 of biomethane for the automotive sector can be generated with more than 90% reduction in CO_2 emissions (4–5 gCO_2eq/MJ fuel).

Deeper studies about grass valorisation impacts could consider also the opportunity to evaluate the Life Cycle Assessment of this biomass, in order to account all the impacts of the grass valorisation chain. Additionally, alternative use of grass as biomass for the treatment of the resulting digestate reveals interesting scenarios. As matter of fact, we have demonstrated also that valorisation streams of grass could involve in composting for digestate management opening interesting perspectives for the reduction of mechanization inputs due to the less amount of product to dispose (Chapter 12).

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ANNEXES

11. PRELIMINARY EVALUATION OF THE PERFORMANCES OF A PURPOSE DESIGNED MACHINE FOR GRASS HARVESTING AND PRE-PROCESSING IN ORCHARDS, VINEYARDS AND UNCULTIVATED AREAS

One specific combined machine, aimed at increasing the energetic exploitation of the herbaceous biomass from grass-planted vineyards, orchards and riverbanks, has been designed and manufactured by BERTI Macchine Agricole (Caldiero, Verona, Italy). Compared to the technical solutions already available in the market, it allows to cut, pre-process and harvest the grass (whose average biogas potential is 356 ± 100 Nm^3/t_{VS}) in one passage, pushing forward the sustainability and the profitability of the supply chain. Machine testing in vineyards showed it has adequate manoeuvrability and operative performances: the operative working rate of 0.94 h·ha-1 and the 3.33 m^3 effective capacity of the loader make it capable to mow, harvest and shred up to 283 m of fruit trees/vines rows at a time allowing the supplying of up to 6.7 t of grass to the biogas plant.

11.1 Introduction

Biogas production has been intensifying throughout Europe in such a way that concern about the sustainability of agricultural biogas units has arised (Boscaro et al., 2017).
As a matter of fact, energy crops (biomasses whose volatile solids –VS – content per unit mass of feedstock is higher than raw manure) if on the one hand allow the achievement of higher biogas productions, compared with raw manure (Fantozzi and Buratti, 2009), on the other have been leading to a global reconsideration of the biogas production chain because of the reallocation of some resources, including agricultural products and land, for bioenergy production (Auer et al., 2017). Energy crops and residues are a renewable energy resources with significant potential: the former have the disadvantage of creating competition between food and non-food products on arable land, the latter need specific supplying chains to be set up (Pezzuolo et al., 2017).
Given the increasing importance of AD for biogas/biomethane production, the need to retrieve adequate amounts of feedstocks not competing with food production is actually essential and has led to the consideration of agricultural wastes, by-products and

perennial biomass crops (Baldini et al., 2017; Caicedo et al., 2016; Kiesel and Lewandowski, 2017).

Herbaceous biomasses in particular are of great interest, provided that their exploitation is followed by adequate mechanization (needed to not only solve the problem of labour shortage, but also to enable ease of transportation and reduced costs) and logistics (Neiva de Figueiredo and Mayerle, 2014).

Although it is not used for energy purposes, grass is widely available within the territory: reclamation areas and/or rural areas (including vineyards and orchards) could become reservoirs providing significant amounts of it (Boscaro et al., 2015). Because of the economy of its production (actually it hasn't direct costs) and of the absence of competition with food production (Carlsson et al., 2017), grass is an important potential feedstock for agricultural biogas units even though there are some disadvantages considering the use of grass instead of energy crops in AD mainly related to the intrinsic lower energy density of grass and the lower hydrolysis rate and consequent need for prolonged retention time in the reactor. Its average methane potential is about 300 Nm^3_{CH4}/t_{VS} (Table 25) that is almost the half of that of maize silage.

In the North West European Regions herbaceous biomass is supposed to become the most important agricultural biomass for biogas production (McEniry and O'Kiely, 2013; Prochnow et al., 2009) and studies aimed at defining the operational settings to optimize the AD of grass silage as well as at defining the methane potential of the mown grass from roads and highways margins (Meyer et al., 2014; Wall et al., 2014).

In case of monodigestion of grass silage, the organic loading rate (how many kilograms of organic solids are loaded per m^3 of digester volume and unit of time) enabling the better exploitation of such biomass has been set at 3,5 kg_{VS} m^3/d (Wall et al., 2014).

Among the main problems which still limit the development of a specific valorization chain there is the high cost of herbaceous biomass recovery. In particular, the costs related to the cut, the collection and the logistics turn out to be particularly marked: specific mechanization, harvesting efficiency and logistics rationalization are the targets that should be achieved (Wall et al., 2014) to set up a reliable supply system also under a bio-economic perspective (Lewandowski, 2015).

It follows that vineyard/orchard cover cropping practices, besides the well-known agronomic benefits (Ingels and University of California (System). Division of Agriculture and Natural Resources., 1998; Steenwerth and Belina, 2008), can effectively provide for a valuable energetic potential of biomass with subsequent saving of land that can be more suitably addressed to produce food crops: such action is consistent with the Community provisions for increasing the share of renewable energy to 20% in 2020 (European Parliament, 2009).

The design and the making of an herbaceous biomass harvesting/pre-processing/transport system would therefore increase the availability of "no food" products expanding the existing markets towards bioenergy and coproducts: one aspect actually considered basilar in framework of a global transition towards bioenergy (Williams, 2016).

Table 25: some example of grass anaerobic biogas/methane potential retrieved from literature

Biogas/Methane potential	**Biomass Characterization***	
356.5 ± 100.1 $Nm^3\, t_{VS}^{-1}$ of biogas (CH_4 = 40%)	TS = 57.2% t.q. VS = 90.2% TS	Marchesi et al. (2010)
344 - 383 $Nm^3\, t_{VS}^{-1}$ of CH_4	TS = 201-265 g kg^{-1} VS = 59.2 – 69.4% TS	McEniry et al. (2014)
220 – 390 $Nm^3\, t_{VS}^{-1}$ of CH_4	TS: 18.6 – 28.4% VS: 76.6 – 93.9%	Meyer et al. (2014)
360 – 414 $Nm^3\, t_{VS}^{-1}$ of CH_4	TS = 293 g kg^{-1} VS = 91.5% TS	Wall et al. (2014)

* TS = Total Solids; VS = Volatile Solids

With this aim BERTI Macchine Agricole (Caldiero, Verona, Italy) designed and manufactured a novel all-in-one machine for grass mowing, harvesting, shredding and transport to be used in grass planted orchards, vineyards and non-cultivated areas in order to improve the overall economy of grass mowing and harvesting operations.

11.2 Material and methods

11.2.1 Prototype design and built up

The initial concept of the prototype was a rear mounted half-suspended in line flail-mower: it was made of one rotor shaft (159 mm diameter) with hinged bats (1.8 kg each) holding counter-reciprocating cutting elements.

Thanks to a belt transmission the flail rotor turns at the speed of 2.300 min-1 with the power take off (PTO) set at 540 rpm min-1 blowing the processed biomass in a container (2.1 m^3 of volume).

Starting from this, the development of the machine included the addition of: i) two frontal adjustable blade mowers; ii) one 4 m^3 rear shredder-vacuum self-loader wagon equipped with frontal sliding bulkhead and mounted on twin arm pantograph (Fig. 26).

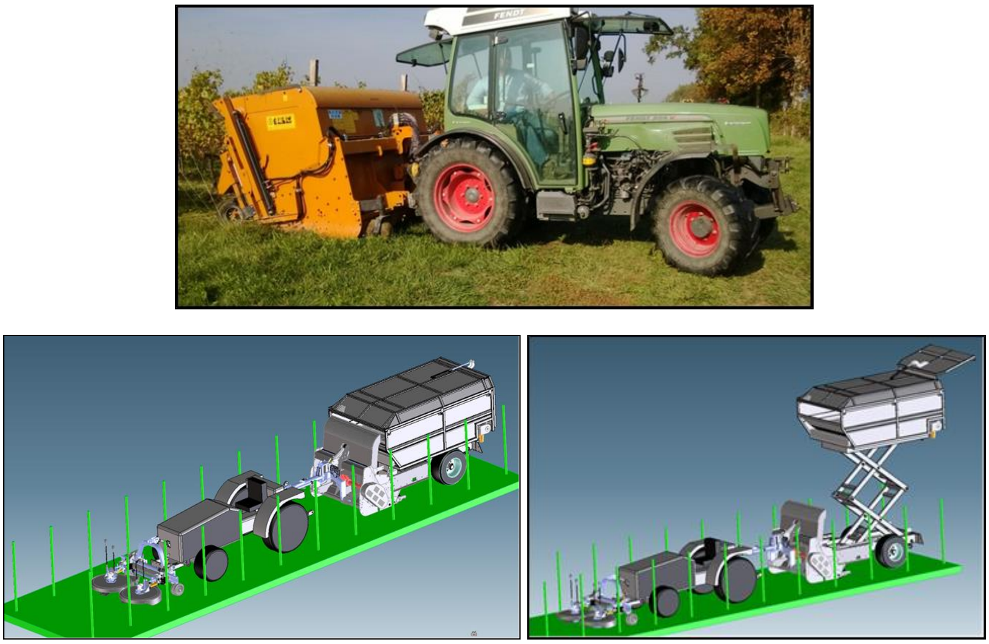

Figure 26: On the top, the first version of the prototype used as reference (year 2013); in the middle and below, rendering pictures of the designed machine describing grass harvesting (on the left) and biomass unloading (on the right) [Courtesy of BERTI Macchine Agricole]

11.2.1 Field testing

Field testing was carried out in one winery placed in Fossalta Maggiore di Chiarano (Treviso, Italy) and in one farm placed in Caldiero (Verona, Italy). During the former testing activity, the machine was tested to verify:

i) its suitability in entering the rows of vines and in performing turns at the end of the row;

ii) the proper collection of the mown grass in the container.

Figure 27: The current version of the machine while exiting the row of vines in Fossalta Maggiore di Chiarano, Treviso, Italy (year 2016)

The testing pointed out three main criticalities: the machine was difficult to steer in and out from the rows of trees, the mown shredded grass did not evenly distribute inside the container and during compaction there was a spill of processed biomass from the container.

Following the results of this testing the machine was improved accordingly:

- Increase of machine manoeuvrability: the coupling drawbar was shortened and frontal blade mowers were equipped with adjustable extensions allowing the widening of the work width as well as their folding in vertical position when idle.
- Increase of biomass compaction inside the container: the height of the frontal sliding bulkhead was increased to prevent the spill of shredded grass during compaction; subsequently, the opening of the loading manifold was raised above the top of the new compacting element.
- Increase of the workload: the loading manifold was given conical shape with subsequent increase of the speed of the blown air to increase the distribution and the transport of the shredded grass inside the container and prevent potential clogging due to high amounts of product. With the same purpose, the

rotor shaft speed was set to 3,000 min-1 to increase the airspeed (and the flux of product) inside the connecting channel. The newly shaped loading manifold was split in two parts to allow the lifting and the tilting of the container.

In Caldiero the final version of the machine underwent full testing to check its proper functionality.

11.3 Results and discussion

11.3.1 The final prototype

The machine comprises two functional components: i) two adjustable blade mowers that, mounted frontally to the tractor, cut the grass and put it in windrow in the width track; ii) one 4 m^3 shredder-vacuum self-loader wagon equipped with frontal sliding bulkhead and mounted on twin arm pantograph: this, placed behind the tractor, compresses the biomass allowing its volume reduction (Fig. 28).

The counter rotating blade mowers, hydraulically connected to the tractor, can be moved to be adapted to the spacing between the rows of trees so that the working width ranges from 2,200 to 3,000 mm. They are covered by protection carters driving the mown grass towards the centre of the carriage to be subsequently picked up by the self-loader wagon whose working width is 1,640 mm (Fig. 28). When not in use, their width varies from 2,000 mm to 1,050 mm when vertically folded (Fig. 29, on the left).

The self-loader wagon, pulled by the tractor and hydraulically connected to it, is equipped with a frontal sliding bulkhead that can be moved towards the back of the wagon to compact the shredded harvested grass (Fig. 29). It is mounted on twin arm pantograph to allow the unloading of the biomass in agricultural wagons or directly in the hopper of the solid feeding system in case the addition of the biomass is done directly into the fermenter (Fig. 26, on the right and Fig. 30).

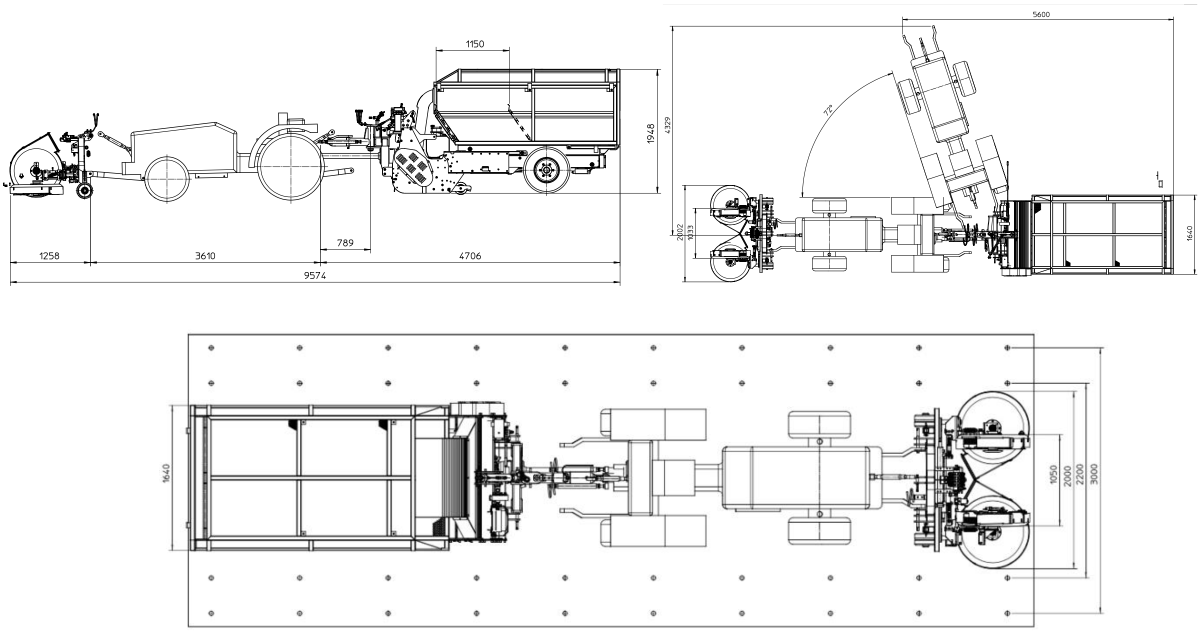

Figure 28: Technical drawings of the final version of the machine [Courtesy of BERTI Macchine Agricole]

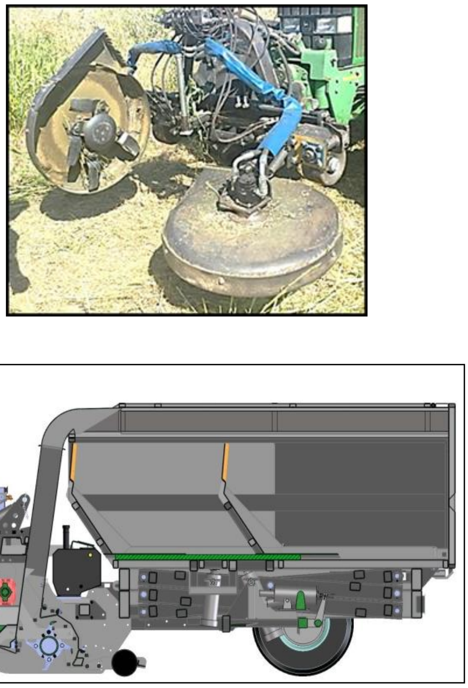

Figure 29: Detail of the counter-rotating blade mowers folded in vertical position (above) and technical rendering that describes the operating of the rear biomass loading/shredding unit (on the right). [Courtesy of Berti Macchine Agricole]

Figure 30: herbaceous biomass download on a trailer (above) or on a site at ground level (below)

11.3.2 Field Testing

The designed prototype has been tested in operative conditions in the two sites (Table 26). The operative working rate resulted to be of 0.94 h·ha-1 with the effective capacity of the loader of 3.33 m^3. This makes the machine capable to mow, harvest and shred up to 283 m of fruit trees/vines rows that corresponds to 2.06 t ha-1 of grass (on wet basis).

Overall, compared to some previous models (Table 27 and Figure 31), the presented machine allows:

- +11 % increase of the amount of harvested grass, on equal terms of row length, following the wider and adjustable working width;
- + 60% increase of biomass density
- -68% of the time requested to unload the biomass;
- +51% increase of the working rate on equal terms of forwarding speed
- +36% of machine efficiency

The length of the machine causes it to need higher times (+ 15%) to turn at the end of the rows of trees and, the power required for its operating requires it to be attached to tractors of adequate nominal power.

According to results, the designed machine can effectively improve the efficiency of the herbaceous biomass supply chain with reference to mowing and harvesting operations: nevertheless, the correct sizing of the whole logistics remains of fundamental importance for the exploitation of grass along riverbanks to supply AD plants.

Currently, grass mowing and harvesting operations require from two to three passages at varying of the machine and this affects harvesting total costs as well as logistics efficiency and working rate. Introducing a purpose designed combined machine capable to carry out grass mowing and harvesting in one passage would improve both the economy of the agricultural operation and of the whole feedstock supply chain.

Table 26: Characterization of the herbaceous biomass mown during the field test carried out in 2013 (with the first version of the prototype) and 2016 (with the current model)

Replicates	**Fossalta di Chiarano (TV). May 2013**			**Caldiero (VR). August 2016**		
	Moisture (%)	**Yield (t_{FM} ha)**	**Yield (t_{DM}/ha)**	**Moisture (%)**	**Yield (t_{FM}/ha)**	**Yield ($t_{DM/}$ha)**
1	58.8	8.75	3.61	75.1	17.2	4.30
2	53.4	8.20	3.82	68.1	1.70	0.50
3	73.3	6.82	1.82	73.2	9.20	2.50
4	74.5	6.81	1.74	78.9	4.90	1.00
Average:	65.0 ± 10.5	7.65 ± 0.98	2.75 ± 1.12	73.8 ± 4.50	8.25 ± 6.71	2.08 ± 1.71

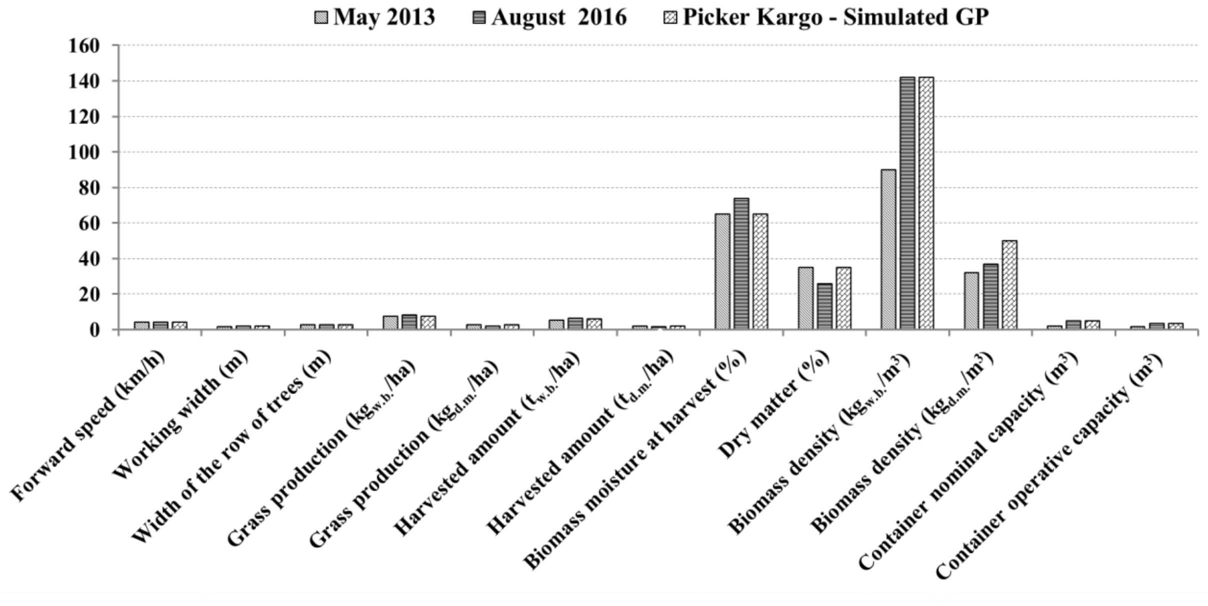

Figure 31: comparison of the measured operative parameters among the different versions of the prototype

Table 27: Operational parameters acquired during field testings

	May 2013	Aug 2016	Picker Kargo-Simulated GP
Container effective capability (t_{FM})	0.14	0.47	0.47
Filling index (%)	0.71	0.68	0.68
Container autonomy (m of row of trees)	98	285	309
Working rate ($h\ ha^{-1}$)	0.87	0.94	0.87
Turning time (s)	25	29	29
Turning times (100 m rows) ($h\ ha^{-1}$)	0.27	0.31	0.31
Unloading time (s)	75	75	75
Unloading times ($h\ ha^{-1}$)	0.82	0.28	0.26
Machine efficiency	0.45	0.61	0.61
Effective field capacity ($ha\ h^{-1}$)	1.14	1.07	1.14
Effective field capacity($t_{FM.}\ h^{-1}$)	6.06	6.81	6.73
Effective field capacity ($t_{DM}\ h^{-1}$)	2.12	1.77	2.36
Operative field capacity ($ha\ h^{-1}$)	0.51	0.65	0.69
Operative field capacity ($t_{FM.}\ h^{-1}$)	2.70	4.18	4.08
Operative field capacity ($t_{DM}\ h^{-1}$)	0.94	1.09	1.43

11.4 Conclusions

The designed prototype has an operative working rate of 0.94 h·ha-1 with the effective capacity of the loader of 3.33 m^3 enabling it the autonomy to mow, harvest and shred up to 283 m of fruit trees/vines rows. The operational feasibility and the subsequent correct sizing of the mowing and harvesting system is of fundamental importance for the exploitation of grass along riverbanks to supply AD plants.

12. COMPOSTING OF DIFFERENT AGRICULTURAL BY-PRODUCTS WITH RAW DIGESTATE: PRELIMINARY CONSIDERATIONS ABOUT TECHNICAL FEASIBILITY

Introducing a composting treatment of raw digestate could provide an interesting opportunity to facilitate the handling due to the volume reducing of by-products to dispose. In order to achieve the right conditions for the composting process, absorbing solid substrates are required.

This work presents the preliminary results related to the technical feasibility of this process utilising different mixtures of absorbing agents. Three different formulations of adsorbing agents with the adding of different amounts of raw digestate were tested for a period of 90 days.

The preliminary results show that the process is feasible under technical aspect, allowing the obtainment of an organic fertilizer respecting the quality parameters required. Interesting results have been obtained considering the reduction of weight and volume. As matter of fact, the composting process could imply a reduction in a range between 78-86% of the initial total weight.

These preliminary results suggest interesting perspectives for the management of liquid agricultural wastes allowing the reduction of mechanisation inputs needed for their disposal.

12.1 Introduction

Livestock waste management plays a key role for the reduction of the environmental impact of farming (Basso et al., 2016). This has strongly encouraged the re-use of animal sewage as raw material for AD (AD) and has been leading to a global reconsideration of farm effluents that, from refuse, are being understood as a resource (Bacenetti et al., 2013; Mata-Alvarez et al., 2000). As matter of fact, AD represent a valid solution to recover energy in form of biogas, a high value product usable for energy production or as bio-fuel for transportation (Prade et al., 2012).

The integration of AD in the agricultural cycle makes available a wide quantity of interesting organic fertilizer for the farm, the digestate. In fact, in this resulting by-product, nutrients contained in raw manure/slurry are still present, but with an improved availability (compared with raw manure) due to higher rates of mineralisation (Alburquerque et al., 2012; Möller and Müller, 2012). This make this by-product very interesting for soil fertilisation and nutrient reintegration during plant growing allowing the closing of waste production cycle towards an optic of a circular economy, where wastes turn as feedstock for new valorisation processes and the final by-products are reintegrated allowing the restarting of a new productive cycle (Lazarevic and Valve, 2017).

Digestate reintegration into the agricultural fields usually is performed in a liquid or solid form throw slurry tankers or manure spreaders. The amount of the liquid and solid part to dispose generally depends on the configuration and wideness of the AD plant, anyway generally the quantity of the liquid part is noticeably higher than solid. Besides, the spreading of digestate is regulated by EU Directive 91/676/EC, in which nitrate vulnerable zones have been set with strict regulations regarding the timing and rates of nitrogen application. In the vulnerable zones, a specific threshold limits the application rate to 170 kg/ha per year for nitrogen whilst, in the remaining areas, the threshold is 340 kg/ha. These factors imply a strong request in term of mechanisation inputs due to the high amount of volumes to spread and limitations in terms of time and volume per hectare requiring wide surfaces for the waste disposal (Brambilla et al., 2015; Calcante et al., 2015).

Although digestate is an already stabilize product that would not need additional processes before its utilisation, introducing a composting treatment of liquid digestate could provide an interesting opportunity to facilitate the handling of this material due to the volume reducing of by-products to dispose (Chiumenti, 2015; Himanen and Hänninen, 2011). When operated for liquid substrates, the main concerns of composting comply with a low dry matter content that does not create the right conditions for the starting of the process. For this reason, an addition of absorbing substrates is needed in order to create the proper composting start up (Bustamante et al., 2012).

Absorbing feedstocks can be represented by non-utilised agricultural residues derived from agricultural productions or biomasses derived from landscape management, such as grass or brushwood (Hensgen et al., 2011; Meyer et al., 2014; Tsapekos et al., 2017a).In fact, these circumstances could lead to the possibility of recover organic matter reusable for soil fertilization from uncultivated areas and to expand the marked for this product (Boscaro et al., 2017, 2015; Romano et al., 2014).

With the aiming to assess the possibility of composting the raw digestate with the adding of solid absorbing feedstocks, this work presents the preliminary results related to the technical feasibility of this process utilising different mixtures of absorbing agents.

12.2 Material and methods

12.2.1 Preparation of the composting process

Three different formulations of adsorbing agents with the adding of different amounts of raw digestate were tested for a period of 90 days. The composters were made of black polyethylene containers, with a total volume of 110L. The substrates were mixed by a pitchfork generally one time per week during the thermophilic phase in order to give the proper aeration for the composting process. Nevertheless, no forced aeration was applied to the composters.
The mixtures were prepared following these proportions based on a wet weight basis:

-C1: 90% grass, 10% of inoculum;
-C2: 62% grass, 28% of wheat straw, 10% of inoculum;
-C3: 62% grass, 28% of vine shoots pruning, 10% of inoculum.

Grass derived from the management of the meadows present at Agripolis University (Legnaro, PD). It was composed principally by *Poaceae spp.,* such as *Poa spp.*, and *Festuca spp.*, with a slight presence also of *Asteraceae spp*. It was collected by a lawnmower and successively it was dried for one day under ambient conditions in order to reduce its dry matter (DM) content. Wheat straw and vine shoots pruning were taken from a farm close to university. An inoculum derived from the solid part of digestate was also added in order to provide the right microbial flora for the composting start up. The physical and chemical characteristics of all substrates are reported in the Table 28.

Table 28: Physical and chemical characteristics of the initial substrates utilized for the composting process

Substrate	**T.S. (%)**	**V.S. (%)**	**TN (% T.S.)**	**TOC (% T.S.)**	**C/N**
Grass	93.9	89.5	2.1	45.1	21.5
Wheat Straw	91.1	96.6	0.9	42.3	47.0
Vine shoots pruning	85.2	96.9	1.2	46.1	37.5
Inoculum	25.6	92.3	2.0	44.3	22.4
Raw digestate	8.0	81.3	2.5	43.2	16.9

The particle length of the substrates was also characterized (**Figure 32**).

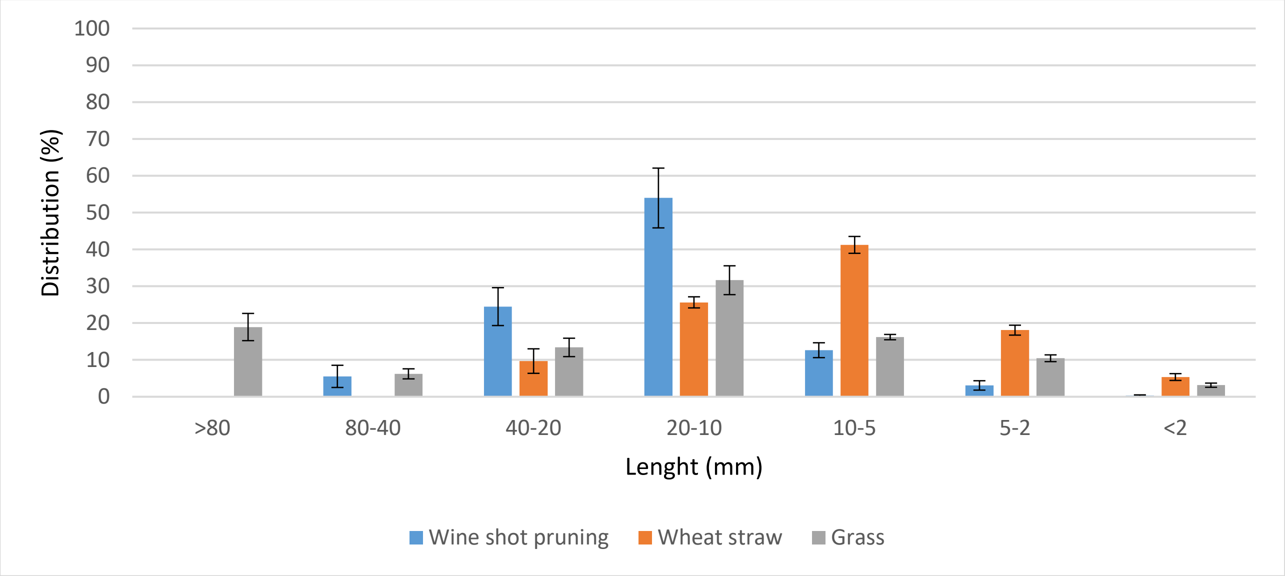

Figure 32: Distribution of the particle length of the several substrate utilized as adsorbing

Grass substrate presented an inhomogeneous particle length due to the different size of its fibers. On the other hand, straw substrate presented a lower particle length mostly concentrated in the interval between 40 and less than 2mm while the vine shoots pruning presented a particle length mostly concentrated between 20 and 5mm.

Once the mixtures were prepared, raw digestate was added at the starting phase and then two times, respectively at the 3rd and 10th day, after the composting initializing (Table 29).

Table 29: Substrates and digestate composted in the several thesis

Mixture	**Grass (kg FM.)**	**Wheat straw (kg FM.)**	**Vine shoots pruning (kg FM.)**	**Inoculum (kg FM.)**	**TOT absorbing agents (kg FM.)**	**Digestate (kg FM.) Day 0**	**Digestate (kg FM.) Day 3**	**Digestate (kg FM.) Day 10**	**TOT digestate (kg FM.)**
C1	7	-	-	0.8	7.8	14	0	2	16
C2	5	2.3	-	0.8	8	22	1	2	25
C3	5	-	2.3	0.8	8	24	1	2	27

The major quantity of digestate was added in the starting phase in order to create the conditions in terms of moisture content and C/N ratio for the composting process. Then during the thermophilic phase of the composting a low amount of digestate was added to control the water evaporation of the composters. Raw digestate was collected from a mesophilic plant that operate only with cow sludge wastes.

12.2.2 Physical and chemical analysis

During the composting process, measurement of temperature and weight of the mixtures were performed, respectively, daily by means of portable Pt100 probes and weekly by means of a digital scale. Total solids (TS), Volatile Solids (VS) were determined weekly according to the standard methods (*Standard methods for the examination of water and wastewater volume 4.*, 2013). Process parameters, represented by reduction–oxidation potential (redox) and oxygen concentration were also collected, respectively, by means of electrolytic probe with data-logger (SHP 02, Steiel, Italy) and by means of a DO 9709 (Delta OHM, Italy) data logger with electrolytic probe (Hamilton, Switzerland).

Total Nitrogen (TN), Total organic Carbon (TOC) were also determined by means of an elemental analyser (Macro Elementar, Elementar Analysensysteme GmbH) while the final product was subject to the determination of the Germination Index (GI) and Humification Index (HI). The GI was carried out on water extracts by mechanically shaking the fresh samples of compost for 1 h (sample: distilled water ratio 1:10 – w/v, dry weight basis). 5.0 mL of each extract was pipetted into a sterilized plastic petri dish lined with a Whatman filter paper. Thirty cress seeds (*Lepidium sativum L.*) were placed on the filter paper and incubated at 25 °C in the dark for 48 h. The test were evaluated by counting the number of germinated seeds, and measuring the length of roots and if GI is >0.60 the compost is defined as non phytotoxic (Tambone et al., 2015; Zucconi et al., 1981). HI was determined according to the procedures proposed by De Nobili and Petrussi (De Nobili and Petrussi, 1988). This parameter is calculated as ratio between non humified fraction (NH) and the humified fraction, represented by Humic Acids (HA) and Fulvic Acids (FA) (Chiumenti, 2005), as reported in the following equation:

$HI = NH / (HA+FA)$ $HI = NH / (HA+FA)$

HA and FA are determined by chemical extraction with alkaline sodium pyrophosphate and adsorption on polyvinyl pyrrolidone columns. If the value of HI is less than 0.5, the compost is classified as stabilized (De Nobili and Petrussi, 1988).

12.3 Results

12.3.1 Evolution of temperature

The monitored temperature during the composting process of the different mixtures is reported in the Figure 33.

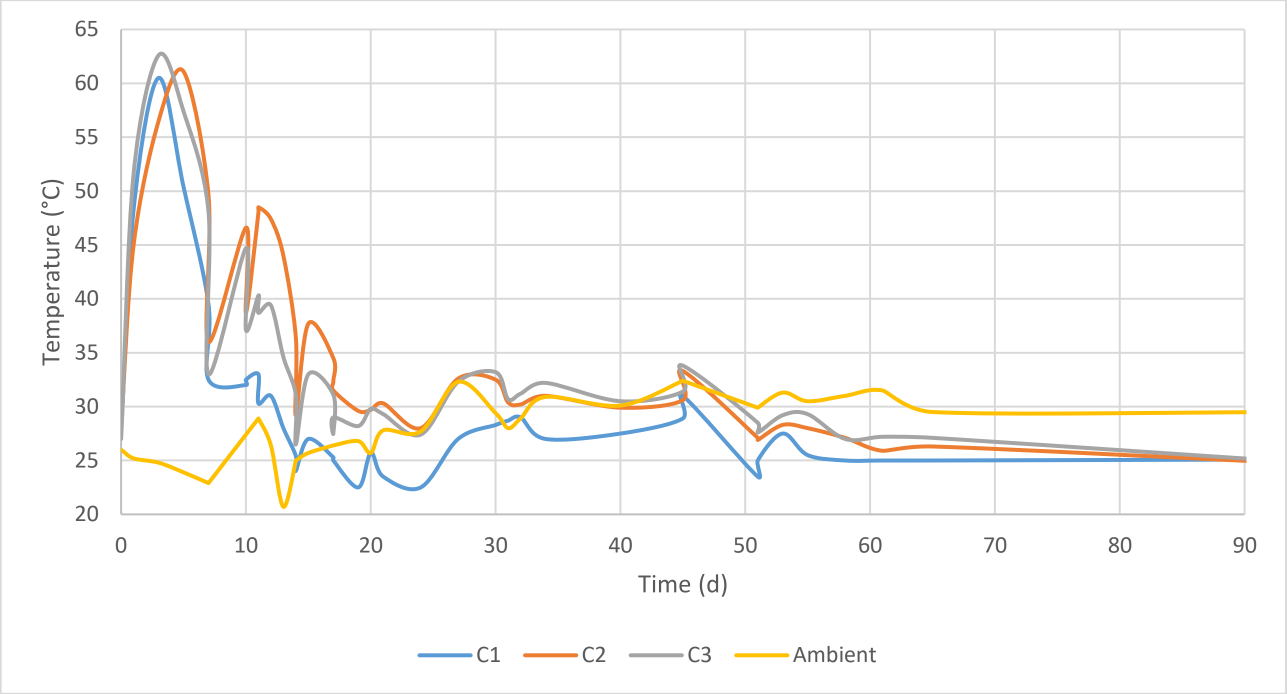

Figure 33: Evolution of the temperatures of the different compost mixtures

Temperature is one of the main parameters useful to monitor a composting process since its variation is well correlated to the intensity of the breakdown of bonds of organic matter operated by the microorganisms (Chiumenti, 2015; Tambone et al., 2015).

From a biological point of view, three intervals govern the composting process: temperatures above 55 °C to maximise sanitisation, between 45 and 55 °C to improve the degradation rate and between 35 and 40 °C to increase microbial diversity (Bustamante et al., 2013; Stentiford, 1996). The intensity and duration of high temperatures depends on many factors, including oxygen level, moisture of the feedstock, C/N, availability, and degradability of organic matter.

The mixtures tested present an optimal temperature evolution indicating that the substrates utilized are high adapted for the proliferation of the right microbial species for composting. As matter of fact, it is markedly evident that at the beginning of the process the temperature increase evidently reaching the thermophilic conditions during the first treatment week. The maximum temperatures have been of, respectively, 60.5 °C for the C1, 61.1 °C for the C2 and 62.6 °C for the C3, meaning also that the right conditions for the sanitation of the substrates were achieved. In the period between the 8^{h} and 17th day the temperature generally tends to drop in the mixture C1 while in the mixtures C2 and C3 the temperature growth again probably due to the last addition of digestate. This means that in the grass mixture the bio-oxidative phase was finished before than the other two mixtures and the adding of digestate did not recreate the right condition for the re-starting of the composting process. The thermophilic phase of the mixtures was considered as concluded when the temperature was close to the ambient temperature, and then the stabilization phase started.

12.3.2 Mass balance

The mass balance of the composting process of the different mixtures is reported in the Figure 34.

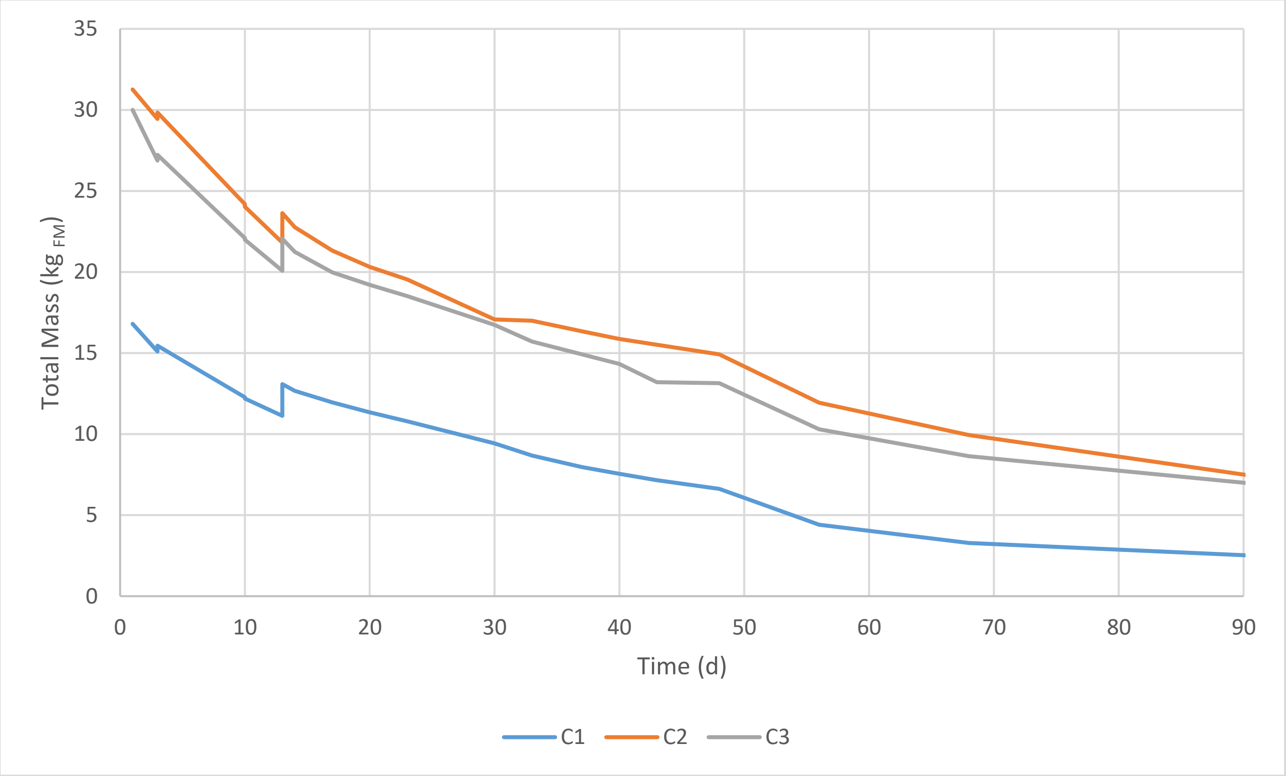

Figure 34: Mass balance based on wet basis of the different mixtures

As expected, the composting treatment leads to a reduction of the starting mass in terms of wet weight (Stentiford, 1996). The main reason of the weight drop is the water evaporation, promoted by the high temperatures reached in the thermophilic phase.
In the three experiments the reached mass reduction was, respectively, of the 86% for the C1, 79% for the C2 and 78% for the C3. These values are a little bit higher than the values reached in previous experiments carried out by Thompson et al. (Thompson et al., 2004), but in line with the experiments reported by Chiumenti (Chiumenti, 2015) utilising similar absorbing substrates.

Concerning the digestate treatment capacity of the several mixtures, the mixture C2 and C3 have been the highest treatment capacity, reaching, correspondingly, 0.29 $kg_{substrate}/kg_{digestate}$ and 0.27 $kg_{substrate}/kg_{digestate}$ while the mixture C1 the treatment capacity was of 0.43 $kg_{substrate}/kg_{digestate}$, substantially less than the other. The reason could be due to the less absorbing capacity of grass than the other mixtures that has not allowed treating more digestate without compromise the right composting conditions.

12.3.3 Physical and chemical analysis

The final physical and chemical characteristics of the compost produced in the three different mixtures is reported in the Table 30.

Table 30: Final physical and chemical characteristics of the compost produced in the several mixtures

	TS (%)	**VS (%)**	**TN (% T.S.)**	**TOC (% T.S.)**	**C/N**
C1	87.7	62.1	3.7	34.1	9.2
C2	56.2	60.4	4.2	35.6	8.3
C3	59.0	66.2	4.0	39.0	9.7

Considering that the initial TS and VS contents of the several mixtures were of, respectively, 36.28% and 84.31% for the C1, 29.01% and 84.08% for the C2, 27.28% and 83.93% for the C3, the composting has led to an increase of the TS content thanks to the evaporation of the water of the mixtures. Additionally, the values obtained have overcome the minimum required value of 50% according to the Italian laws. On the other hand, the reduction of VS is evident reaching values of, respectively, 23.91% for C1, 25.53% for the C2 and 17.71% for the C3.

The initial C/N ratio, which is another parameter to determine the maturity and the achievement of the composting treatment (Bernal et al., 2009), is, correspondingly, 21 for the C1 and 26 both for the C2 and C3. According to the final C/N obtained (Table 30) the compost can be considered as stabilized (Mathur et al., 1993) and in line with the quality parameters fixed by Italian laws.

Concerning the GI after 90 days, it was of, respectively, 0.69 for the C1, 0.77 for the C2 and 0.66 for the C3 while the HI values were of 0.37 for the C1, 0.36 for the C2 and 0.42 for the C3. These values indicate a good quality compost achievement, both considering the phytotoxic characteristics, both considering the stabilisation of the organic matter.

12.4 Conclusions

The preliminary results reported in this study show that the composting of raw digestate in combination with different solid biomasses is practicable under technical aspects allowing the obtainment of an organic fertilizer respecting the quality parameters required concerning the stability and phytotoxicity.

The addition of absorbing substrates such as wheat straw or vine shoots pruning seem to improve the treatment capacity of the raw digestate allowing to process a quantity of digestate about three time than their initial weight. Regarding the reduction of weight and volume, it emerged that the composting process could imply a reduction in a range between 78-86%.

According to these preliminary results, producing composted organic fertilizer from raw digestate and agricultural by-products can be considered a feasible way to valorise by-products and improve their handling provided that quality management and quality control procedures throughout the AD and composting are introduced to comply with the requirements for agricultural use.

Further studies will be conducted in order also to highlight the environmental impacts that these process could imply due to the greenhouse gases emissions.