UNIVERSITÀ
degli STUDI
di CATANIA

Department of Agriculture, Food and Environment

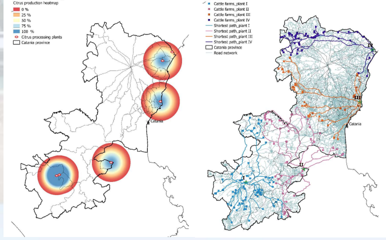
D*i*3A

PhD Thesis in Agricultural, Food and Environmental Science
XXX Cycle

SUSTAINABLE DEVELOPMENT OF REGIONAL BIOGAS PRODUCTION

GIS-Based Techno Economic Assessment in Southern Italy

Dr. Eng. Francesca Valenti



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PhD attended during 2014/2017

Acknowledgements

Through the following words, I want to thank many people and institutions for the support I have received in the professional, personal and economic fields, in a direct way or indirectly.

First of all, I would like to express my sincere thanks to my advisor, prof. Simona MC Porto, for her continuous involvement in my research activities and for her precious advices and suggestions, always from a very constructive point of view. A special mention deserves prof. Giovanni Cascone, for his essential scientific guide as well as for the confidence he has placed in me during the last few years. Basically, he made possible my PhD period, which was very important for my professional growth and my life in general.

I would also like to thank all the research team within the section "Building and land engineering" of the Department Di3A of Catania University for helping me in their domains of expertise and for the past three years spent together.

Moreover, it is a real pleasure for me to express my gratitude to prof. Wei Liao, co-advisor of my PhD thesis, and to all the researchers and staff of the Department of Biosystems and Agricultural Engineering of the Michigan State University (MSU) for the help, the suggestions, the enthusiasm, and the hospitality given to me during my 6-month period in Lansing, MI, USA. Prof. Liao and his group were fundamental to plan, execute and finalize my research work. Moreover, a special thank goes to prof. Bruce E. Dale, who gave me the opportunity to meet prof. Liao, and for his initial advices on the bioenergy sector.

During these three years of PhD I travelled a lot and visited other research groups in Italy, so now I would also say thank to prof. David Bolzonella for hosting me in his Department of Biotechnology at the University of Verona. My sincere gratitude

goes also to the professors Attilio Toscano and Giovanni Molari, together with the research team at the Department of Agricultural and Food Sciences of the University of Bologna, for the opportunity to work with them when the prof. Liao was in Bologna and for the great hospitality offered to me.

Finally, I would like to thank the president of the Italian Association of Agricultural Engineering (AIIA), prof. Giacomo Scarascia Mugnozza, and the entire Association, that gave me the honor to receive the award for the best PhD thesis in Agricultural Engineering, cycle XXX, during the 11th AIIA Conference – Biosystems Engineering Addressing the Human Challenges of the 21st Century.

At last but not least, I would like to say THANKS to all my loved ones, especially to my family, my mother, father and sister for their precious and constant encouragement and support, for the patience and trust that they have always showed to me. Above all, I would like to thank and dedicate this thesis to my grandfather Vincenzo. I know he would be proud of me, the end of this PhD was addressed with and for him… always you will be wherever I will be…

> *"...Le persone più felici non sono necessariamente coloro che hanno il meglio di tutto, ma coloro che traggono il meglio da ciò che hanno. La vita non è una questione di come sopravvivere alla tempesta, ma di come danzare nella pioggia.."*
>
> *Kahlil Gibran*

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Abstract

Renewable energies have attracted increasing attention in the past decades due to the need to reduce consumption of energy from fossil fuels and GHG emissions. In this respect, energy production from agri-food biomass has been researched and developed regarding both processes and biomass feedstocks (food crops, non-food crops, and by-products and residues). Recently, an innovative system based on both intensification of crop rotation and use of by-products was derived from BIOGASDONERIGHT concept, which aims to sustainably make more biogas. Therefore, the main objective of this thesis was to apply advanced GIS modeling and biomethane potential test to investigate availability of byproducts and wastes, and conclude suitable biogas production system in the region of Sicily.

A hypothetical regional biogas power generation system based on multiple biomass feedstocks for the Catania province in Sicily was developed using GIS modeling tools, and evaluated by techno-economic assessment and economic sensitivity analysis. The analysis of availability and distribution of the multiple biomass feedstocks identified the best locations of four biogas plants in terms of optimization of biomass logistics. The size and location of four biogas plants in the system were determined by buffer zone and road network analyses. Moreover, the effects of mixing six feedstocks (citrus pulp, olive pomace, cattle manure, poultry *litter, whey, and corn silage) on anaerobic digestion of biogas production have been investigated by this study using a combined biomethane potential (BMP) and semi-continuous anaerobic digestion –(AD) testing approach, in order to maximise the biogas production. The system demonstrates excellent economic performance with a payback period of less than three years for all four biogas plants. The economic sensitivity analysis clearly presents that, after establishment of the regional biogas plants according to feedstock availability and transportation, some customized adjustments on operations at local level could be carried out to further improve the economic performance of individual biogas plants. The system offers a sustainable solution for renewable electricity generation and soil amendment production from agricultural residues and food wastes in the region of Sicily.*

Riassunto

Negli ultimi 20 anni il settore della produzione di biogas mediante digestione anaerobica ha avuto un forte incremento. Nella maggior parte delle regioni italiane, specialmente nell'Italia settentrionale, il biogas è prodotto da colture energetiche dedicate che implicano la nascita di problemi economici, sociali e soprattutto ambientali, legati alla competizione dei prodotti food-no food. Di recente è stato sviluppato un nuovo concetto per la produzione di biogas, noto nell'ambito della letteratura di settore con il nome di BIOGASDONERIGHT. Tale sistema si basa sullo sviluppo del doppio raccolto, riduzione dei concimi chimici necessari alla coltivazione ed utilizzo di sottoprodotti agro-industriali come biomasse alternative. Per incoraggiare la crescita di impianti a biogas secondo tale concetto, la quantificazione e la relativa localizzazione delle biomasse presenti in un determinato territorio risulta essere cruciale.

L'obiettivo generale della presente tesi è stato quello di contribuire allo sviluppo sostenibile degli impianti di biogas in aree in cui il settore è ancora in via di sviluppo.

La Sicilia è tra le regioni del sud-Italia in cui il settore del biogas tarda a svilupparsi. Considerando la rilevante attività agricola e il settore agro-alimentare/industriale annualmente vengono prodotti circa 3,9 milioni di tonnellate di residui di biomasse. A tale scopo è stato sviluppato, per la provincia di Catania, un sistema di produzione di biogas basato su più fonti di biomasse, utilizzando strumenti di modellazione GIS. L'analisi della disponibilità e della distribuzione delle biomasse considerate ha contribuito a individuare la posizione migliore, per quattro nuovi impianti a biogas, in termini di ottimizzazione della fase logistica *durante l'approvvigionamento delle biomasse. La dimensione e l'ubicazione dei quattro impianti di biogas sono state determinate tenendo in considerazione i dati sulle biomasse individuate ed applicando un'analisi della rete stradale per la creazione di bacini di approvvigionamento. Inoltre, sono stati studiati gli effetti dei mix delle sei biomasse selezionate (pastazzo, sansa, deiezioni avicole, deiezioni bovine, siero di latte e insilato di mais) sulla produzione di biogas utilizzando un'analisi combinata di potenziale di biometano (BMP) e digestione anaerobica (AD) semi-continua, al fine di massimizzare la produzione di biogas. Il sistema dimostra eccellenti prestazioni economiche con un periodo di ritorno inferiore a tre anni per tutti e quattro gli impianti di biogas. L'analisi della sensitività economica dimostra chiaramente che, dopo la creazione degli impianti di biogas, in base alla disponibilità e al trasporto di materie prime, potrebbero essere effettuati adeguamenti personalizzati per migliorare ulteriormente la performance economica di singoli impianti di biogas. Questo studio offre una soluzione sostenibile sia per la produzione di energia da fonti rinnovabili che per la produzione di fertilizzanti naturali ottenuti dalla valorizzazione di residui agricoli e sottoprodotti agro-industriali della Sicilia.*

1 Introduction

1.1 Preface

Rapid growth of the population, along with accelerating industrialization and expanding urbanization, has dramatically changed our world. Signs of climate change rise concerns for the future of the planet (Ragauskas et al., 2006). Emissions of carbon dioxide have increased by more than 80% since the early 70's, mainly due to the increase in consumption of fossil fuels (IPCC, 2007) and changes in land use (Allen et al., 2013; Kucharik et al., 2001). The 2015 United Nations Climate Change Conference (officially known as Conference of the Parties COP 21) concluded the Paris Agreement (United Nations, 2015), a global agreement on the reduction of climate change, in which global warming is set at the increase of less than 2 degrees Celsius (°C) compared to pre-industrial levels and the CO_2 emissions reduction of 50% by year 2050. 85% of current energy consumption is based on fossil fuels, which is the most responsible source for greenhouse gas (GHG) emissions. According to the estimate of world energy requirement, demand would increase approximately 36% between 2008 and 2035 (Ruiz-Arias et al., 2012). To sustain- ably satisfy this demand, **renewable energy technologies** must be implemented to balance and reduce fossil energy use.

The renewable energy sources represent a suitable alternative to conventional fossil fuels, due to both the advantages in terms of environmental impact reduction according to the Kyoto protocol (Lanfranchi et al., 2014; Schneider et al., 2007). The issues related to reduction of environmental impact have been widely analysed and discussed by Rösch and Kaltschmitt (1999) who recognised “the environmental advantages which are associated with the energy use of biomass instead of fossil fuels”. In fact, it is well known that the consumption of fossil fuels causes major environmental challenges such as global climate change, acid rain, and atmo-spheric ozone layer depletion. Renewable energy generation could significantly facilitate the reduction of CO_2 and other GHG emissions (Rösch and Kaltschmitt, 1999).

Many renewable energy alternatives (i.e., solar, wind, hydro, geothermal, and biomass) have been intensively studied and developed in past decades. Considering cost effectiveness, practicability, scalability, positive externalities and energy density, **bioenergy** often offers a versatile and realistic solution, particularly for rural communities where massive quantities of agricultural biomass and residues are produced (Perlack et al., 2011). It has been estimated that, with implementation of advanced bioenergy technologies, land-based biomass (excluding biomass for food production) has an annual energy potential of between 200 and 500 Exajoule, which can make a major contribution to satisfying the world primary energy demand (500 Exajoule in 2008 and predicted 600 - 1000 Exajoule by 2050) (Council WE, 2013),

Biomass resources, which are widely available and allow the production of bioenergy at reasonable prices, have been acquiring particular interest in recent years because of the progressive exhaustion of conventional fossil fuels. The biomass utilization can trigger environmental and socio-economic improvement such as crop diversification, greenhouse emission reduction and creation of new jobs (Rösch and Kaltschmitt, 1999; Testa et al., 2014).

A recent trend in bioenergy solutions is the renewed interest in using **anaerobic digestion (AD)** technology to treat agricultural wastes and biomass for biogas production (Edwards et al., 2015; Smith et al., 2015). Anaerobic digestion is a biological process in which a consortium of anaerobic microbes (bacteria and archaea) synergistically work together to generate biogas (approximately 60% methane and 40% carbon dioxide with smaller amounts of other gases), contain nutrients (primarily phosphorus and nitrogen), and control odor. Many studies have been conducted to improve digestion efficiency and enhance its economic performance. These include the design of new reactor configurations to better digest different feedstocks (Ward et al., 2008), running co-digestion (by using multiple feedstocks to balance nutrient conditions) to improve biogas production (Mata-Alvarez et al., 2014), and upgrading raw biogas to high-quality fuels such as vehicle fuel and pipeline-quality biomethane as a replacement for fossil natural gas (Sun et al., 2015).

Besides development of digestion technologies, **feedstock supply and logistics** have also been studied to provide decision support information and facilitate establish biogas production systems at local, regional, and national levels (Balaman and Selim, 2014; Galvez et al., 2015). With advancements in geographical information system (GIS) tools, **GIS** has been intensively used to carry out in-depth analyses of feedstock supply and logistics for biogas production around the world. In this context, the assessment of biomass resources for feeding and locating biogas plants could be carried out by acquiring and managing a wide variety of geographical data within Geographical Information Systems (GIS). The GIS tool has been considered as an appropriate platform for spatially-related issues and have been applied for assessing the potential biomasses for biogas production (Batzias et al., 2005; Höhn et al., 2014; Noon and Daly, 1996) and for site-location analysis (Fiorese et al., 2005; Kurka et al., 2012; Sliz-Szkliniarz and Vogt, 2012; Sultana and Kumar, 2012; Zhang et al., 2011; Zubaryeva et al., 2012). Franco et al. applied a fuzzy weighted overlap dominance procedure to integrate GIS data and multiple social, technical, and environmental criteria to identify the most suitable biogas production locations (Franco et al., 2015). Brahma et al. used a GIS-based planning approach to identify an optimized agricultural residues supply network for a specified biogas plant location in India (Brahma et al., 2016). Zubaryeva et al. applied GIS to assess local biomass availability for distributed biogas production in Lecce, Italy (Zubaryeva et al., 2012). Sliz-Szkliniarz and Vogt took a GIS-based approach to determine suitable locations for biogas production from livestock manure and crops at regional scale (Sliz-Szkliniarz and Vogt, 2012). Batzias et al. developed a GIS-based model to estimate biogas production potential from livestock manure (Batzias et al., 2005). Höhn et al. (2014) used GIS data to analyse the spatial distribution and amount of potential biomass feedstock for biomethane production and optimal locations, and also the size and number of biogas plants in southern Finland (Höhn et al., 2014).

Since there is evidence of a scarce or even a lack of presence and development of biogas plants in Southern Italy, it appears valuable to evaluate the biomass availability in those territories, and lead to a correct planning action of new biogas plants.

Thus, in the following Sections an extensive analysis of literature is carried out (Section 1.2) to investigate the state of the art, which constitutes the knowledge base of this thesis work, and subsequently the objectives of the thesis work (Section 1.3) are described with reference to the highlighted issues in the field.

1.2 State of the art

1.2.1 Biogas sector in Europe and Biogas plants in Italy

The sector of biogas production has been developed for more than 20 years with great success in Europe and mainly in Germany where about 8,000 plants were installed at the end of 2012. It is four times the number of plants present in the U.S. territory (Lopolito et al., 2011). By analysing the current and potential biogas production in U.S. territory, recent studies showed that there is a possibility of reaching 11,000 plants in relation to the actual sources of available biomasses and the methane potential production for three different biomass categories, such as landfills, wastewater, and livestock manure. Anaerobic digestion of livestock manure has been adopted by the State of California as an eligible project type for the generation of offsets under its statewide cap-and-trade program (Caputo et al., 2005).

While the spread of biogas plants has earlier and continuously increased in Europe, it is more recent in Italy: the sector started growing since the beginning of the new century, registered a very high development after 2009, when the TO (omni-comprehensive tariff) including a high energy price and a financial incentive came into force. The number of biogas plan quickly increased to 989 in three years with an overall installed power of approximately 770 megawatts at the end of 2012. In the TO period (2008-2012), biogas plants have mostly spread in the livestock farms of Northern Italy, with the objective of obtaining methane from animal wastes for energy purposes. Afterwards, co-digestion with other by-products, waste products or specifically cultivated crops, has been developed due to their good contribution to biogas production. Several biogas plants are currently designed by taking into account that a relevant part of the daily organic load comes from dedicated energy crops and/or by-products of agri-food industry. Their use actually makes it possible to achieve higher electricity production than the digestion only using livestock wastes.

BIOGASDONERIGHT

In most Italian regions, especially in North-Central Italy, the biogas is produced using dedicated energy crops (e.g., beetroot, sugar cane, sorghum, and corn and wheat), which arises environmental, social and economic concerns related to food vs. fuel competition (Boscaro et al., 2015). As a consequence, there is the necessity to analyse the possibility of using alternative biomass sources (non-food sources) for the production of methane by anaerobic digestion (Thompson and Meyer, 2013). Therefore, a new concept to produce biogas, integrating sustainable intensification of crop rotation and the use of agro-industrial wastes, was developed (Dale et al., 2016). The basis of the double-cropping system is that row crops such as corn only occupy the land for a few months of the year, often less than half of the photosynthetically active period for plants. During the rest of the year, the land is essentially inactive. The sun is shining, but no photosynthesis is occurring because nothing is planted and growing. Double crops are often cool-season grasses whose most highly active photosynthetic periods are before or after the productive growth periods of food crops such as maize (corn). Typically, the double crops are planted after corn or soybeans are harvested in the fall. They grow in the fall and over winter, grow rapidly in the spring, and then are harvested before the corn/soybean crop is planted in the early summer (Dale et al., 2016; Feyereisen et al., 2013). The adoption of this new system of production would reduce the environmental, economic and social impacts related with the cultivation of dedicated energy crops and the presence of waste generated by agro-industrial activities (Dell'Antonia et al., 2013). To date, the development of biogas plants in Sicily is still very limited, despite the importance of the agricultural sector for the island. It is urgently needed to develop a strategic plan to realize such development in Sicily in near future.

1.2.2 Improving the biogas sector in Sicily

Sicily, a Region of the Southern Italy, is subdivided into 9 provinces (Figure 1) and is bounded by three seas, the Tyrrhenian Sea to the North, the Ionian Sea to the East, and the Mediterranean on the remaining coasts. It covers 25,707 km^2 and, apart from being the largest island in the Mediterranean, is the largest Italian Region. The surface of the island has a complex and irregular morphology. Almost two-thirds (61.4%) of the island is hilly and a quarter (24.5%) is mountainous. A small portion of the land is plains and all along the coast.

The mountainous area has six main elevations, the highest being Mount Etna (3323 m a.s.l.), the most active volcano in the Europe, which overlooks an important and extensive plain in Sicily with fertile soils made by volcanic deposits: the

Catania plain. It covers 430 km^2 amounting to a fifth of the total plains of the island. The other important plains are Gela plain and 'Conca D'Oro' (Golden Basin).

The weather conditions are certainly not favourable for agriculture: precipitation is meagre, i.e., on the coastal and internal plains (about 500 mm/year). And, irrigation system is only used to produce high-value crops (e.g., fruit tree cultivation and vegetable crops).

In Sicily, as well as in the rest of Southern Italy, employment in agriculture is much higher than the national average but with the lowest wages. According to official statistics, Sicily has a high proportion of agricultural employment with 220,000 agricultural and livestock farms (Istat, 2013), despite having fallen by 37% since 2000, and with an 8% increase in agricultural land to 1.4M hectares. This increase runs counter-wise to the trend observed for the other regions of Italy where the countryside is being abandoned and over the last ten years has increasingly been put to other uses.

The data also indicate Sicily as the region with the greatest extension of agricultural land. Agriculture has been one of the major economic resources of Sicily due to the quality and wide variety of products. By considering the surface area dedicated to agriculture, Sicily leads in cereal production and orange production (52% of the entire national production).

The unique climate pattern (mild/wet winter and hot/dry summer) and a large agricultural land area (citrus, olive, grape, wheat, cattle and sheep) make Sicily a region with a great potential for renewable energy production.

Renewable energy (4,709 GWh/year) provided approximately 25% of total power generation in Sicily in 2013 (Agency IT, 2014). Wind (2,976 GWh) and solar (1,492

GWh from photovoltaics) power were the dominant renewable energy sources. Bioenergy provided only around 70 GWh (less than 0.5% of total power generation in Sicily). By considering the extensive and intensive farming and food processing operations in Sicily, it is evident that biomass is underutilised for renewable energy production.
ISTAT (Italian Institute of Statistics) data indicate that Sicily is one of the regions in Italy with highest concentration of growing areas, which equals about 231 thousand hectares. Furthermore, just considering the Sicilian agricultural sector, the main plants are olive and citrus cultivation, which represent 90% of the total cultivations in Sicily.

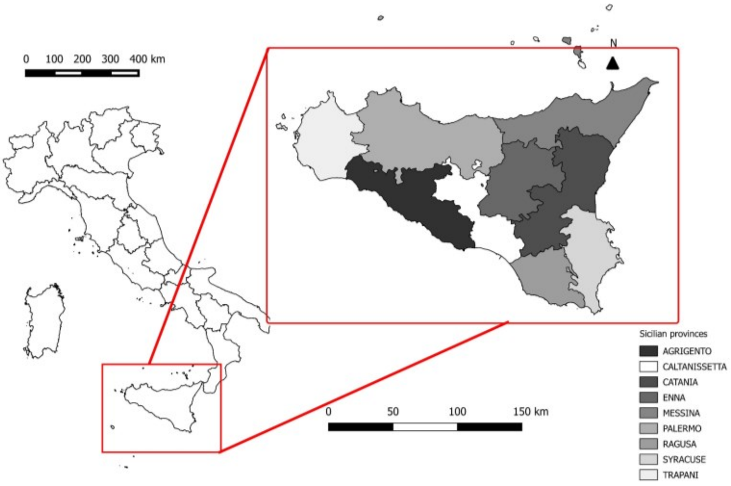


Figure 1. Geographical position of Sicily (Italy).

1.2.2.1 *Main by-products available in Sicily and the related environmental concerns*

Approximately 3.9 million metric tons of biomass residues are produced annually by Sicilian agriculture, representing a large untapped resource. The biomass includes wastes from agro-food processing (i.e., citrus pulp, olive pomace, and whey), livestock wastes (mainly from cattle), crop residues, some energy crops, and agricultural residues (waste fruit and vegetables) (Chinnici et al., 2015). Among them, wastes from agro-food processing and livestock production account for more than 60% of the total biomass produced (Comparetti et al., 2012). Food wastes and animal manures are very good feedstocks for anaerobic digestion to produce biogas and liquid/solid fertilizers (Aguilar Alvarez et al., 2016; Azevedo, 2015; Valenti et al., 2017a, 2017b, 2016).

As regard the management of agro-industrial by-products, citrus pulp and olive pomace, is a challenge issue for the processing facilities from both economic and environmental perspectives.

In olive oil sector, several studies have proven the negative effects of these wastes on soil microbial populations (Rana et al., 2003), on aquatic ecosystems, and even in air medium (Casa et al., 2003).

An excess amount of water is consumed during olive oil extraction, with an annual wastewater generation being estimated at around 30 million m^3 (Azbar et al., 2009; Rincón et al., 2009). Olive oil is produced with either a two- or three-phase extraction method; olive mills (OM), however, are mostly operated under a two-phase method due to their low water consumption and less generation of waste streams (Legislative Decree no. 574, 1996; Milanese et al., 2014). In addition to olive mill wastewater (OMWW), olive mill effluents contain a highly polluted solid residue as well (Legislative Decree no. 574, 1996). Olive mill solid residue

(OMSR) – also known as pomace – contains a considerable amount of humidity. Indeed, one ton of processed olives generates around 800 kg of OMSR under a two-phase extraction system (Milanese et al., 2014).

For these reasons, the amount of olive mill effluent that can be applied to agricultural soil is limited and regulated by national laws (Caputo et al., 2003). In this context, the valorisation of these by-products for energy production could be beneficial to solve problems related to their disposal (Ramachandran et al., 2007).

Several studies have been conducted during the last two decades with the aim to examine the thermochemical characteristics and performance of solid olive wastes. Various methods and technologies have been investigated (Ghimire et al., 2015; Kassaveti, 2008), and the potential exploitation of solid olive wastes for energy purpose was evaluated by isolating the yeast strains with the potential to utilize xylose and produce ethanol (Abu Tayeh et al., 2014) or also by adopting biogasification (olive pomace and water) (Tekin and Dalgiç, 2000).

With regard to citrus pulp, in Italy the managing and the possible re-use of this by-product have been influenced by a norm that was unable to constructively deal with the problems connected. In fact, the extensive interpretation of 'waste' and a lack of clarity in the law (Legislative Decree no.152/2006, 2006; Legislative Decree no.4/2008, 2008; Legislative Decree no. 22/1997, 1997) have limited the management of citrus pulp and generated a meddling interest of the waste disposal industry due to the high profit.

As a result, the 'waste' has emerged to include various agro-industrial by-products and among them citrus pulp. In 2010, a later Legislative Decree (Legislative Decree no.205/2010, 2010) clarified the concept of by-product making it wholly distinguishable from the concept of 'waste', which refers to whatever substance or object the holder intends to or is obliged to get rid of. Only, recently, in Sicily there has been greater clarity after the document Prot. 14843 of 01/03/2012, issued by the Regional Department of Agri-food Resources on the ‘Use of the by-products of the Sicilian citrus processing industry’ which clarified that citrus pulp is defined as a by-product instead of a waste. In the past years, norms have been enacted to solve the debate on waste/by-product including alternative uses of citrus pulp other than landfilling, which produces high transport costs and environmental pollution.

Broadening citrus pulp uses, in fact, allows more adequate valorisation of this by-product. For instance, the use as livestock feed would be chosen if there are cattle and/or sheep farms nearby, otherwise the agronomical use would be preferable.

Therefore, the environmental burden due to citrus pulp and olive pomace disposal could be limited by reusing them as a renewable energy resource. In fact, the resulted biogas can be used for multiple purposes, i.e., to produce electricity, energy, heat, and biomethane.

Table 1. Analysis of growing areas per species in Italy.

Province	Apple	Pear	Peach	Apricot	Citrus fruit				Table grapes	Olive	Actinidia	Cherry	Total
					Orange	Lemon	Small citrus fruit	Total citrus fruit					
Piedmont	4793.6	1198.3	5954.2	852.5	6.8	3.4	1.7	11.9	253.0	1019.8	5921.9	345.8	20351.0
Aosta Valley	187.8	5.5	3.5	1.6	1.2	0.0	0.0	1.2	0.1	45.2	0.6	0.7	246.2
Lombardy	1764.5	1020.1	589.4	67.0	21.8	0.9	5.9	28.6	95.8	1963.2	585.4	127.0	6241.0
Liguria	67.2	28.0	123.5	71.4	14.0	23.8	14.1	51.9	27.4	11108.1	8.4	35.7	11521.7
Trentino-South Tyrol	29338.0	94.9	21.0	75.5	7.5	0.0	5.0	12.5	19.0	393.8	102.9	315.4	30372.9
Veneto	5957.1	3824.9	4069.2	402.8	17.7	0.1	8.8	26.6	161.8	5180.0	4072.2	2567.3	26261.7
Friuli-Venezia Giulia	1543.5	198.5	216.9	14.6	0.4	0.4	0.3	1.1	82.3	425.3	714.0	39.6	3235.7
Emilia-Romagna	4514.9	22128.2	19247.1	5021.8	-	-	-	0.0	117.2	3813.9	4357.8	2668.9	61869.6
Tuscany	932.3	513.0	1016.2	315.3	44.6	12.6	9.3	66.5	116.0	91907.3	92.8	313.9	95273.3
Umbria	263.1	57.7	175.5	92.3	1.2	0.1	1.4	2.7	12.3	30387.3	1.8	138.9	31131.5
Marches	394.5	161.2	912.9	291.6	29.7	2.9	9.3	41.9	93.0	13514.7	51.8	294.6	15756.2
Lazio	423.8	242.6	1432.9	289.0	348.8	54.9	187.6	591.3	397.0	67438.0	7292.6	845.5	78952.6
Abruzzo	248.3	69.1	1195.1	133.3	24.9	0.7	6.7	32.3	306.8	42983.0	153.5	341.0	45462.4
Molise	164.9	41.7	348.1	151.9	16.9	0.5	2.8	20.2	23.3	15043.6	11.9	76.4	15882.1
Campania	2299.6	509.3	12691.6	2904.9	630.5	703.7	513.6	1847.9	72.0	72623.3	741.4	1754.6	95444.6
Apulia	191.9	197.1	4607.1	736.7	3934.3	137.0	5250.8	9322.1	24427.4	373285.0	112.2	12301.7	425181.3
Basilicata	359.3	205.5	3414.0	3766.5	4320.0	44.7	2074.6	6439.4	686.6	28002.3	406.2	197.0	43476.8
Calabria	469.3	272.7	3396.7	633.4	16257.7	619.7	18307.9	35185.3	193.2	185914.7	1058.0	444.4	227567.6
Sardinia	251.6	293.5	1065.2	149.5	2554.9	148.0	1401.7	4104.6	441.0	36471.7	1.7	171.3	42950.1
Sicily	**565.8**	**1479.5**	**5474.7**	**853.6**	51318.0	13671.0	6144.1	**71133.1**	**9779.4**	**141809.8**	**14.0**	**648.9**	**231758.9**
Italy	54731.1	32541.4	65954.7	16825.1	79551.0	15424.5	33945.6	128921.1	37304.5	1123329.7	25700.9	23628.6	1508937.0

1.2.2.2 Citrus cultivation, citrus processing industries and the related by-products

In Italy, citrus production is relevant since it covers an area of 142,011 ha with a production of 2.7 million tons, according to the most recent official statistical data. The southern regions include 99.5% of cultivated area and 99.9% of total harvested production: Sicily contributes to the national production with 56.6% of the total national production with a cultivation area of 52.3%, followed by the Calabria region with 26.4% of the cultivation area and 28.9% of the production. The remaining regions have very low percentages of the total national production (Istat, 2015).

The citrus production data (Table 2) highlighted that the average production in the last four-year period (Istat, 2015) (years 2011–2014) was 1,454 million tons per year and was composed of oranges (about 70%), lemons (about 22%), and other species altogether (about 7.9%).

Sicilian citrus production is mainly located in Eastern Sicily, especially in the provinces of Catania and Syracuse, even though it is also a traditional and typical cultivation in Western Sicily and particularly in the Palermo territory (mainly lemon and mandarin).

Citrus orchards are generally located in irrigated areas within coastal areas, valley floors, or flatlands; however, some of them are on steep slopes with land terracing where mechanization and cultivation are difficult.

Figure 2 shows the dynamics of Sicilian citrus growing areas over the period 2011 to 2014. The citrus growing area fell from 87,720 ha in 2011 to 80,445 ha in 2014 (about 10%). The surface area losses are mainly for mandarin (7%) and clementine (14%) compared to orange and lemon.

Table 2. The dynamics of Sicilian citrus production per province and species. (*)

	Mean production (2011/2014)											
	Oranges		Lemons		Mandarins		Clementines		Other citrus fruit		Total citrus fruit	
	t	%	t	%	t	%	t	%	t	%	t	%
Agrigento	99,670.75	9.8	1,846.63	0.6	1,034.00	1.8	2,830.63	5.7	0.00	-	105,382.00	7.2
%	94.6		1.8		1.0		2.7		-		100.0	
Caltanissetta	1,805.00	0.2	152.50	0.0	176.15	0.3	101.25	0.2	0.00	-	2,234.90	0.2
%	80.8		6.8		7.9		4.5		-		100.0	
Catania	406,250.00	40.0	96,250.00	29.7	19,625.00	33.6	18,000.00	36.2	300.00	4.4	540,425.00	37.1
%	75.2		17.8		3.6		3.3		0.1		100.0	
Enna	62,274.88	6.1	190.63	0.1	434.15	0.7	679.73	1.4	0.00	-	63,579.38	4.4
%	97.9		0.3		0.7		1.1.		-		100.0	
Messina	20,900.00	2.1	48,812.50	15.1	5,325.00	9.1	702.50	1.4	0.00	-	75,740.00	5.2
%	27.6		64.4		7.0		0.9		-		100.0	
Palermo	6,295.00	0.6	40,442.50	12.5	15,020.00	25.8	425.75	0.9	0.00	-	62,183.25	4.3
%	10.1		65.0		24.2		0.7		-		100.0	
Ragusa	61,500.00	6.1	8,250.00	2.5	6,000.00	10.3	11,600.00	23.3	0.00	-	87,350.00	6.0
%	70.4		9.4		6.9		13.3		-		100.0	
Syracuse	349,805,25	34.4	123,046.60	38.0	8,851.70	15.2	13,698.98	27.5	6,575.63	95.6	501,978.15	34.5
%	69.7		24.5		1.8		2.7		1.3		100.0	
Trapani	7,160.00	0.7	4,800.00	1.5	1,862.50	3.2	1,700.00	3.4	0.00	-	15,522.50	1.1
%	46.1		30.9		12.0		11.0		-		100.0	
Total	**1,015,660.88**	**100.0**	**323,791.36**	**100.0**	**58,328.50**	**100.0**	**49,738.83**	**100.0**	**6,875.63**	**100.0**	**1,454,395.18**	**100.0**
%	69.8		22.3		4.0		3.4		0.5		100.0	

(*) Source: ISTAT.

Citrus cultivation has a strategic role for employment and revenue of the local Sicilian society. In fact, 47% of Italian citrus fruit farms are located in Sicily. In 2013, Gross Saleable Production (GSP) for the sector reached about €694 million (official statistics), 58% of national production, down by 10% over ten years. This sector contributes to 15.7% of the Regional GSP (Inea, 2014a, 2014b).

Sicilian citrus cultivation focuses on the following species: oranges and lemons together representing 90.7% of the cultivation area and 92.1% of harvested production. Other species like mandarin and clementine are important only in certain areas where soil and climatic conditions can guarantee optimum crop production.

Data from the 2010 Agricultural Census highlight that approximately half (46%) of citrus farms are located in Sicily whereas the other Regions have no more than 8%, except for Calabria at 26% (Table 3).

There are 79,589 citrus farms in Italy (Table 4), which are mostly located in Sicily and Calabria (72%). Sicily has the highest number of orange, lemon, and mandarin farms, and Calabria has a significant number of farms producing clementine and minor citrus fruits (grapefruit, citron, and bergamot) in Italy (Istat, 2015).

Oranges together with lemons, are the most utilised among citrus fruits in the citrus processing industry. Table 4 lists the numbers of orange farms in different region in Italy. The citrus fruit produced is utilized for fresh consumption or for juice production. Seventy percent of the transformed product supply is represented by orange juice, while slightly more than 20% is represented by lemon juice. Orange juice is one of the most widely consumed beverages today.

Consequently, the orange cultivation has become a major industry and an important economic sector in the United States and most Mediterranean countries. A high percentage of orange production (70%) is used to manufacture derivative products and approximately 50–60% of the processed fruit is transformed into citrus waste (peel, seeds and membrane residues) (Martín et al., 2010; Wilkins et al., 2007).

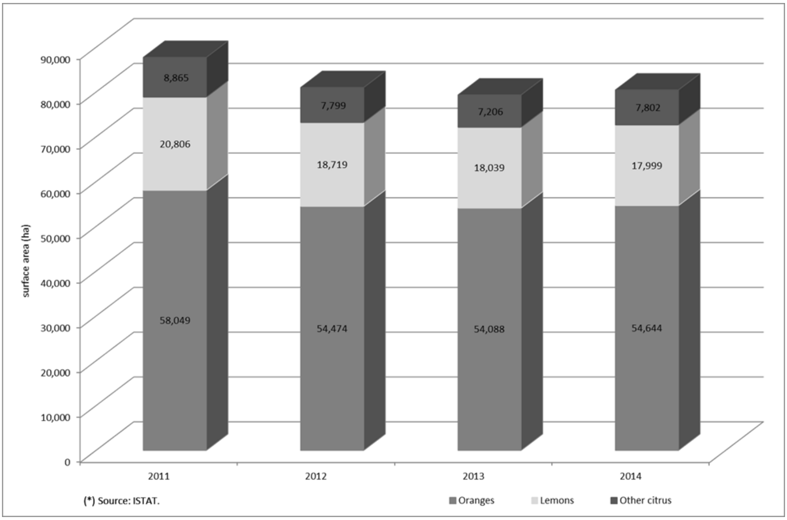


Figure 2. The dynamics of the citrus areas in Sicily per species. (*)

The main by-product of citrus processing industries is the citrus pulp, which is commonly known as "*pastazzo*" in Italy. It is essentially composed of insoluble carbohydrates, sugars, acids (mainly citric acid and malic acid), lipids, mineral elements (principally nitrogen, calcium, and potassium), volatile components (e.g. alcohols, aldehydes, ketones, esters, and hydrocarbon), flavonoids, essential oils (d-limonene at 95%), enzymes, pigments, and vitamins (Bampidis and Robinson, 2006).

This citrus pulp is characterized by high acidity, with a pH ranging from 3.5 to 5.8 (Bampidis and Robinson, 2006). A general chemical characterization, which distinguishes between citrus pulp obtained from oranges and that from lemons (i.e., the two citrus fruit having the most important production worldwide), is reported in Table 5.

Table 3. Number of citrus farms per region and species in Italy. (*)

	Farms											
	Oranges		Lemons		Mandarins		Clementines		Other citrus fruit		Total citrus fruit	
	No.	%	No.	%	No.	%	No.	%	No.	%	No.	%
Liguria	350	0.6	470	2.4	136	0.9	41	0.3	142	2.7	678	0.9
%	51.6		69.3		20.1		6.0		20.9		100.0	
Lazio	1,035	1.8	349	1.8	314	2.1	219	1.7	96	1.8	1,205	1.5
%	85.9		29.0		26.1		18.2		8.0		100.0	
Campania	2,921	5.1	3	13.8	1,631	10.8	569	4.4	429	8.0	4,679	5.9
%	62.4		57.0		34.9		12.2		9.2		100.0	
Apulia	4,344	7.5	1,055	5.5	1,467	9.7	2,107	16.2	433	8.1	6,038	7.6
%	71.9		17.5		24.3		34.9		7.2		100.0	
Basilicata	3,036	5.3	135	0.7	712	4.7	849	6.5	138	2.6	3,508	4.4
%	86.5		3.8		20.3		24.2		3.9		100.0	
Calabria	14,148	24.5	1,354	7.0	3,823	25.3	6,002	46.2	2,158	40.7	20,974	26.3
%	67.4		6.5		18.2		28.6		10.3		100.0	
Sicily	27,020	46.8	12,362	63.8	5,112	34.0	1,821	14.0	1,415	26.7	36,981	46.5
%	73.1		33.4		13.8		4.9		3.8		100.0	
Sardinia	4,467	7.7	781	4.0	1,782	11.8	1,341	10.3	407	7.7	4,946	6.2
%	90.3		15.8		36.0		27.1		8.2		100.0	
Other regions	413	0.7	216	1.0	106	0.7	47	0.4	90	1.7	580	0.7
%	71.2		37.2		18.3		8.1		15.5		100.0	
Total	**57,724**	**100.0**	**19,389**	**100.0**	**15,083**	**100.0**	**12,996**	**100.0**	**5,308**	**100.0**	**79,589**	**100.0**
%	72.5		24.4		19.0		16.3		6.7		100.0	

(*) Source: ISTAT 2010

This information is useful for biogas producers because they could use the data to calculate carbon:nitrogen ratios in their feed and decide the amount of citrus pulp that they can feed their digesters.

Table 4. Orange-producing farms in Italy. (*)

	Farms			
	Oranges		Total citrus	
	N.	%	N.	%
Liguria	350	0.6	678	0.9
%	51.6		100.0	
Lazio	1,035	1.8	1,205	1.5
%	85.9		100.0	
Campania	2,921	5.1	4,679	5.9
%	62.4		100.0	
Puglia	4,344	7.5	6,038	7.6
%	71.9		100.0	
Basilicata	3,036	5.3	3,508	4.4
%	86.5		100.0	
Calabria	14,148	24.5	20,974	26.4
%	67.5		100.0	
Sicilia	27,020	46.8	36,981	46.5
%	73.1		100.0	
Sardegna	4,467	7.7	4,946	6.2
%	90.3		100.0	
Other regions	4,467	7.7	4,946	6.2
%	90.3		100.0	
Total	**57,724**	**100.0**	**79,589**	**100.0**
%	72.5		100.0	

(*) Source: Istat.

Citrus pulp has been utilised as the feedstock for production of animal feed simply burnt (due to its high calorific power: 4,545 kcal kg^{-1} dry matter), fertilizer, essential oils, pectin, ethanol, industrial enzymes, single cell proteins, pollutant absorbents and paper pulp supplement. However, these processes generate a large quantity of polluted wastewater, giving the fact that the pressing stage requires the addition of quicklime. Other factors that limited the reuse, exploitation, and valorisation of citrus pulp were the lack of official data related to the quantities, in terms of volumes, and the spatial localisation of the actual quantities of this by-product. Therefore, feasibility studies of citrus pulp valorisation were scarcely conducted by scientific communities.

Table 5. Chemical composition of citrus pulp (re-elaborated from Bampidis and Robinson, 2006).

	Orange pulp			Lemon pulp	
	fresh (pressed)	silage	dried	fresh (pressed)	dried
pH	3.6	3.1	-	-	-
DM* (g kg^{-1})	975	193	892-912	184-220	903
OM (g kg^{-1} DM)	216-250	954	906-912	967	948
CP (g kg $^{-1}$ DM)	51-65	81	68-72	58-74	90
Crude fat (g kg $^{-1}$ DM)	-	-	20-40	16	36
Sugar (g kg $^{-1}$ DM)	-	-	573	191	-
Lignin (g kg $^{-1}$ DM)	-	-	3-7	-	-
Calcium (g kg $^{-1}$ DM)	7.3	-	18-53	7-8	-
Phosphorus (g kg $^{-1}$ DM)	1.7	-	3-4	1-2	-
Magnesium (g kg $^{-1}$ DM)	-	-	1-2	0.8	-
Potassium (g kg $^{-1}$ DM)	-	-	7.00	8.7	-
Sodium (g kg $^{-1}$ DM)	-	-	0.3	0.04	-

(*) DM: dry matter; OM: organic matter; CP: crude protein.

1.2.2.3 Olive oil cultivation, processing industries and the related by-products

In the Mediterranean region olive farming and olive oil industry are of both economic and social importance, and more than 98% of the world's olive oil is produced from the region with an estimated value of 2.5 million metric tons/year) (FAOSTAT, 2009; IOCC, 2010). The leading olive oil producing countries are Spain, Italy, Greece and Portugal. Olive oil has excellent nutritional properties, and its consumption, traditionally restricted to the Mediterranean area (77% of the worldwide input), is increasing worldwide, prompting countries such as Argentina, the United States and South Africa to emerge as producers. In the last decade, olive oil production has increased by approximately 40% worldwide.

Looking more closely at the situation in Italy, olive oil industry is not only the second largest producer (27% and 20% of European and world production, respectively), but also the biggest consumer (followed by Spain and the USA), the biggest importer (followed by the USA and France), and the second most important exporting country (after Spain) (FAOSTAT, 2009; UNCTAD, 2015). There are about 150 million olive trees growing in 18 of the 20 regions in Italy. Olive cultivation is largely concentrated in the southern regions, divided among an extremely high number of growers (about 1,200,000) and characterized by a wide and complex differentiation of cultivars, which vary considerably from one location to another. No other olive oil producing countries have such a great variety, as the less variable environmental conditions that they have compared to Italy (Salomone and Ioppolo, 2012; Unaprol, 2009).

Based on the ISTAT data, the Italian olive production is reported in Table 6. The olive farms (olive oil firms and table-olive firms) are mostly located in the southern regions of Italy, which have the highest percentage of cultivated surface. Sicily, as a whole, comes behind Apulia and Calabria for the number of olive farms and olive growing areas, but ahead for table-olive cultivation. The VI Agriculture General Census 2010 (Istat, 2013) showed that in Italy the olive farms are 907,197, 98.7% of these farms are composed of olive oil firms, whereas 1.3% are related to table-olive firms. As for the olive growing area, the Census recorded 1,077,467.10 ha of cultivation land, 98.8% of the land are olive oil producing areas whereas the remaining land is for table-olive cultivation.

Table 6. Olive farm number and surface area per region and species in Italy. (*)

	Table olives		Olive oil		Total		Table olives		Olive oil		Total	
	No.	%	No.	%	No.	%	Ha	%	Ha	%	Ha	%
Toscana	369	3.3	50,017	5.6	50,386	5.6	377.06	2.9	78,975.53	7.4	79,352.59	7.4
%	0.7		99.3		100.0		0.5		99.5		100.0	
Umbria	84	0.7	24,122	2.7	24,206	2.7	89.40	0.7	29,541	2.8	29,630	2.7
%	0.3		99.7		100.0		0.3		99.7		100.0	
Marche	419	3.7	25,261	2.8	25,680	2.8	145.29	1.1	10,941.65	1.0	11,086.94	1.0
%	1.6		98.4		100.0		1.3		98.7		100.0	
Lazio	1,637	14.4	67,399	7.5	69,036	7.6	1,476.35	11.3	64,335.92	6.0	65,812.27	6.1
%	2.4		97.6		100.0		2.2		97.8		100.0	
Abruzzo	448	3.9	54,559	6.1	55,007	6.1	286.71	2.2	42,294.18	4.0	42,580.89	4.0
%	0.8		99.2		100.0		0.7		99.3		100.0	
Campania	638	5.6	85,369	9.5	86,007	9.5	370.82	2.8	71,067.43	6.7	71,438.25	6.6
%	0.7		99.3		100.0		0.5		99.5		100.0	
Apulia	2,027	17.9	226,229	25.3	228,256	25.2	2,878.85	22.0	352,567.54	33.1	355,446.39	33.0
%	0.9		99.1		100.0		0.8		99.2		100.0	
Basilicata	213	1.9	32,617	3.6	32,830	3.6	218.38	1.7	27,403.30	2.6	27,621.68	2.6
%	0.6		99.4		100.0		0.8		99.2		100.0	
Calabria	1,337	11.8	113,159	12.6	114,496	12.6	1,555.82	11.9	183,040.55	17.2	184,596.37	17.1
%	1.2		98.8		100.0		0.8		99.2		100.0	
Sicily	2,361	20.8	138,751	15.5	141,112	15.6	4,249.40	32.5	134,838.98	12.7	139,088.38	12.9
%	1.7		98.3		100.0		3.1		96.9		100.0	
Sardegna	1,206	10.6	30,763	3.4	31,969	3.5	1,063.84	8.1	33,750.33	3.2	34,814.17	3.2
%	3.8		96.2		100.0		3.1		96.9		100.0	
Other regions	608	5.4	47,604	5.3	48,212	5.3	359	2.8	35,639	3.3	35,999	3.3
%	1.3		98.7		100.0		1.0		99.0		100.0	
Total	**11,347**	**100.0**	**895,850**	**100.0**	**907,197**	**100.0**	**13,071.40**	**100.0**	**1,064,395.70**	**100.0**	**1,077,467.10**	**100.0**
%	1.3		98.7		100.0		1.2		98.8		100.0	

(*) Source: ISTAT.

Apulia has over 228,000 olive farms and an olive growing area of 355,446.39 ha, moreover it has the highest investments in this sector, being ahead of Calabria and Sicilia, followed by the other Italian regions. The olive oil production in Italy reaches 452,000 t (average 2011-2014 value), 38% of the production is in Apulia (170,000 t), 28% in Calabria (126,000 t), and 10% in Sicily (45,000 t).

From this analysis, Sicily is the third olive oil producing region in Italy (approximately 8% of the Italian production) after Puglia and Calabria (DellaGreca et al., 2001; Paredes et al., 1986; Salomone and Ioppolo, 2012). There are over 141,000 olive farms in Sicily, which occupy 139,088.00 ha of land (Table 7). Olive oil production in Sicily was 32,216.4 t in 2014 from 199,000 growers and 692 mills (Salomone and Ioppolo, 2012; Unaprol, 2009).

The largest olive cultivation in Sicily is Messina followed by Agrigento and Trapani, while Agrigento is the province with the highest production followed by Catania and Palermo (Salomone and Ioppolo, 2012; Unaprol, 2009).The Sicilian olive oil production is concentrated in Palermo with 10,775 t (average 2011-2014 value), followed by 7,450 t in Catania, 6,604 t in Agrigento, 5,729 t in Trapani, and 3,209 t in Messina.

Table 7. Olive farm number and surface area per province and species in Sicily.

	Table olives		Olive oil		Total		Table olives		Olive oil		Total	
	No.	%	No.	%	No.	%	Ha	%	Ha	%	Ha	%
Agrigento	200	*8.5*	24,072	*17.3*	24,272	*17.2*	253.29	*6.0*	26,750.07	*19.8*	27,003.36	*19.*
%	*0.8*		*99.2*		*100.0*		*0.9*		*99.1*		*100.0*	
Caltanissetta	72	*3.0*	10,129	*7.3*	10,201	*7.2*	69.16	*1.6*	8,096.02	*6.0*	8,165.18	*5.9*
%	*0.7*		*99.3*		*100.0*		*0.8*		*99.2*		*100.0*	
Catania	371	*15.7*	13,578	*9.8*	13,949	*9.9*	409.37	*9.6*	10,642.99	*7.9*	11,052.36	*7.9*
%	*2.7*		*97.3*		*100.0*		*3.7*		*96.3*		*100.0*	
Enna	148	*6.3*	11,760	*8.5*	11,908	*8.4*	108.34	*2.5*	10,565.97	*7.8*	10,674.31	*7.7*
%	*1.2*		*98.8*		*100.0*		*1.0*		*99.0*		*100.0*	
Messina	233	*9.9*	20,176	*14.5*	20,409	*14.5*	168.55	*4.0*	20,949.32	*15.5*	21,117.87	*15.*
%	*1.1*		*98.9*		*100.0*		*0.8*		*99.2*		*100.0*	
Palermo	166	*7.0*	27,523	*19.8*	27,689	*19.6*	195.56	*4.6*	25,683.29	*19.0*	25,878.85	*18.*
%	*0.6*		*99.4*		*100.0*		*0.8*		*99.2*		*100.0*	
Ragusa	41	*1.7*	6,275	*4.5*	6,316	*4.5*	53.54	*1.3*	7,073.92	*5.2*	7,127.46	*5.1*
%	*0.6*		*99.4*		*100.0*		*0.8*		*99.2*		*100.0*	
Syracuse	128	*5.4*	7,383	*5.3*	7,511	*5.3*	122.77	*2.9*	8,199.97	*6.1*	8,322.74	*6.0*
%	*1.7*		*98.3*		*100.0*		*1.5*		*98.5*		*100.0*	
Trapani	1,002	*42.4*	17,855	*12.9*	18,857	*13.4*	2,868.82	*67.5*	16,877.43	*12.5*	19,746.25	*14.*
%	*5.3*		*94.7*		*100.0*		*14.5*		*85.5*		*100.0*	
Total	**2,361**	***100.0***	**138,751**	***100.0***	**141,112**	***100.0***	4,249.40	***100.0***	134,838.98	***100.0***	139,088.38	***100.***
%	*1.7*		*98.3*		*100.0*		*3.1*		*96.9*		*100.0*	

(*) Source: ISTAT.

1.3 Objectives of the thesis work

Since geographical location of biomass resource does not often match biogas demand, a key issue for sustainable biogas production is to find the most suitable locations for biogas plants in order to minimize GHG emissions and biomass logistic cost (Noon and Daly, 1996). On this basis, the main goal of this thesis was to investigate the effects of biomass availability, spatial localization, and biomethane potential of different biomass on establishing a biogas sector in Sicily, which will conclude solutions to address issues and challenges highlighted in the preface (Section 1.1). Correspondingly, three objectives were carried out to realize the goal. Objective 1 was about estimating availability of two main by-products of the Sicilian agro-industrial sector, citrus pulp and olive pomace, for sustainable biogas production. A method for estimating potential biogas production from citrus pulp and olive pomace was developed, aimed at finding optimal locations for biogas plants in view of developing the biogas sector.

In order to establish a regional biogas production system based on agro-food wastes and agricultural residues in Sicily, other biomasses were also taken into account to find suitable locations for biogas plants for sustainable development.

Objective 2 conducted a GIS based modeling and techno-economic assessment to map the availability of biomass feedstocks, determine the preferred location and size of biogas plants, and establish a technically feasible and economically sound biogas production solution.

Objective 3 focused on studying the feasibility of anaerobic co-digestion of multiple feedstocks. The effects of mixing six feedstocks (citrus pulp, olive pomace, cattle manure, poultry litter, whey, and corn silage) on anaerobic digestion of biogas production were investigated using a combined biomethane potential (BMP) and semi-continuous anaerobic digestion (AD) testing approach. The results from this objective would facilitate the development of biogas production on multiple organic by-products and wastes in Sicily as well as in other regions in Italy.

1.4 Work organization

The materials and methods used to achieve the development of biogas sector in the study area are reported in Section 2 of this thesis.

The whole Section 2 was sub-set in 6 different sub-sections. Sub-section 2.1 contains detailed information about the selected study area. The model applied to evaluate the availability of the two main by-products, olive pomace and citrus pulp, and other feedstocks considered for the anaerobic digestion is reported in sub-section 2.2 and 2.3.

In the sub-sections 2.4 and 2.5 the methodology adopted to characterize each feedstock and analyse the blends for anaerobic digestion were detailed.

The GIS-based analysis for biogas plants site selection with the technical and economic assessment, to locate new biogas plants in the study area were reported in sub-section 2.6, in detail sub-section 2.6.1 and 2.6.2, respectively.

In the sections 3 and 4, the results are shown and discussed. The whole Section 3 was sub-set in 7 sub-sections, and the Section 4 in 4 dub-sections.

The advance in the state of the art achieved in this PhD study is highlighted in Section 5.

2 Materials and methods

2.1 The selected study area

In Sicily, when considering olive pomace and citrus pulp as possible matrices for biogas production, in the province of Catania the highest incidence of these type of by-products could occur, since it has a wide surface of both citrus and olive growing areas (Figure 3), as well as a high presence of the related agro-food industries. Therefore, this province was selected as the study area of this research work.

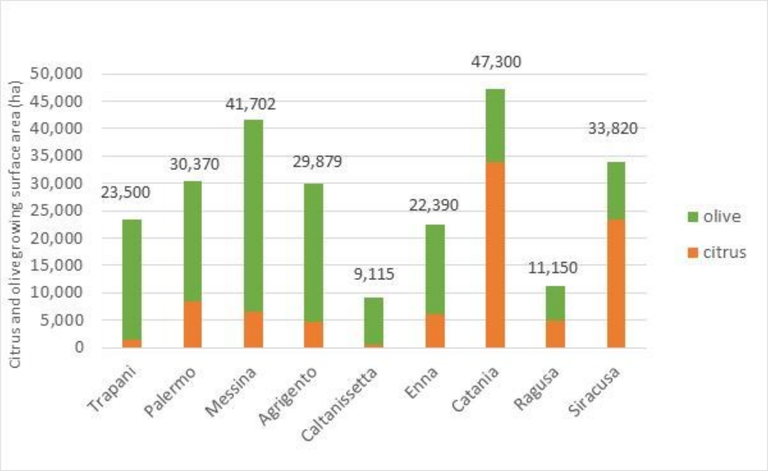


Figure 3. Surface areas of citrus and olive orchards within Sicily.

2.2 Estimation of citrus pulp and olive pomace availability for biogas production

2.2.1 The GIS-based model

In this section, a model for the estimation of citrus pulp and olive pomace potential availability for biogas production at an established territorial scale (e.g., national, regional, or local) is proposed. The model is described in mathematical form. The choice of a rigorous mathematical form makes it possible to fulfil the repeatable nature of the scientific research without misinterpretation.

The model requires the use of a set of indicators that must be previously defined and quantified by means of suitable databases and field surveys.

In order to estimate citrus pulp and olive pomace potential availability the following steps are required:

- Sub-setting of the study area (Catania province) in n zones (municipalities) suitable to compute the different levels of the index (i = 1 to n). Although the study area subdivision could be carried out by following different criteria (e.g., physiographic units, landscape units, geomorphologic units, geological units, iso-slope zones, agricultural units, and road-bounded areas), in this model the discretization methodology based on administrative boundaries makes it possible to obtain data from databases of agricultural production or other supports such as regional technical maps and ortho-photo images. Image processing for the classification of high-resolution satellite images could also be used for this purpose (Arcidiacono and Porto, 2012, 2008).
- For each i-th zone, computation of the indicators reported below:
    - Citrus and olive producing area S_{citrus_i} and S_{olive_i} which quantify the surface area, measured in hectares, for citrus and olive production within an established

time interval.

- Citrus and olive production P_{citrus_i} and P_{olive_i} which quantify the average production of citrus fruits and olive, measured in tons, within the same time interval defined for S_{citrus_i} and S_{olive_i} .

To compute citrus and olive production, P_{citrus_i} and P_{olive_i} at municipal level, firstly the yields of citrus and olive producing areas (Y_{citrus} and Y_{olive}) were calculated at the provincial level (Catania province), then they were applied to obtain P_{citrus_i} and $P_{olive_i}$by adopting the following relation:

$$P_{citrus\_i} = Y_{citrus} \times S_{citrus\_i} \tag{1}$$

$$P_{olive\_i} = Y_{olive} \times S_{olive\_i} \tag{2}$$

Where the yields of citrus Y_{citrus} and olive Y_{olive} producing areas were computed by the following equations:

$$Y_{citrus} = \frac{P_{citrus\_prov}}{S_{citrus\_prov}} \tag{3}$$

$$Y_{olive} = \frac{P_{olive\_prov}}{S_{olive\_prov}} \tag{4}$$

- Estimation of the average percentage of citrus pulp and olive pomace, named $Cp_{average\,\%}$ and $Op_{average\,\%}$ respectively, hereafter, obtained from the processing industries of citrus fruit and olive oil located in the study area by means of field surveys.

The data used for the computation of $Cp_{average\,\%}$ and $Op_{average\,\%}$ were obtained by utilizing a specific questionnaire (Figure 4) which was developed and used to survey all citrus processing industries (m) and a sample of k olive-oil industries, about 30% of the industries located in the study area, by using GIS-tool. The questionnaire was organized in two sections that contained the following information: general information regarding the processing industry, period of activity, the amount of processed olives or citrus fruits, the amount and the type of olive pomace or citrus pulp obtained, and the reference year of the survey (Figure 4).

The data, obtained from each industry and for each campaign (two harvest campaign related to the years 2012/2013 and 2013/2014 for citrus and 2013/2014 and 2014/2015 for olive), was then elaborated, in anonymous form, by using the descriptive statistics, by providing minimum, maximum, and mean productions of both olive oil and pomace, and citrus fruits and pulp, and the standard deviation (SD).

The average percentage of olive pomace and citrus pulp, $Op_{average\%}$ and $Cp_{average\%}$ were computed by the following Equations:

$$Cp_{\mathrm{average\%}} = \frac{\sum_{\mathrm{j}}^{\mathrm{y}} \frac{\sum_{\mathrm{j}}^{\mathrm{m}} \mathrm{Cp}_{\mathrm{average\%}_{\mathrm{j}}}}{\mathrm{m}}}{\mathrm{y}} \qquad (5)$$

$$Op_{\mathrm{average\%}} = \frac{\sum_{\mathrm{j}}^{\mathrm{y}} \frac{\sum_{\mathrm{j}}^{\mathrm{k}} \mathrm{Op}_{\mathrm{average\%}_{\mathrm{j}}}}{\mathrm{k}}}{\mathrm{y}} \tag{6}$$

where $Cp_{average\,\%}$ and $Op_{average\,\%}$ are computed for each processing industry j of the sample by the ratio between the produced citrus pulp/olive pomace and the amount of citrus/olive processed, and y is the number of campaigns.

- For each i-th zone, computation of the amount of citrus pulp Cp_i obtained from the processing industries following the relation:

$$Cp_i = Cp_{average\,\%} \times Ca_{citrus} \times P_{citrus\_i} \tag{7}$$

$$Op_i = Op_{average\,\%} \times Ca_{olive} \times P_{olive\_i} \tag{8}$$

Where the coefficients of availability, named Ca_{citrus} and Ca_{olive}, were fixed to 0.3 and 1, respectively (Inea 2014a; 2014b).

Then, the evaluation of biogas potential production associated to the estimated citrus pulp Cp_i and olive pomace Op_i, was carried out.

- For each i-th zone, the theoretical biogas potential (B_{tot}) was calculated by using the following relation:

$$B_{tot\_i} = C_{p_i} \times Y_{citrus_{pulp}} + O_{p_i} \times Y_{olive_{pomace}} \tag{9}$$

where $Y_{citrus_{pulp}}$ and $Y_{olive_{pomace}}$ are the biogas potential of citrus pulp and the biogas potential of olive pomace, respectively. They were equal to 89.3 Nmc/ttq (Cerruto et al.,

2016) and 131.00 Nmc/ttq (Reale et al., 2009), respectively.

2.2.2 Suitable zones where locating biogas plants

The *i-th* zones of the considered study area should be grouped into classes related to the surface area (S_{mun}) of their territorial boundaries. This criterion allows the comparison of the densities of the citrus and olive growing areas among the classes by using descriptive statistic tools. The categorisation of the zones into classes could be obtained by using a data clustering method designed to determine the best arrangement of values into different classes. Among the different algorithms available in GIS software, the Jenks Natural Breaks classification method can be used. This algorithm aims at finding natural groupings of data to create classes by maximising the variance between individual classes and minimising the variance within each class.

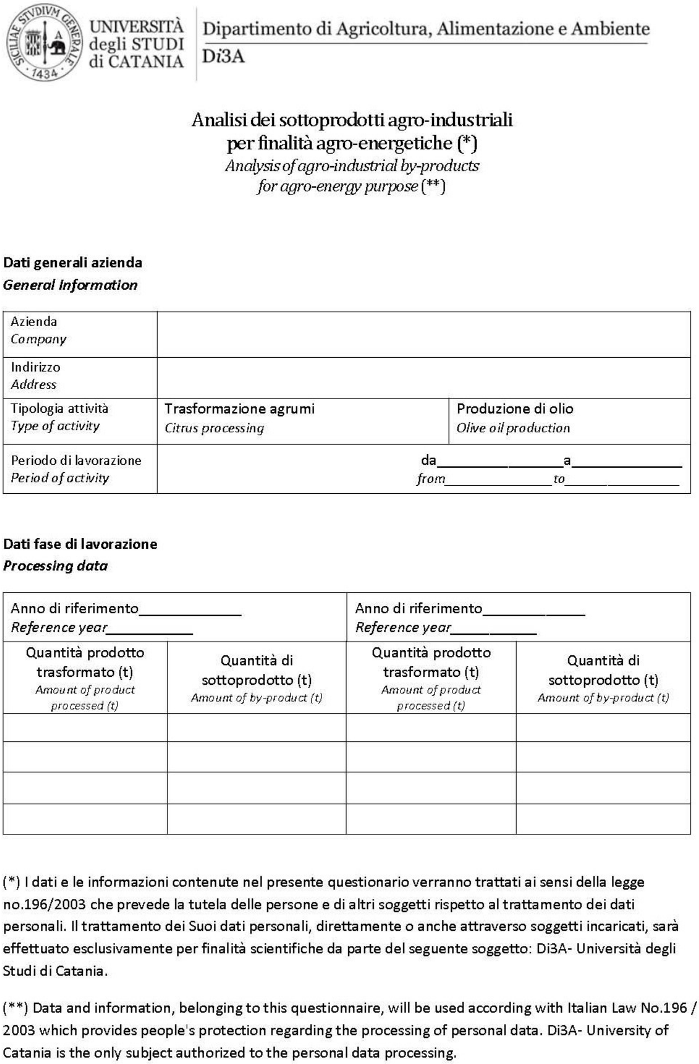
After the definition of the classes, the territorial boundaries of the zones belonging to the classes having a density of citrus and olive growing areas higher than that of the whole study area should be selected to be overlaid with the feature class containing the localisation of the agro-industries. This operation allows the selection of the zones where planning the development of new biogas plants.

2.2.3 Base maps and database

The base maps used in the GIS-model included the Regional Technical Map (RTM 2008) and the digital colour orthoimages of the Sicilian territory (2008). RTM 2008 is an upgrade of previous versions of the RTM 2005 numerical edition (sites CDE), 2001 edition (sites 7-8-9), 2004 edition (site B) and 2003 edition (site A). The updated version of

RTM released in 2008 was made by using the digital colour ortho-images ATA0708 which had a geometrical resolution of 25 cm x 25 cm. Among the layers included in the RTM 2008, the Vegetation Layer (G) was chosen, especially (GO_A and G1), the Citrus Layer and the Olive Layer in order to calculate the extension of citrus producing areas. With regard to the database, different sources, i.e., the Italian National Institute of Statistics (ISTAT) for years 2011–2014, and the Italian Agricultural Census 2010, were used (Istat, 2014, 2013). ISTAT, (Istat, 2015) which is a public research body, is the main producer of official statistics. It is specialized in production and communication of statistical information, as well as high-quality analysis and projections. ISTAT produces information on different economic, social, territorial and environmental aspects by performing general censuses and sample surveys. The censuses, in particular, provide a broad information base with fine territorial detail. The 6th Agricultural Census, which is the last available, provides a complete data framework on the structure of agriculture and animal husbandry system at a national, regional, and local level, updated to 2010. This census provides a detailed description of the agricultural world: from the number of farms to the ownership of land, from the land use to the size of livestock breeding farms, from the manual labour involved to the associated economic activities.

Firstly, the localisation of the citrus and olive growing areas obtained from RTM2008 was assessed through an overlay on the orthoimages. Generally, if these ortho-images were not available, other methods to obtain this kind of information could be the automatic detection of soil coverage by using procedures based on automated image analysis applied to remote sensing images (Arcidiacono and Porto, 2008, 2010, 2012; Banerjee and Srivastava, 2013; Stellmes et al., 2013; Modica et al., 2016a, 2016b) Then the surface areas of the citrus and olive cultivation obtained from the ISTAT database were validated through the comparison with the surface areas of the previously validated polygons of the Citrus and the Olive Layers.



UNIVERSITÀ
degli STUDI
di CATANIA

Dipartimento di Agricoltura, Alimentazione e Ambiente
D*i*3A

Analisi dei sottoprodotti agro-industriali
per finalità agro-energetiche (*)
Analysis of agro-industrial by-products
for agro-energy purpose (**)

Dati generali azienda
General Information

Azienda *Company*		
Indirizzo *Address*		
Tipologia attività *Type of activity*	Trasformazione agrumi *Citrus processing*	Produzione di olio *Olive oil production*
Periodo di lavorazione *Period of activity*	da_______________a_____________ *from*_____________*to*______________	

Dati fase di lavorazione
Processing data

Anno di riferimento____________ *Reference year*__________		Anno di riferimento____________ *Reference year*__________	
Quantità prodotto trasformato (t) *Amount of product processed (t)*	Quantità di sottoprodotto (t) *Amount of by-product (t)*	Quantità prodotto trasformato (t) *Amount of product processed (t)*	Quantità di sottoprodotto (t) *Amount of by-product (t)*

(*) I dati e le informazioni contenute nel presente questionario verranno trattati ai sensi della legge no.196/2003 che prevede la tutela delle persone e di altri soggetti rispetto al trattamento dei dati personali. Il trattamento dei Suoi dati personali, direttamente o anche attraverso soggetti incaricati, sarà effettuato esclusivamente per finalità scientifiche da parte del seguente soggetto: Di3A- Università degli Studi di Catania.

(**) Data and information, belonging to this questionnaire, will be used according with Italian Law No.196 / 2003 which provides people's protection regarding the processing of personal data. Di3A- University of Catania is the only subject authorized to the personal data processing.

Figure 4. Questionnaire for the biomass survey.

2.3 Selection and quantification of the other feedstocks for biogas production

The other feedstocks for biogas production considered in this study were: livestock manure (poultry and cattle manure and whey); agro-industrial waste (citrus pulp and olive pomace); and forage crops (silage). These different types of feedstock were chosen on the basis of diet actually used in Sicilian biogas plants.

The quantity and location of the different feedstocks were analysed by using spatial information, statistics, other research studies and by interviewing major agro-industrial waste producers.

2.3.1 Whey

Whey is the main by-product of dairy processing. Most whey is used to produce cheese, cream, and butter. Approximately 5% of the whey is acid whey, a waste that could be used for anaerobic digestion of biogas production (Perlack et al., 2011).

Data on cattle farms from the Department of Veterinary Prevention of the Provincial Health of Catania, which provided GPS coordinates, type of farms and the number of animals, were combined with information from the literature to calculate the amount of whey potentially available for biogas production (Council WE, 2013; Edwards et al., 2015; Perlack et al., 2011; Smith et al., 2015) and located on maps by using GIS-tool.

2.3.2 Cattle and poultry manure

In order to estimate the cattle and poultry manure all farms of

Catania province were analysed and located on the map with GIS-model, by using the data provided by the Department of Veterinary Prevention of the Provincial Health Company of Catania.

The amounts and availability of cattle manure and poultry manure from individual farms were calculated based on the size and location of animal farms. The data on farm size (animal numbers) and farm locations were combined with the waste generation data for cattle and poultry from the literature (EUROSTAT, 2015a; 2015b; 2015c) to estimate the amount of manure production for individual animal farms.

2.3.3 Silage

Silage is a biomass feedstock that has been widely used for biogas production in Europe (Amon et al., 2007; Santi et al., 2015). Silage is also valuable for other applications (i.e., cattle feed, animal bedding, and biofuel production) (Singh et al., 2008).

For each silage production site, the surface area and the related location were generated by using the regional technical map (RTM 2008) and the data from the Italian agricultural census 2010 (Istat, 2013, 2014).

Several studies that estimated the energy potential of agricultural (Voivontas et al., 2001; Elmore et al., 2008; Banowetz et la., 2008; Singh et al., 2008; Junginger et al., 2008) residues have been published and different methods were proposed (Roberts et al., 2015; Scarlat et al., 2010,2011; Jingura and Matengaifa, 2008). Among these, the relation proposed by Roberts et al., (2015) was adopted to evaluate the potential availability of silage ($SB_{available}$, Ton/year):

$$SB_{available} = A \times Y \times RPR \times RA \qquad (10)$$

Where A is the area of crop land (Hectare), Y is the crop yield (Ton/hectare/year) from the Italian National Institute of Statistics (ISTAT) (Istat, 2014, 2015), RPR is the residue-to-product rate, and RA is the silage biomass availability rate. RA was adopted to calculate the amount of available silage for biogas production without competing with its other use (Roberts et al., 2015).

Based on this result, silage collection points for available silage biomass were established using the RTM 2008 and GIS-tool. Selection of the collection points is based on the following conditions: individual collection points are set for maximum 500 hectare production size, and they are located near the main roads to reduce transportation cost and time.

2.4 Characterization of feedstocks

The characterization of feedstocks was performed to the Department of Biosystems & Agricultural Engineering of Michigan State University during a six-month research-period of my PhD Doctorate.

To perform the analyses for the feedstocks characterization, the cattle manure, the silage and the whey used for the experiments were taken from the Dairy Teaching and Research Centre at Michigan State University (MSU). The poultry manure was collected from the MSU chicken farm. The whey was taken from a milk processing facility in Lansing, MI. The citrus pulp was obtained from processing oranges using a bench-scale orange juice processor (Black & Decker Citrus Juicer, Black & Decker, Beachwood, OH). The oranges were purchased from a local supermarket, and processed by a lab food processer to collect the CP. Two OP samples (OP2 and OP3) from two-phase and three-phase olive processing systems, respectively, were collected in Italy and shipped to Michigan in coolers. The three-phase system applies a decanter to generate three fractions from olive: olive oil, olive husk (olive pomace, OP3), and olive mill wastewater. While, the two-phase system just uses the extraction process to extract olive oil and generate a mixture of olive husk and olive mill wastewater as the wet pomance (OP2). A blender (Waring Commerical Laboratory, Model No. 34BL97(7012)) was used to reduce particle size of individual samples. After size reduction, all samples were stored at -20°C prior to use.

2.4.1 Total solid (TS) and Volatile solid (VS) analyses

Total solid (TS) and Volatile solid (VS) were computed as follows:

$$Ts = \frac{(C+dry)-(C)}{(C+wet)-(C)} \tag{11}$$

$$Vs = \frac{(C+dry)-(C+ash)}{(C+dry)-(C)} \tag{12}$$

where C is the weight (gr) of the empty container, $C + wet$ is the weight (gr) of the container and the analyzing feedstock, $C + dry$ is the weight (gr) of the container and the analyzing feedstock ($C + wet$) after the oven treatment, set at 105°C per 12 hours, $C + ash$ is the weight (gr) of the container and

the analysing feedstock ($C + dry$) after the muffle-furnace treatment set at 550°C per 5 hours.
Each measurement was repeated twice.

2.4.2 Chemical Oxygen Demand (COD) analysis

The Chemical Oxygen Demand (COD) was analysed by using the USEPA Reactor Digestion Method, Method 8000 (USEPA, 1980), with digestion solutions (Figure 5) in the range 200 to 15,000 mg/L COD (HR Plus).

Figure 5. Digestion solutions (HACH), range 200 to 15,000 mg/L COD (HR Plus).

2.4.3 Total nitrogen (TN) analysis

Total nitrogen (TN) was analysed by using TNT 828 kit (HACH) (Figure 6) for total nitrogen within 20 – 100 mg/L N Ultra High Range. The TNT 828 kit contains reaction Tubes (Ø 20 mm) and three reagents: Sodium hydroxide (solution A); Oxidant tablet (B); and MicroCap (C), and solution D.

Figure 6. TNT 828 kit (HACH).

The procedure reported below was followed two times for each feedstock in order to add, in quick succession, to a dry 20 mm reaction tube: 0.2 mL feedstock sample, 2.3 mL solution A, 1 tablet B. The solution obtained was preheated in DRB200 reactor (Figure 7) by setting the temperature to 100°C for one hour.

After that the temperature cool down, 1 MicroCap C was added to the solution and it was inverted 2 – 3 times until the freeze-dried contents of the MicroCap C are fully removed and all streaks are vanished. Then, slowly, 0.5 mL of the solution was pipet into a reaction Tube and, next, 0.2 mL of solution D was added. The Tube was immediately cap and inverted 2 – 3 times until no more streaks could be seen. After 15 minutes, thoroughly the outside of the Tube was cleaned and, then the Tube was inserted into the Portable Spectrophotometer DR 2800 (Figure 8). The Barcode program was selected in order to identify automatically the TN value of the tested feedstock.

2.4.4 *Total phosphorous (TP analysis)*

To analyse the total phosphorus content of each feedstock,

the Molybdovanadate Method with Acid Persulfate Digestion Test ’N Tube™ Procedure, Method 10127, was applied. In this analysis, the Reagent Set 2767245 for High Range total Phosphate (Figure 9) was used. It contains Total Phosphorus Test ’N Tube™ Vials, Potassium Persulfate Powder Pillows, Sodium Hydroxide solution 1.54N, Molybdovanadate Reagent and Deionized (demineralized) water.
The procedure reported below was followed two times for each feedstock sample.

Figure 7. DRB200 Reactor (HACH).

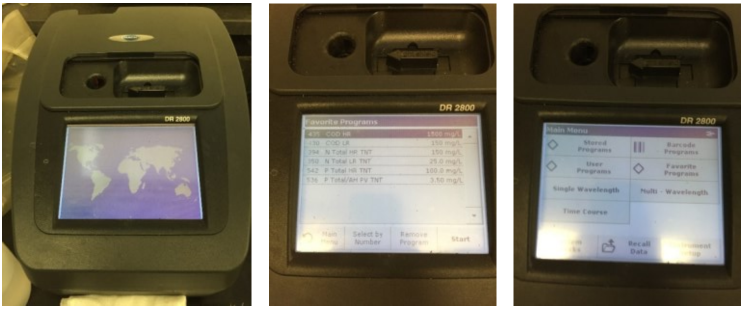


Figure 8. Portable Spectrophotometer DR 2800 (HACH).

To prepare the feedstock sample, a TenSette® Pipet was used to add 5.0 mL of feedstock sample to a Total Phosphorus Test ‘N Tube Vial.

The blank-control was obtained by adding 5.0 mL of deionized water to a Total Phosphorus Test ‘N Tube Vial.

Then it was used a funnel to add the contents of one Potassium Persulfate Powder Pillow for Phosphonate to each vial (samples and blank).

Figure 9. Reagent Set 2767245 for High Range total Phosphate.

Each vial was shake to dissolve and place for the digestion in the DRB200 Reactor. The DRB200 Reactor (HACH) was set to 150 °C for 30 minutes. After the digestion, the vials were placed in a test tube rack to allow to cool to room temperature, then, by using a TenSette Pipet it was added 2.0 mL of 1.54 N sodium hydroxide to each vial and mixed. Then, it was added 0.5 mL of Molybdovanadate Reagent to each vial, by using a polyethylene dropper and inverted to mix. Before to read the value of TP contained in each vial, it was necessary to wait the reaction period (7-minutes). Then, a Portable Spectrophotometer DR 2800 (HACH) was used (Figure 11). The selected program was 542 P Total HR, the first analysed vial was the blank-control, it was insert into the cell holder and ZERO was selected so the display showed 0 or 0.0 mg/L PO4, for the calibration. After calibration, the prepared feedstock sample were insert into the cell holder and by pushing READ the values were showed in mg/L phosphate (PO4).

2.4.5 *Fibre composition analysis (Cellulose, Xylan and Lignin content)*

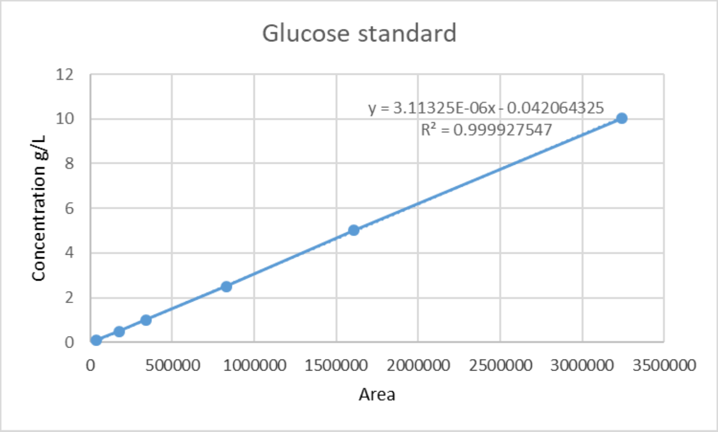
Cellulose, Xylan and Lignin contents were measured for each feedstock sample by following the LAP (Laboratory Analytical Procedure) developed by the NREL (National Renewable Energy Laboratory). The fibre composition was performed for citrus pulp, olive pomace (two and three phases), silage and manure (cattle and poultry). Each feedstock sample was tested twice.

The concentration of glucose and xylose were determined by a HPLC (high-performance liquid chromatography) system (Shimadzu Co., Kyoto, Japan), equipped with: a carbohydrate analytical column (Aminex HPX-87P, Bio-Rad Laboratories, Inc., Hercules, CA); a de-ashing refill cartridge (Micro Guard, Bio-Rad Laboratories, Inc., Hercules, CA); and a differential refractive index detector (RID-10A, Shimadzu

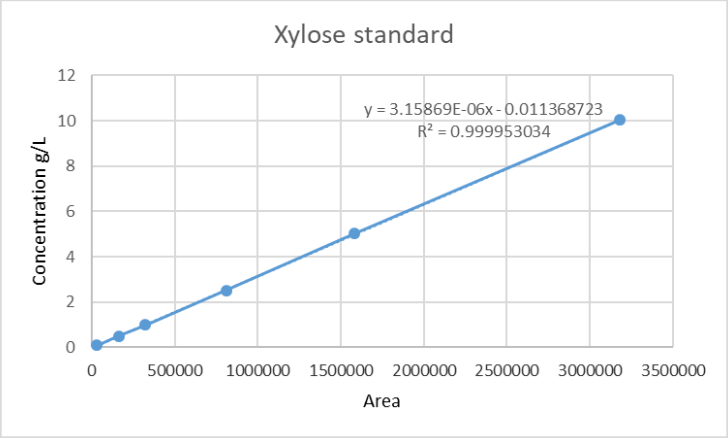
Co., Kyoto, Japan). During the mobile phase the feedstock sample was degassed by Milliporewater with a flow rate of 0.6 mL min^{-}1. Oven temperature was set at 65 °C for the analytical column, while the de-ashing was placed outside of the oven at a room temperature of 22 °C.

High purity standards of glucose (Catalog Number: 49158) and xylose (Catalog Number: 95729) were purchased via Sigma (St. Louis, MO).

By considering the glucose and xylose standard curves (Figure 10) and the absorbance, performed for each feedstock sample with UV Spectrophotometer -1800 (Figure 11) the Cellulose, Xylan and Lignin contents (g/L) were obtained.



(a)



(b)

Figure 10. Glucose (a) and xylose (b) standard curves.

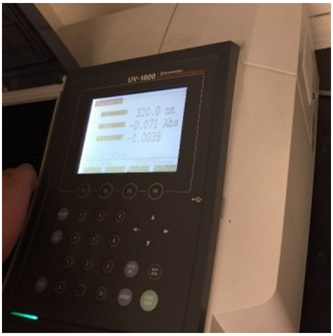


Figure 11. UV Spectrophotometer -1800 (SCHIMADZU).

2.4.6 Lipid analysis

The lipid content analysis was performed for olive pomace (two and three phases), silage and poultry manure. These analyses, which were repeated twice for each feedstock sample, was carried out by adopting the following procedure:

- Dry biomass (from filtration) in desiccator (Figure 12);
- Put around 0.5 gr of dry biomass (take the exactly weight) in clean 50mL conic tube (after grinding).

Under the fume cabinet, use three different conic tubes for Methanol, Chloroform, and demineralized water to be added to the feedstock sample with the following sequence:

- 5 mL of Methanol;
- 2.5 mL of Chloroform;
- Blend for three minutes;
- With the blend on, add 2.5 mL of Chloroform and blend for 1 minute;

- With blend on, add 2.5 mL of demineralized water and blend for 1 minute;
- By using a filter paper and pump, filter the mixture and transfer the filtered sample to a clean conic tube.
- Wait the lipid separation (different colors), by using a TenSette Pipet take the liquid on the bottom and put in aluminium crinkles (Tab). Before to put the liquid take the weight of the empty tab;
- Leave the sample overnight and the day after take the weight.

$$Lipid\ \% = \frac{(Tab+Lipid)-(Tab)}{biomass} \tag{13}$$

Figure 12. Desiccator.

2.5 *BMP test and semi-continuous anaerobic digestion to maximize biogas production*

The BMP test and semi-continuous anaerobic digestion were performed to the Department of Biosystems & Agricultural Engineering of Michigan State University during a six-month research-period.

2.5.1 Design of the experiment for BMP analysis

By considering the selected and analysed feedstocks and based on an actually used diet, different mixtures were proposed as reported in Table 8.

Six feedstock mixtures (FMs) of different feedstocks were prepared for the BMP test based on the amounts of agricultural residues available in Catania, Sicily, Italy (Table 8). CM, PL, CS, and WH were fixed at 5%, 13%, 18%, 20% (dry matter (DM)), respectively. The sum of CP and OP was 44% (DM). The CP was varied from 0% to 44% (DM), and the OP was correspondingly changed from 44% to 0% (DM). The weight ratio of OP2 and OP3 in the OP was fixed at 1:2.

Table 8. Blends composition.

	SC 1 [%]	SC 2 [%]	SC 3 [%]	SC 4 [%]	SC 5 [%]	SC 6 [%]
CP	44.0	35.2	26.4	17.6	8.8	0.0
CS	18.0	18.0	18.0	18.0	18.0	18.0
CM	5.0	5.0	5.0	5.0	5.0	5.0
PM	13.0	13.0	13.0	13.0	13.0	13.0
W	20.0	20.0	20.0	20.0	20.0	20.0
OP2	0.0	2.9	5.9	8.8	11.7	14.7
OP3	0.0	5.9	11.7	17.6	23.5	29.3

2.5.2 BMP analysis

The BMP test was modified based on the methods developed by Owen et al. and Speece (Owen et al., 1979; Speece, 2008) and described as follows. The experimental apparatus included two 500 mL glass Wheaton bottles and a volumetric cylinder connected by tubes. One of the 500 mL bottles with rubber septa cap served as the reactor containing a 200 mL of the substrate. A needle was inserted into the rubber septa to collect the biogas.

After the substrate was introduced, the reactor was purged by nitrogen gas for 10 minutes at a flow rate of 750 mL/minute to remove oxygen in the headspace. The reactors were then placed on a MaxQ 4000 benchtop orbital shaker (ThermoFisher Scientific Inc. Waltham, MA. U.S.A.) (Figure 13), and cultured at 35 ± 1 °C and 150 rpm for 26 days. The other 500 mL bottle was used as the gasholder and initially filled with water. The reactor (through the needle), gasholder and volumetric cylinder were sequentially connected by tubes. As biogas was produced, the biogas pushed the water from the gasholder into the volumetric cylinder. The volume of the water collected in the volumetric cylinder was recorded every day as the amount of biogas produced. This is one of the most commonly used laboratory methods for the quantification of small amounts of biogas as it produces low experimental uncertainty (Battista et. al., 2016; Da Ros et al., 2016; Ruggeri et al., 2015).

The substrate for the BMP test was prepared by mixing the FM and seed at a VS ratio of 1:2 for 15 seconds in a blender (Waring Commercial Laboratory, Model No. 34BL97(7012)) (Table 9).

Figure 13. ThermoFisher Scientific Inc. Waltham, MA. U.S.A, used during the BMP test.

Deionized water was added into the substrate to the targeted DM content of ~2.5%. The seed was used as the control. All tests were ran in duplicates. Methane content in the biogas was analysed, by using an SRI GC Multiple Gas Analyser with valve injection.

CH_4 and CO_2 were measured using a thermal conductivity detector (TDC) and H_2S was measured using a flame photometric detector (FPD). Both columns are operated isothermally at 40 °C with a total run time of two minutes per sample. For biogas analysis, 3 mL of gas was extracted from the headspace of each serum bottle using a five mL syringe (SGE, INC) outfitted with a lock valve. This volume was compressed to 3 mL and then the valve was quickly opened and closed to equalize the pressures between the sampled gas and atmosphere prior to injection.

VS and pH of the substrates before and after the BMP test were monitored as well. The difference on methane production between the FM and control was used to calculate BMP regarding the VS input.

Figure 14. SRI GC Multiple Gas Analyser.

The BMP (mL methane/g VS loading from FM) calculation equation is as follow:

$$BMP = \frac{V \times G - V_{control} \times G_{control}}{VS_{FM}} \quad (14)$$

Where V is the accumulated biogas volume from the BMP test of the FM (mL), G is the methane content of the biogas from the BMP test of the FM (% v/v), $V_{control}$ is the accumulate biogas volume from the BMP test of the control (ml), $G_{control}$ is the methane content (% v/v) of the biogas from the BMP test of the control (% v/v), and VS_{FM} is the total amount of VS (g) loading from the FM (not including the VS from the seed).

Table 9. Preparation of FM solutions for BMP test [a]

	FM1	FM2	FM3	FM4	FM5	FM6
Citrus pulp (CP) (g, wet)	8.34	5.92	3.99	2.41	1.10	0.00
Olive pomace, Phase 2 (OP2) (g, wet)	0.00	0.49	0.89	1.21	1.47	1.70
Olive pomace, Phase 3 (OP3) (g, wet)	0.00	0.99	1.77	2.41	2.95	3.39
Corn silage (CS) (g, wet)	3.41	3.03	2.72	2.47	2.26	2.09
Cattle manure (CM) (g, wet)	0.95	0.84	0.76	0.69	0.63	0.58
Poultry litter (PL) (g, wet)	2.46	2.18	1.96	1.78	1.63	1.51
Whey (WH) (g, wet)	3.79	3.36	3.02	2.74	2.51	2.32
AD filtrate (g)	295.09	295.09	295.09	295.09	295.09	295.09
DI water (g)	185.3	188.10	189.79	191.19	192.35	193.32
Total mass (g)	499.34	500.00	499.99	499.99	499.99	500.00

[a] It is based on the feedstock ratios in FMs.

2.5.3 Anaerobic digestion

The selected FMs from the BMP tests were used as feeds to run semi-continuous anaerobic digestion. The digestion was carried out in 750 mL bottles (reactor) with rubber septa caps. The working volume for all reactors was 500 mL with a headspace of 250 mL. Needles were also used to penetrate the rubber septa to release and collect biogas. Duplicate reactors were prepared for individual runs. The reactors were placed on a MaxQ 4000 bechtop orbital shaker (ThermoFisher Scientific Inc. Waltham, MA. U.S.A.) (Figure 13) and cultured at 35±1 °C and 150 rpm. The hydraulic retention time (HRT) was set at 25 days. The DM of all reactors was maintained at approximately 5% (w/v).

The pH for all reactors was controlled in a range between 6.70 and 6.90 by dosing 30% (w/w) sodium hydroxide (NaOH) solution.

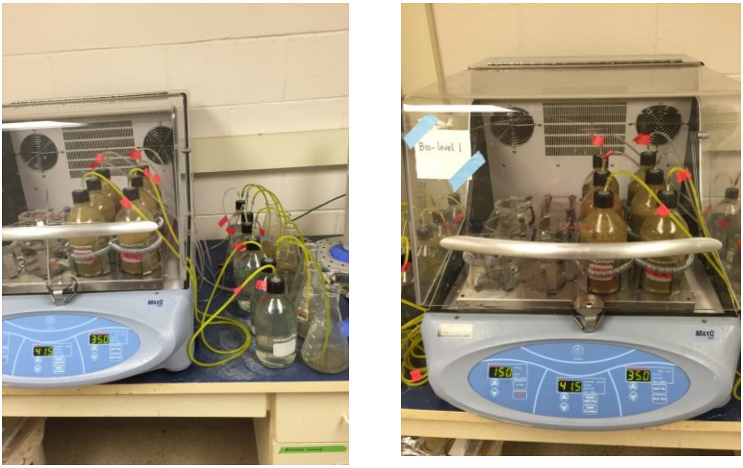


Figure 15. ThermoFisher Scientific Inc. Waltham, MA. U.S.A., during the semi-continuous anaerobic digestion.

The daily biogas production from each reactor was measured using the same water displacement method described in the

BMP test section. Sampling and feeding of the reactors were performed using an automatic atmosphere chamber (Plas Lab, Lansing, MI) (Figure 16).

The chamber was purged with a medical grade specialty gas from Airgas, composed of 85% nitrogen (N_2), 10% hydrogen (H_2) and 5% carbon dioxide (CO_2). A palladium catalyst heater was used to make the chamber completely anaerobic. FMs at 5% DM were made every 10 days and stored in a refrigerator at 4 °C. 50 mL of the FM were fed to the reactor every other day, and the same amount of the AD effluent was removed from the reactor and stored in the -20 °C freezer.

Biogas samples from the reactors were also periodically collected for gas composition analysis. The entire duration for the semi-continuous anaerobic digestion was 78 days, approximately 3 HRTs.

Figure 16. Automatic atmosphere chamber (Plas Lab, Lansing, MI).

2.5.4 BMP test and semi-continuous anaerobic digestion analytical and statistical method

Methane, carbon dioxide, and hydrogen sulfide contents in biogas were quantified using a SRI GC Multiple Gas Analyzer with valve injection. Methane and carbon dioxide were measured using a thermal conductivity detector (TDC), and hydrogen sulfide was measured using a flame photometric detector (FPD). Both columns are operated isothermally at 40 °C with a total run time of two minutes per sample. Hydrogen and helium were carrier gases, and maintained at 21 psi. The biogas sample volume was 100 µL, and the syringe (5 µL) was purged three times before sample injection. Total solids (TS), volatile solid (VS), chemical oxygen demand (COD), total nitrogen (TN) and total phosphorus (TP) of the samples (pre and post digestion) were determined according to the standard methods (APHA, 1998).

ANOVA, multiple means comparison, and Tukey pair-wise comparison were conducted on biogas production, biogas composition, and volatile solids reduction to identify significant differences among experimental runs. R (Version 3.2.4, the R foundation for Statistical Computing) was the software to carry out the statistical analysis (Section 6.1).

2.5.5 BMP test and semi-continuous anaerobic digestion mass and energy balance

Mass and energy balance analysis were carried out based on the experimental data and local environmental conditions at Sicily, Italy. The analysis was conducted based on 1 kg dry raw feed. The data from the last HRT were used to carry out the analysis.

The methane (CH4) production (M, g methane/kg dry FM) was calculated based on the following equation:

$$M = \frac{P \times G \times 16}{0.082 \times T} \tag{15}$$

Where P is biogas productivity (L biogas/kg dry FM loading), G is the volumetric percentage of methane in the biogas (%), T is the biogas temperature (K), 16 is molecular weight of methane (g/mol), and 0.082 is the gas constant (L atm/K/mol).

The energy balance was analyzed based on high heat value of methane, local temperature, and thermal efficiencies of combined heat and power (CHP) unit. Energy inputs and outputs were assigned as negative and positive, respectively. The biogas was assumed to be used by a combined heat and power (CHP) unit to generate heat and electricity. The energy outputs as heat (Eheat, kWh-e/kg dry FM) and electricity (Eelectricity, kWh-e/kg dry FM) were calculated using the following equations.

$$E_{heat} = M \times 55 \times 0.6 \times 0.0002778 \tag{16}$$

$$E_{electricity} = M \times 55 \times 0.3 \times 0.0002778 \tag{17}$$

Where 55 is the high heating value of methane (kJ/g), 0.6 is the thermal efficiency of a typical CHP (Kurchania et al., 2011), 0.3 is the electrical efficiency of a gas engine, and 0.0002778 is the conversion factor of kJ to kWh.

The energy inputs for the digestion operation include heat (W_{heat}, kWh-e/kg dry FM) to maintain the digestion temperature as well as electricity ($W_{electricity}$, kWh-e/kg dry FM) to power pumps, mixers, and other accessary quipment. The energy inputs were calculated as follows:

$$W_{heat} = E_{heat} \times 30\% \qquad (18)$$

$$W_{electricity} = E_{electricity} \times 9\% \qquad (19)$$

Where 30% and 9% are the percentages of the heat and electricity required to power digester system (Sliz-Szkliniarz and Vogt, 2012).

2.6 Localisation of biogas plants in the study area

A three-step approach was adopted to carry out the analysis (Figure 17). Data required for the GIS-based analysis such as the amount of biomass amount, municipal boundary, and locations of farms and food processing facilities were first collected and organized based on biomass type. GIS-based analysis was then conducted on the biomass data to locate biogas plants and determine the size and collection areas supplying individual biogas plants. Finally, techno-economic assessment was applied on these biogas plants to evaluate the feasibility of a regional biogas production system. The proposed method was adopted specifically for the case study, Catania province, but it was also applied at regional level.

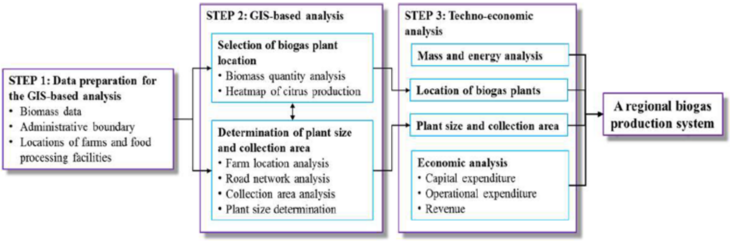


Figure 17. Flow diagram of analytic steps.

2.6.1 <u>GIS-based analysis for biogas plants site selection</u>

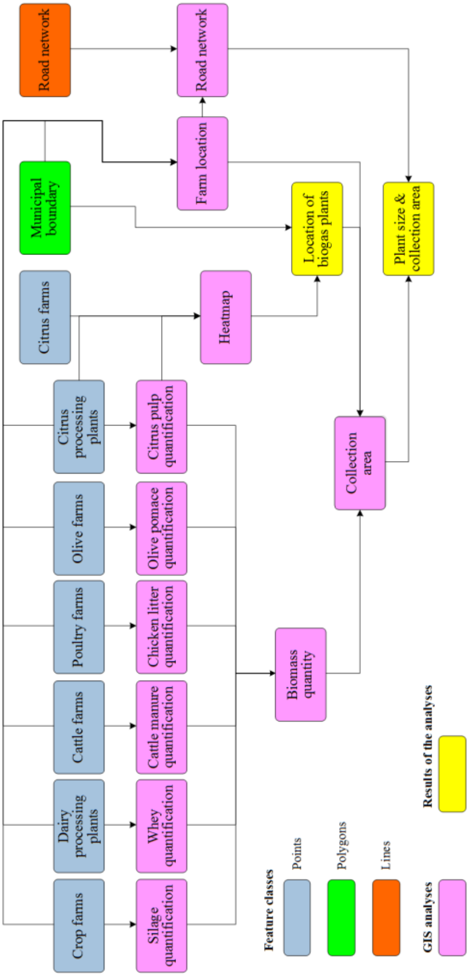
QGIS software (Ver. 2.16) was used to carry out the GIS-based analysis. The cartographic modelling approach was adopted to determine the location of biogas plants and corresponding plant size and collection area (Figure 18). Maps layers were assigned to the target parameters of citrus processing plants, olive farms, dairy processing plants, cattle farms, poultry farms, crop farms, road networks, and municipal boundaries of Catania. The production of each feedstock was detailed on the corresponding farm and processing plant layers. Different combinations of these layers were used to generate the target information of location, size, and collection area for biogas plants.

The layers of citrus processing plants and municipal boundaries were integrated with the heatmap of citrus production to find locations for potential biogas plants. The heatmap of citrus production was created with using a specific GIS-tool which required information on the feedstock which had the highest availability and the lowest number of farms. This assumption was made in order to optimize the logistics transportation costs of citrus supply.

The information required to build the heatmap, was obtained from the surveys of the processing industries.

Given the large amounts of citrus wastes, the primary citrus production areas were selected as the potential biogas plant sites. With these selected locations for biogas plants, the biomass quantity and farm location analyses were then conducted on the layers of citrus processing plants, olive farms, dairy processing plants, cattle farms, poultry farms, and crop farms to estimate the availability of individual biomass materials at individual farms.

Figure 18. Flow chart of the GIS-based model.



Building upon the biomass quantities and farm location data, collection areas and road network analyses were conducted to determine the size of the biogas plants and the corresponding collection boundaries. The minimization of the transportation costs is the key criterion in this analysis. A buffer zone (vector spatial) analysis was used to determine the collection boundary and calculate the transportation distances. The biogas plants were considered as vector points. A radius of 45 km around the vector points was set as buffer zone. The OpenStreetMap database and regional technical map (RTM 2008) were used to generate transportation networks. The road graph plugin tool in QGIS software was applied on the datasets of highways and primary and secondary roads to calculate the distance from individual farms and processing facilities to the biogas plants. For the farms and processing facilities that fell into intersecting areas between different buffer zones, the shortest path to reach the nearest biogas plant was computed (Table 10).

Table 10. Examples of selection of Distance calculation to decide which biogas plants.

Farm or processing facility	Distance to biogas plant I	Distance to biogas plant II	Distance to biogas plant III	Distance to biogas plant IV
Olive processing facility No.59	51.62	28.51	24.51*	49.07
Cattle farm No.45	86.81	68.77	53.49	49.79*
Poultry farm No.10	49.88	27.1	21.99*	50.15
Silage collection point No.34	52.46	29.67	26.48*	49.69

*: The shortest distance corresponding to the biogas plant

2.6.2 Technical and economic assessment

2.6.2.1 Technical assessment

Mass and energy balance analyses were carried out for individual biogas plants according to the data from the GIS-based modeling. The biogas plant unit operations include anaerobic digestion, liquid/solid separation of digestion effluent, biogas clean-up, and combined heat and power (CHP) generation. The digestion is operated under 35°C and 10% TS with a hydraulic retention time of 20 days. The products of the biogas plants are electricity, heat, and digestates as fertilizers and soil amendment. The biogas production (B, m^3/year) was calculated as follows based on the volatile solids and biogas productivity.

$$\mathrm{B} = \mathrm{Feedstock_{VS}} \times \mathrm{R_{VS}} \times \mathrm{P} \tag{20}$$

Where $Feedstock_{VS}$ is the total amount of volatile solids (VS) in the feedstock biomass (kg VS/year), P is the average biogas productivity of 0.89 m^3/kg VS reduced, and R_{VS} is the average VS reduction of 50% during the digestion. Biogas is assumed to contain 50% (v/v) methane. The data on biogas productivity, VS reduction, and methane content were obtained from laboratory tests.

After anaerobic digestion of biogas production, the digestion effluent is separated by a liquid/solid separator to obtain solid digestate and liquid digestate. The total solids (TS) in solid digestate and liquid digestate are assumed at 25% and 4%, respectively. The amounts of the digestion effluent ($\mathrm{A_{dig\_eff}}$, kg/year), solid digestate (A_{sol_dig}, kg/year), and liquid digestate (A_{liq_dig}, kg/year) were calculated as follows:

$$A_{dig\_eff} = \frac{Feedstock_{TS}}{10\%} - (Feedstock_{VS} \times R_{VS}) \tag{21}$$

$$A_{sol_{dig}} = \frac{[Feedstock_{TS} - (Feedstock_{vs} \times R_{VS})] - A_{liq_{dig}} \times 4\%}{25\% - 4\%} \tag{22}$$

$$A_{liq\_dig} = A_{dig\_eff} - A_{sol\_dig} \tag{23}$$

Where $\text{Feedstock}_{\text{TS}}$ is the total TS in the feedstock (kg/year), 10% is the TS content of the feed for the digestion operation, and 25% and 4% are the TS contents in solid digestate and liquid digestate, respectively.
The size of the engine for biogas utilization is calculated based on the methane content, the lower heating value of methane, and the biogas engine efficiency.

$$E_{GasEng} = \frac{B \times 50\% \times 36 \times 0.3 \times 0.2778}{7000} \tag{24}$$

Where E_{GasEng} is the electricity output of the engine (kW-e) of gas engine on biogas, 50% is the volumetric methane content in the biogas, 36 is the lower heating value (MJ/m^3 methane) of methane gas, 0.3 is the average thermal efficiency of gas engine to convert methane heating value to electricity energy, 0.2778 is the conversion factor of MJ to kWh, and 7000 is the operational hours of the gas engine in a year considering the recommended top-end overhaul maintenance for the CHP unit (EPA US, 2015).
Considering both electricity and thermal efficiencies of gas-engine CHP, The net annual electricity (E_{El}, kWh-e/year) and heat (E_{Heat}, kWh-e) generation from biogas plant for uses outside the plant can then be calculated as follows.

$$E_{El} = B \times 50\% \times 36 \times 0.2778 \times 0.3 \times (100 - 9)\% \quad (25)$$

$$E_{Heat} = B \times 50\% \times 36 \times 0.2778 \times 0.6 \times (100 - 30)\% \quad (26)$$

Where 9 and 30 in equations (25) and (26) above are the percentage of electricity and heat, respectively, that are used internally by the biogas plants, and are thus not available for export to the larger society (Sliz-Szkliniarz and Vogt, 2012); and 0.3 and 0.6 are set as electricity and thermal efficiencies, respectively.

2.6.2.2 Economic and sensitivity analysis

Based on the mass and energy balance data, an economic analysis was then conducted to determine the viability of the four regional biogas production systems. The capital expenditure (*CapEx*) and operational expenditure (*OpEx)* of individual biogas plants were analysed and used for the economic assessment. *CapEx* includes the costs of anaerobic digester, biogas cleaning unit, and CHP unit. The *CapEx* of individual unit operations were then calculated using the following equations.

The *CapEx* for the anaerobic digester ($CapEx_{Dig}$, €/digester) is expressed as a function of the biogas flow rate (Sliz-Szkliniarz and Vogt, 2012).

$$CapEx_{Dig} = [14{,}239 \times (\frac{B}{7{,}000})^{-0.2209}] \times \frac{B}{7{,}000} \quad (27)$$

Where *B* is the annual biogas production (m^3/year), 7,000 is the operational hours per year of the biogas plant (hr) based on the CHP operation.

The *CapEx* for the CHP (€/CHP with an engine size of E_{GasEng}) is correlated with the electrical power output of the engine. The following lognormal expression is applied to obtain the *CapEx* (Sliz-Szkliniarz and Vogt, 2012).

$$CapEx_{CHP} = [3{,}814.8 \times \left(E_{GasEng}\right)^{-0.2916}] \times E_{GasEng} \quad (28)$$

A biological H_2S removal is adopted to clean biogas. The *CapEx* for the cleaning unit ($CapEx_{biogasClean}$, €/unit) is also calculated based on biogas flow rate. The following equation was obtained using power regression to fit literature data for biogas production in the range of 200 m^3/hour to 2,000 m^3/hour (Allegue and Hinge, 2014).

$$CapEx_{biogasClean} = \left[56{,}297 \times \ln\left(\frac{B}{7{,}000}\right)\right] - 197{,}310 \quad (29)$$

The total *CapEx* for a biogas plant with a given biogas production ($CapEx_{Tot}$, €/biogas plant) can then be calculated as:

$$CapEx_{Tot} = CapEx_{Dig} + CapEx_{BiogasClean} + CapEx_{CHP} \quad (30)$$

The *OpEx* includes the costs of feedstock, transportation fuels, feeding, plant operation and maintenance, feedstock storage and effluent handling, and labour and administration. It is calculated based on feedstock, transportation, digester operation, and CHP operation.

Both food processing wastes (citrus pulp, olive pomace, and whey) and livestock wastes (poultry litter and cattle manure) are considered as wastes, so that there are no feedstock costs for them to be used by biogas production. However, the forage crops (corn silage) has a production cost. According to the corn price (0.2 €/kg corn) in Italy and the weight ratio (1:8) of corn to wet corn silage, the cost of the corn silage is calculated at 0.025 €/kg corn silage with a moisture content of 65%.

The *OpEx* for the feedstock ($OpEx_{feedstock}$, €/year) is calculated as follows.

$$OpEx_{feedstock} = 0.025 \times Feedstock_{cs} \tag{31}$$

Where $Feedstock_{cs}$ is the amount of corn silage used for the biogas plants (kg/year) and 0.025 is the cost of corn silage (€/kg wet corn silage).

The *OpEx* for the transportation ($OpEx_{Transp}$€/year) is computed based on the annual round-trip transportation mileage and fuel cost.

$$OpEx_{Transp} = 2.41 \times Mileage \tag{32}$$

Where *Mileage* is the annual round-trip transportation mileage for each biogas plant (km/year), and 2.41 €/km (including fuel consumption, labor, insurance, truck rental, toll, and truck maintenance etc.) was the cost per unit distance for the truck with a load of 30 tons, which is determined based on the Italian Decree no. 133/2008 (Legislative Decree no. 133/2008).

The *OpEx* for the anaerobic digester and CHP are fixed at 4% and 3% of total *CapEx* per year, respectively (Sliz-Szkliniarz and Vogt, 2012). The following equations are used to the *OpEx* for both unit operations.

$$OpEx_{Dig} = 0.04 \times CapEx_{Tot} \tag{33}$$

$$OpEx_{CHP} = 0.03 \times CapEx_{Tot} \tag{34}$$

Where $OpEx_{Dig}$ and $OpEx_{CHP}$ are the *OpEx* (€/year) for anaerobic digestion and CHP operationsthe biogas clean-up operations, respectively.

Then, the annual *OpEx* for a biogas plant with a given biogas production ($OpEx_{Tot}$, €/year) can also be calculated as:

$$OpEx_{Tot} = OpEx_{Transp} + OpEx_{Dig} + OpEx_{CHP} \tag{35}$$

The renewable electricity and solid digestate provide the plant revenues. According to Italian Norm D.M. 5046/2016 (Legislative Decree no. 5046/2016), liquid and solid digestates after liquid/solid separation are both considered as useful products for agricultural uses. In this study, it is assumed that the solid digestate is sold at €0.02/wet kg according to the current market price in Italy, and the liquid digestate is free and transported back to crop farms. The revenues from electricity (Rev_{el}, €/year) and solid digestate (Rev_{sol_dig}, €/year) is then calculated as:

$$Rev_{el} = 0.28 \times E_{El} \tag{36}$$

$$Rev_{sol\_dig} = 0.02 \times A_{sol\_dig} \tag{37}$$

Where 0.28 is the price (€/kWh) of the renewable electricity in Italy, and 0.02 is the price (€/wet kg) of the solid digestate. The Modified Accelerated Cost Recovery System (MACRS) was used to calculate the annual depreciation of *CapEx*. The annual depreciation rates from MARCRS are: 0.100, 0.188, 0.144, 0.115, 0.092, 0.074, 0.066, 0.066, 0.065, 0.065, 0.033, and 0.033 (after 10 years). The depreciation period is set at 20 years. In addition, an annual inflation of 1% was set for *OpEx* and revenues based on the current average inflation rate in Italy. The net cash flow based on depreciated *CapEx* and inflated *OpEx* and revenues was conducted to determine the payback period.

2.6.2.3 Economic and sensitivity analysis

An economic sensitivity analysis was carried out on both OpEx and revenue parameters to elucidate their impacts on payback period of the biogas plants and identify the most influential factors. Twenty five percent of their base values was used to elucidate their impact.

3 Results

3.1 Citrus pulp potential availability

To calculate S_{citrus_i} and P_{citrus_i} at the municipal level, Agricultural Census 2010 data were elaborated and reported in Table 11. Data analyses regarded the amount of citrus growing area, the amount of produced citrus fruits and, consequently, the amount of processed citrus fruits. Table 11 shows that the average amount of processed citrus fruits equals 3,263.1 t, with a standard deviation of 7,399.17 t. The minimum value regarded 22 municipalities where citrus producing areas are not present.

Table 11. Minimum, maximum and mean values of S_{citrus_i}, P_{citrus_i}, and $P_{processed\_citrus\_i}$ obtained by elaborating the data related to the 58 municipalities of the province of Catania.

	S_{citrus_i} [ha]	P_{citrus_i} [t]	$P_{processed\_citrus\_i}$ [t]
Minimum (t)	-	-	-
Maximum (t)	8,282.7	134,594.2	40,378.3
Mean (t)	669.4	10,877.0	3,263.1
Standard deviation	1,517.8	24,663.9	7,399.2
Range of variation (*)	8,282.7	134,594.2	40,378.3

Source: Data collected through direct survey.

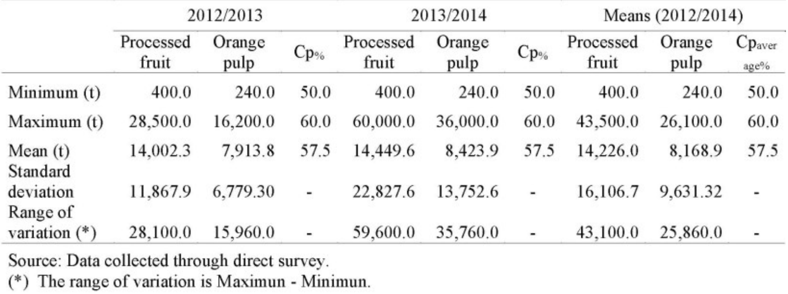
(*) The range of variation is Maximun - Minimun.

The citrus processing industries were all identified in the territory and localised on the georeferenced ortho-photos by using their GPS coordinates to produce a feature class in the base-map describing the distribution of citrus growing areas in Catania province (Figure 19).

Figure 19 shows that citrus processing industries are not equally distributed in the entire province. In fact, some of the industries are too close to each other.

The data collected by the surveys were elaborated by using descriptive statistical tools in order to highlight the main production aspects. The data elaborations, which are referred to the two last available campaigns (2012/2013 and 2013/2014) and reported in Table 12, provided minimum, maximum, and mean values of the productions of citrus fruits and citrus pulp, their standard deviation (SD), and the percentage of citrus pulp obtained $Cp_{average\%}$.

Table 12. Computed $Cp_{average\%}$ indicator.



	2012/2013			2013/2014			Means (2012/2014)		
	Processed fruit	Orange pulp	$Cp_{\%}$	Processed fruit	Orange pulp	$Cp_{\%}$	Processed fruit	Orange pulp	$Cp_{average\%}$
Minimum (t)	400.0	240.0	50.0	400.0	240.0	50.0	400.0	240.0	50.0
Maximum (t)	28,500.0	16,200.0	60.0	60,000.0	36,000.0	60.0	43,500.0	26,100.0	60.0
Mean (t)	14,002.3	7,913.8	57.5	14,449.6	8,423.9	57.5	14,226.0	8,168.9	57.5
Standard deviation	11,867.9	6,779.30	-	22,827.6	13,752.6	-	16,106.7	9,631.32	-
Range of variation (*)	28,100.0	15,960.0	-	59,600.0	35,760.0	-	43,100.0	25,860.0	-

Source: Data collected through direct survey.
(*) The range of variation is Maximun - Minimun.

The elaborations carried out for the six citrus processing industries located in the province of Catania, showed that the average amount of processed citrus fruits, during the two investigated harvests (2012/2013 and 2013/2014), equals 14,226.0 t, with a variation of 43,100.00 t, since it ranges between 400.0 t and 43,500.000 t.

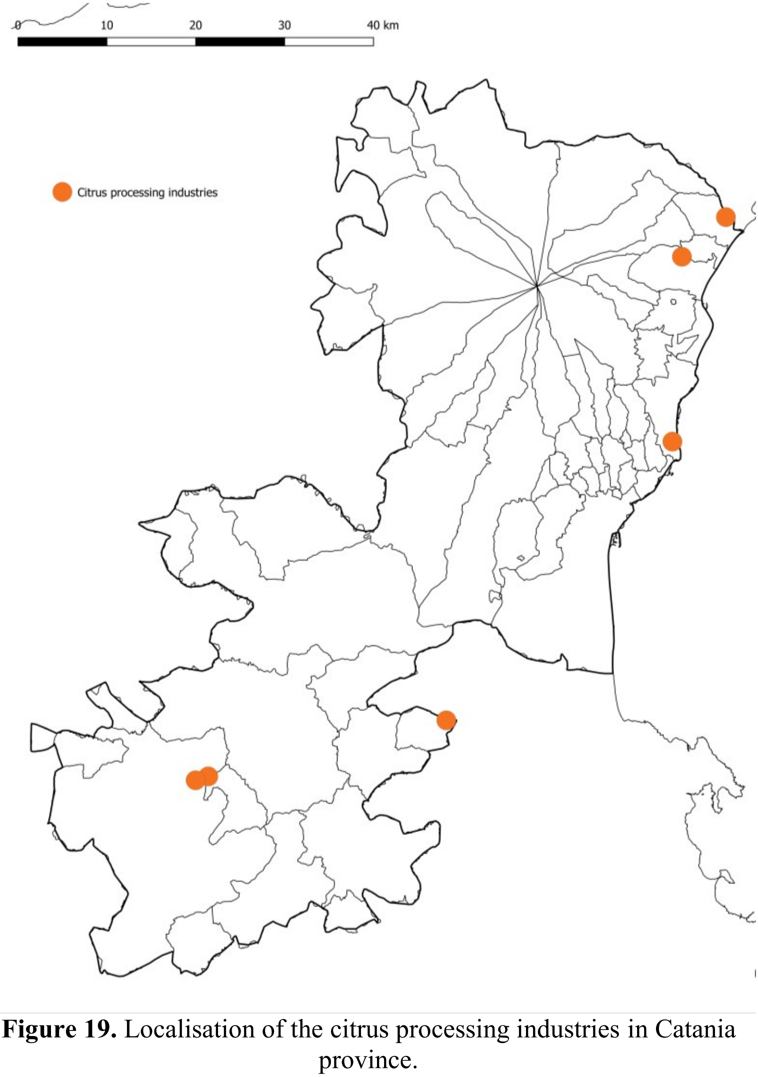


Figure 19. Localisation of the citrus processing industries in Catania province.

The table also shows that, during the second campaign (2013/2014), the processed citrus fruits reached a maximum value of 60,000.0 t, which was about 50% more than the value related to the previous campaign, while the average amount increased by about 3% compared to the previous campaign. In fact, the average amount of processed fruits is affected by the different production of each citrus processing industry, due to the decrease of the consumer price and a consequent deliver of the excess production to the citrus processing industries. The amount of citrus pulp produced by the citrus processing industries is a direct consequence of the amount of processed citrus fruits and the production process for juice extraction adopted by each company. In fact, the obtained citrus pulp varied between a maximum value of 26,100.0 t and a minimum of 240.0 t, with an average value of 8,168.9 t. The SD confirms the citrus processing industry variability. Based on the data obtained from the survey, the indicator $Cp_{average\%}$ was computed for the province of Catania (Table 12); its average value, which was equals to 57.5 %, was considered for the following elaborations.

The citrus pulp production $Cp_{\_i}$ was computed according to Eqn. 7 (Table 14) and was reported on the base-map of GIS (Figure 20).

Figure 20 shows the relevance of citrus pulp production in several areas of the municipalities belonging to the Catania Plan district. The area with the highest citrus pulp production is contained in six municipalities of the province of Catania.

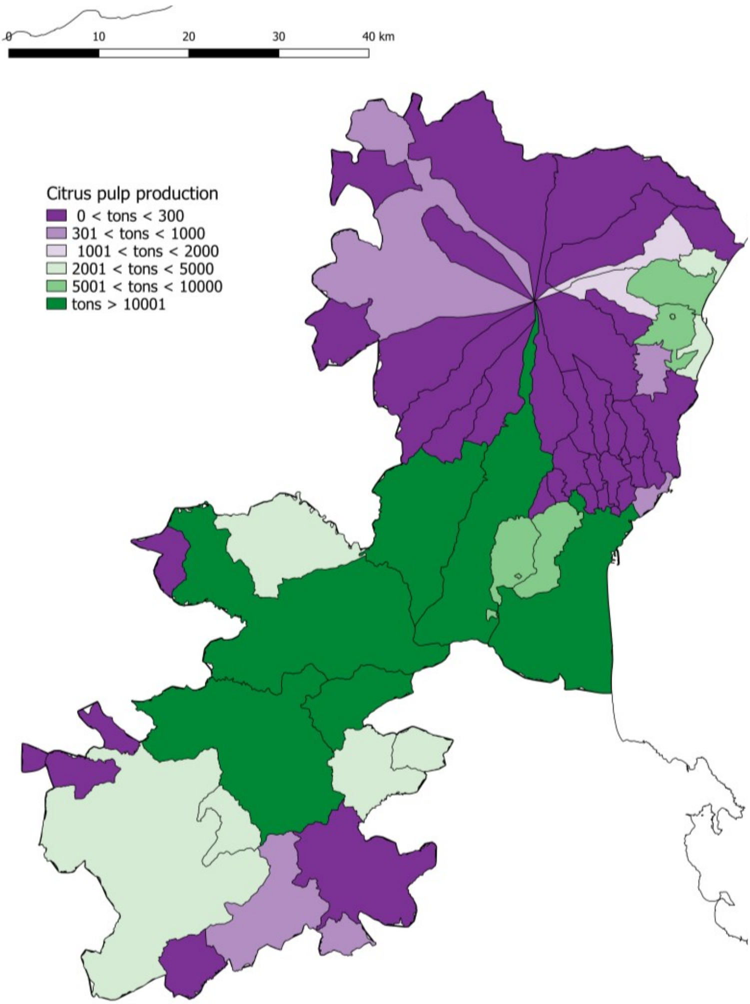


Figure 20. Territorial distribution of citrus pulp production C_{p_i} .

3.2 Olive pomace availability

The same methodology applied for the estimation of citrus pulp availability, was adopted to estimate the olive pomace availability. To calculate the indicators S_{olive_i} and $P_{olive\ \_i}$ at the municipal level, the data from Agricultural Census 2010 and from ISTAT (2011-2014) were elaborated (Table 14). The data analysis on RTM 2008 highlighted the relevance of olive production in several areas of the municipalities, which are also the most productive areas for citrus fruit (Valenti et al., 2017a, 2016).

The identification and the localisation of the olive processing industries in the territory by using their GPS coordinates made it possible to produce a feature class in the GIS base map, which describes the distribution of olive producing areas in the province of Catania (Figure 21).

Figure 21 shows a uniform distribution of the olive processing industries with a higher concentration in the inner areas of the province. The surveyed data from the sample of 29 industries have been summarized in Table 13. The collected data were elaborated by using descriptive statistical tools in order to highlight the main production aspects. The elaborations which were carried out on 29 olive processing industries located in the province of Catania showed that the average amount of processed olives equals 664.58 t, with a variation of 1,300.0 t, since it ranges between 200.0 t and 1,500.0 t. The obtained olive oil production varied between a minimum value of 30.0 t and a maximum of 222.0 t, with an average value of 103.58 t. The by-products of olive oil processing industries are olive oil pomace, olive vegetation water, and olive pits. In the sample of olive processing industries examined, different oil yields as well as by-product yields were registered in close relation to the oil extraction process (two or three-phases process).

Table 13. Computed $Op_{average\%}$ indicator.

	Olives [t]	Olive oil [t]	Olive virgin pomace [t]	Olive vegetation water [t]	Olive pits [t]	Op_average [%]
Minimum	200.0	30.0	90.0	90.0	35.0	35.0
Maximum	1,500.0	222.0	650.0	740.0	90.0	55.0
Mean	664.5	103.5	294.8	311.3	55.0	44.9
Standard deviation	344.6	58.5	149.0	175.3	30.4	4.7
Range of variation (*)	1,300.0	192.0	560.0	650.0	55.0	20.0

Source: Data collected through direct survey.
(*) The range of variation is Maximun - Minimun.

In fact, on average the production of olive virgin pomace equals 294.88 t, the production of olive vegetation water stands at 311.33 t, whereas the production of olive pits is about 55.0 t. The olive pomace yield reaches 44.92 t on average, with a variation range of 20.0 t since it varies from a minimum of 35.0 t to a maximum of 55.0 t. The values of the standard deviation confirms the sample variability due to the oil extraction technology adopted by the different olive processing industries. The olive pomace production O_{p_i} was computed for each municipality, according to Eqn.8, and reported in Figure 22. Figure 22 shows the relevance of olive production in several areas of the municipalities belonging to the Catania Plan district (i.e. Caltagirone, Mineo, Ramacca, Belpasso, Paternò, Adrano, and Bronte), which is also the most producing area for citrus fruit (Figure 20).

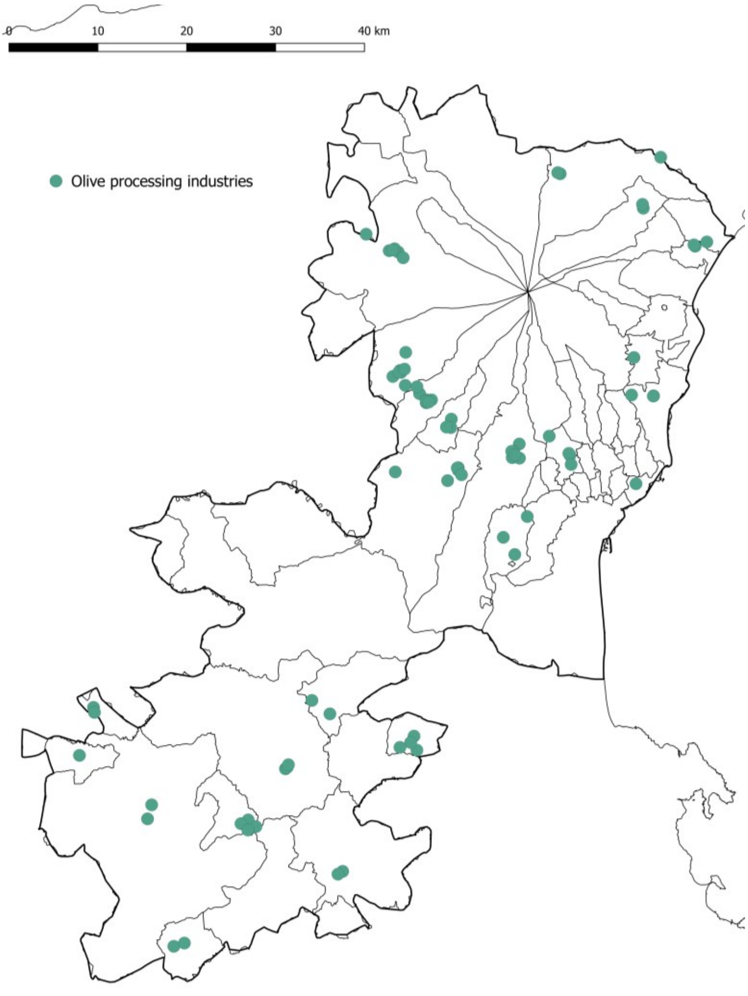


Figure 21. Localization of olive processing industries in the province of Catania.

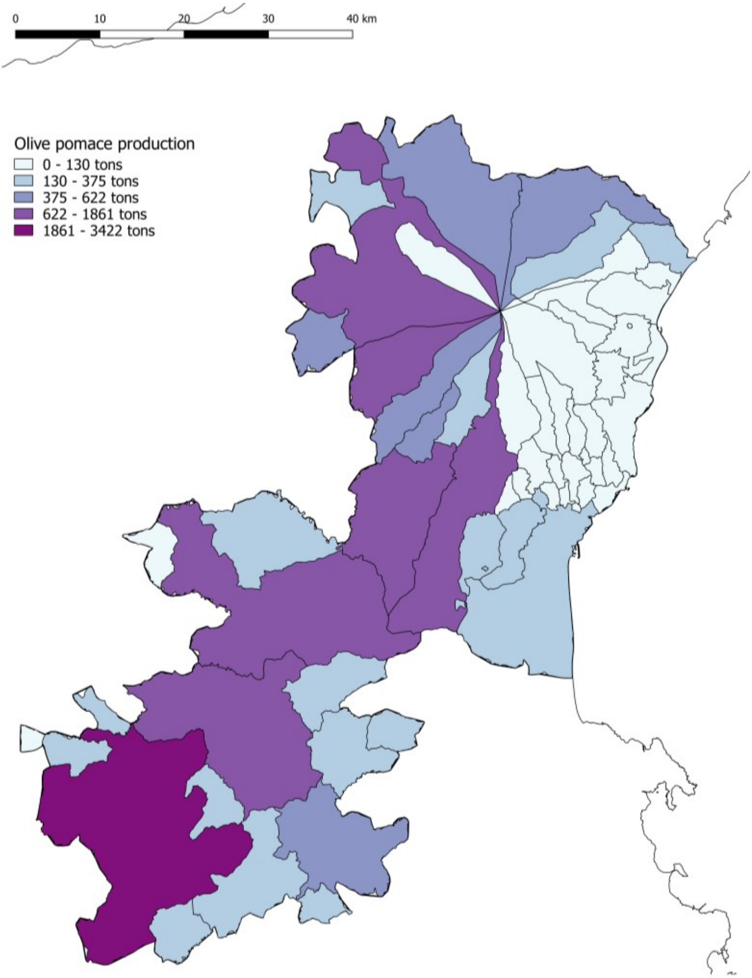


Figure 22. Territorial distribution of olive pomace production O_{p_i} in the province of Catania.

3.3 *Suitable areas for the development of new biogas plants*

For each municipality, the computed values of O_{p_i} and C_{p_i} , which describe the potential olive pomace and citrus pulp production, respectively, were reported in Table 14. With regard to the citrus pulp production, only five municipalities out of 58 (Belpasso, Catania, Mineo, Palagonia, and Ramacca) contributed with more than 60% of the total production, which was equal to about 108,824 tons. Whereas, the olive pomace production was equally distributed in each municipality, except for three municipalities (Belpasso, Caltagirone, and Mineo), which produced the 30% of the total olive pomace, which was about 14,868 tons.

For each municipality, the values of the estimated B_{tot_i}, computed by applying Eq. 9 were also reported in the Table 14 and mapped in Figure 23. Therefore, for the whole province of Catania, the total biogas production was estimated to be about 11.665.815 Nm^3. In order to select suitable areas for the location of new biogas plants, the municipalities were grouped into the five classes reported in Table 15 and for each of them the main statistic parameters of S_{citrus_i} and S_{olive_i} were showed in Table 16.

In the municipalities belonging to the first class, which has an average value of S_{mun} equal to about 1,158 ha, the 8% of the whole surface is for olive and citrus cultivation, which are the 3% e 5% of the whole S_{mun} respectively, corresponding to 26.28 ha of olive groves and 61.73 ha of citrus growing areas on average.

Table 14. Olive pomace O_{p_i}, citrus pulp C_{p_i} and biogas potential production $\mathbf{B_{tot}}$ for each municipality.

	S_{mun}*** [ha]	S_{olive_i} * [ha]	P_{olive_i}** [t]	$Op_{\_i}$ [t]	S_{citrus_i} * [ha]	P_{citrus_i}** [t]	$Cp_{\_i}$ [t]	B_{tot_i} [Nm^3]
Aci Bonaccorsi	171.0	1.0	3.1	1.4	-	-	-	183.0
Aci Castello	878.0	16.6	51.7	23.2	118.0	575.5	330.9	32,597.9
Aci Catena	846.0	2.6	8.2	3.7	-	-	-	486.8
Aci Sant'antonio	1,424.0	5.9	18.5	8.3	-	-	-	1,088.9
Acireale	4,037.0	56.2	175.0	78.6	-	-	-	10,301.5
Adrano	8,266.0	477.8	1,486.0	667.5	-	-	-	87,446.9
Belpasso	16,521.0	884.5	2,750.8	1,235.6	4,230.1	20,622.1	11,857.7	1,220,770.1
Biancavilla	6,981.0	331.1	1,029.8	462.6	-	-	-	60,601.4
Bronte	24,912.0	663.4	2,063.4	926.9	64.9	316.4	181.9	137,675.0
Calatabiano	2,632.0	112.9	351.4	157.8	34.4	167.8	96.5	29,296.6
Caltagirone	38,114.0	1,393.3	4,333.2	1,946.5	649.0	3,164.0	1,819.3	417,455.9
Camporotondo Etneo	651.0	43.3	134.9	60.6	-	-	-	7,940.7
Castel di Iudica	10,257.0	249.2	775.2	348.2	475.0	2,315.6	1,331.4	164,518.2
Castiglione di Sicilia	11,812.0	417.1	1,297.1	582.6	-	-	-	76,332.8
Catania	18,163.0	261.1	812.3	364.8	4,549.9	22,181.2	12,754.1	1,186,749.2
Fiumefreddo di Sicilia	1,207.0	12.5	39.1	17.5	583.7	2,845.5	1,636.2	148,417.8
Giarre	2,711.0	21.0	65.5	29.4	1,290.6	6,291.8	3,617.8	326,925.9
Grammichele	3,083.0	106.4	330.9	148.6	482.7	2,353.1	1,353.0	140,301.1
Gravina di Catania	513.0	-	-	-	-	-	-	-
Licodia Eubea	11,174.0	227.3	706.9	317.5	97.2	473.9	272.5	65,935.7
Linguaglossa	5,982.0	115.6	359.6	161.5	3.1	15.4	8.8	21,954.1
Maletto	4,069.0	52.0	161.7	72.6	6.3	31.1	17.9	11,119.6

(continue)

Maniace	3,758.0	218.7	680.3	305.6	2.2	11.0	6.3	40,601.3
Mascali	3,751.0	30.5	94.8	42.6	1,407.0	6,859.2	3,944.0	357,785.6
Mascalucia	1,617.0	17.7	55.2	24.8	-	-	-	3,248.4
Mazzarrone	3,457.0	154.8	481.6	216.3	49.9	243.5	140.0	40,846.6
Militello in Val di Catania	6,207.0	245.8	764.5	343.4	840.1	4,095.6	2,355.0	255,290.2
Milo	1,655.0	4.4	13.7	6.1	42.1	205.6	118.2	11,367.3
Mineo	24,482.0	892.6	2,776.0	1,247.0	3,676.3	17,922.1	10,305.2	1,083,615.0
Mirabella Imbaccari	1,521.0	119.7	372.5	167.3	-	-	-	21,920.7
Misterbianco	3,742.0	101.2	314.9	141.4	1,514.1	7,381.3	4,244.2	397,546.3
Motta Sant'anastasia	3,547.0	204.4	635.7	285.5	1,149.83	5,605.4	3,223.1	325,234.9
Nicolosi	4,236.0	14.4	44.7	20.1	-	-	-	2,635.3
Palagonia	5,742.0	121.3	377.4	169.5	3,838.3	18,711.8	10,759.3	983,018.9
Paterno'	14,374.0	620.1	1,928.5	866.2	3,402.7	16,588.6	9,538.4	965,266.8
Pedara	1,910.0	3.2	10.0	4.5	-	-	-	589.2
Piedimonte Etneo	2,635.0	90.7	282.3	126.8	211.8	1,032.5	593.7	69,631.1
Raddusa	2,325.0	44.6	138.7	62.3	3.9	19.4	11.1	9,162.7
Ragalna	3,928.0	145.9	453.8	203.8	-	-	-	26,706.4
Ramacca	30,453.0	692.8	2,154.7	967.9	8,282.7	40,378.2	23,217.5	2,200,118.3
Randazzo	20,426.0	329.5	1,024.9	460.4	-	-	-	60,314.1
Riposto	1,309.0	5.1	16.0	7.1	556.5	2,713.1	1,560.0	140,257.5
San Cono	659.0	16.7	52.1	23.4	-	-	-	3,069.0
San Giovanni la Punta	1,077.0	16.1	50.1	22.5	3.0	14.8	8.5	3,712.9
San Gregorio di Catania	561.0	3.2	10.2	4.6	31.7	154.9	89.0	8,557.2
San Michele di Ganzaria	2,567.0	164.8	512.6	230.3	8.7	42.4	24.3	32,346.7
San Pietro Clarenza	623.0	20.8	64.8	29.1	-	-	-	3,817.5
Santa Maria di Licodia	2,608.0	383.5	1,192.9	535.8	-	-	-	70,196.6

(continue)

(…)

Santa Venerina	1,889.0	44.8	139.4	62.6	119.5	582.9	335.2	38,137.4
Sant'agata Li Battiati	309.0	2.0	6.2	2.7	13.9	68.1	39.1	3,862.9
Sant'alfio	2,567.0	14.6	45.4	20.4	284.0	1,384.8	796.3	73,784.3
Scordia	2,415.0	99.0	307.9	138.3	771.8	3,762.8	2,163.6	211,332.7
Trecastagni	1,902.0	8.7	27.1	12.2	-	-	-	1,597.6
Tremestieri Etneo	647.0	3.6	11.2	5.0	-	-	-	660.6
Valverde	548.0	3.6	11.3	5.0	-	-	-	666.1
Viagrande	1,002.0	18.4	57.3	25.7	-	-	-	3,376.5
Vizzini	12,594.0	289.4	900.1	404.3	23.4	114.2	65.7	58,837.4
Zafferana Etnea	7,631.0	43.2	134.4	60.4	2.7	13.4	7.7	8,601.6
Total	**355,078.0**	**10,642.9**	**33,099.7**	**14,868.3**	**38,822.6**	**189,260.5**	**108,824.8**	**11,665,815.2**
Minimum	171.0	-	-	-	-	-	-	-
Maximum	38,114.0	1,393.3	4,333.2	1,946.5	8,282.7	40,378.2	23,217.5	2,200,118.3
Mean	6,122.03	183.5	570.6	256.3	669.3	3,263.1	1,876.2	201,134.7
Standard deviation	8,044.39	272.7	848.3	381.0	1,517.7	7,399.1	4,254.5	406,293.7

(*) Source: Censimento Istat 2010.

(**) Source: Istat 2008.

(***) Source: RTM 2008.

In the municipalities having S_{mun} between 2,414.9 ha and 6,981.2 ha, with an average value of S_{mun} of about 3,904 ha, the citrus growing areas increased. In fact, the density of the olive growing areas remains unchanged, equal to the 3% of the whole surface and equivalent to 128.98 ha, whereas the surface area of the citrus growing areas reached the 19% of the entire surface, which was equal to 729.33 ha on average.

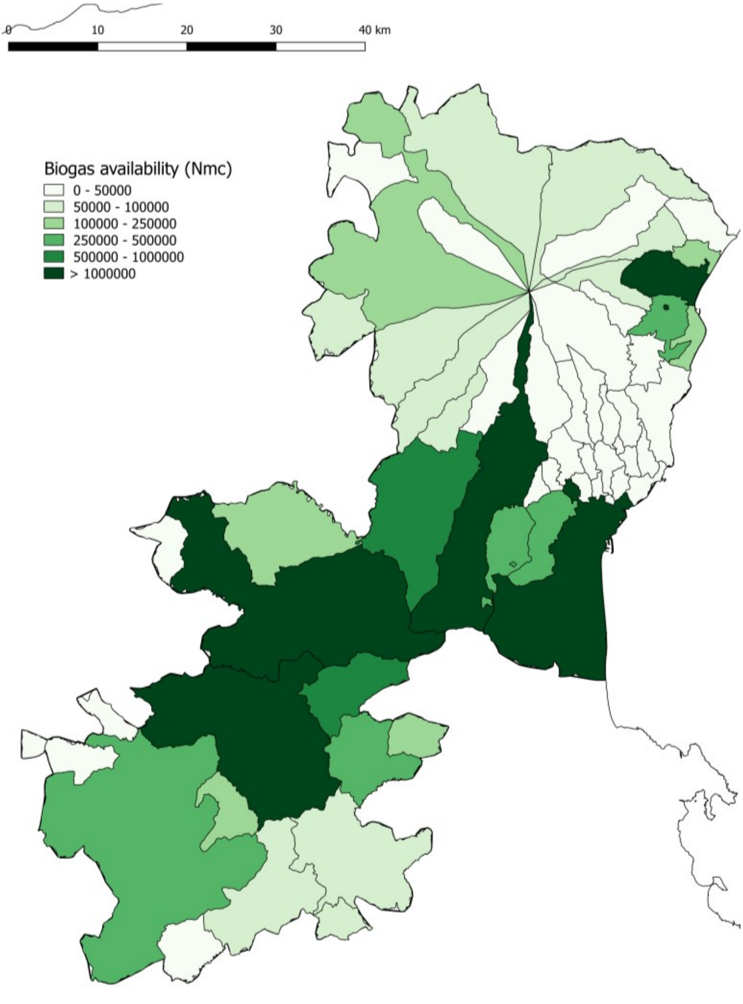


Figure 23. Estimation of Biogas availability at municipal level.

The third class of municipalities, having an average value of S_{mun} equal to about 10,872 ha, shows an overall density of the citrus and olive growing areas equal to 8% of the whole surface. Compared to the second class, a reduction in the density of the citrus growing areas was encountered, which were equal to the 5% of the whole surface that corresponds to 571.60 ha. With regard to the percentage of the olive growing areas, they kept unchanged to 3%, which is equivalent to 332.04 ha.

The analysis of the fourth class of municipalities, having an average value of S_{mun} of about 20,900 ha, revealed an increase in the percentage of the density of the citrus growing areas compared to the third class, whereas the distribution of the olive growing areas remained unchanged. In fact, 606.28 ha are cultivated with olive groves (3% of S_{mun}) and 2,504.29 ha are citrus growing areas (12% of S_{mun}).

In the class of municipalities with S_{mun} higher than 24,912.4 ha, which has an average value of S_{mun} of about 34,283 ha, a slight increase of the citrus growing areas to 13% of S_{mun}, which corresponds to about 4,465 ha, was found whereas the percentage of the olive growing areas kept unchanged to 3%, which corresponds to about 1,043 ha.

These data analyses showed that, for all the considered classes, the density variation in percentage of the citrus growing areas ranged between 5% (first and third classes) and 19% (second class) while the olive growing areas always occupied a surface area equal to about 3% of S_{mun}.

Since the olive growing areas are equally distributed in percentage in all the classes, these results induce to affirm that the potential biogas production could be mainly affected by the density of the citrus growing areas, which showed to have densities higher than that of the whole province (about 10%) in the second class (about 19%), fourth class (about 12%), and fifth class (about 13%). Also, the highest values of B_{tot} mean (Table 15), which were found for the same classes above mentioned, drive to the same conclusion.

Table 15. Classification of municipalities based on municipality surface area.

Class	S_{mun} [ha]	S_{mun}_mean [ha]	$B_{tot\_i}\_mean$ [Nm^3]
1st	<2,414.9	1,158.8	20,261.7
2nd	2,414.9-6,981.2	3,904.3	206,169.9
3rd	6,981.2-14,374.0	10,872.36	203,848.5
4th	14,374.0-24,912.4	20,900.70	737,824.6
5th	>24,912.4	34,283.19	1,308,787.4

In the GIS model, the polygons of the 21 municipalities belonging to these three selected classes (Acireale, Biancavilla, Grammichele, Linguaglossa, Maletto, Mascali, Militello in Val di Catania, Misterbianco, Motta Sant’Anastasia, Nicolosi, Palagonia, Mazzarrone, Maniace e Ragalna, Randazzo, Belpasso, Bronte, Mineo, Catania, Ramacca, Caltagirone) were overlaid with the current location of the citrus processing industries. Figure 24 shows the outcomes of this analysis.

The geographical areas of the five municipalities (Acireale, Calatabiano, Caltagirone, Mascali, and Scordia) obtained by the GIS analysis could be considered the most suitable location for planning the sustainable development of new biogas plants with regard to the minimisation of transportation costs for feedstock supply and logistics, in terms of economic, social and environmental impacts.

Table 16. S_{olive_i} *and* S_{citrus_i} distribution for each municipalities group.

S_{olive_i} *

	Classes				
	1st [ha]	2nd [ha]	3rd [ha]	4th [ha]	5th [ha]
Minimum	0.00	5.95	43.24	261.19	692.84
Maximum	164.85	383.57	620.10	892.62	1,393.33
Mean	26.28	128.98	332.04	606.28	1,043.09
Standard deviation	39.70	104.42	189.08	299.30	495.32

S_{citrus_i} *

	Classes				
	1st [ha]	2nd [ha]	3rd [ha]	4th [ha]	5th [ha]
Minimum	0.00	0.00	0.00	0.00	649.03
Maximum	583.71	4,107.02	3,402.79	4,549.99	8,282.72
Mean	61.73	729.33	571.60	2,504.29	4,465.88
Standard deviation	160.21	1,211.92	1,260.13	2,278.12	5,397.83

(*) Source: Censimento Istat 2010.

Information on other biomasses required for the anaerobic digestion within each municipality of the considered classes could be useful for a more precise localisation of new biogas plants based on their potential availability (see section 2.6.1).

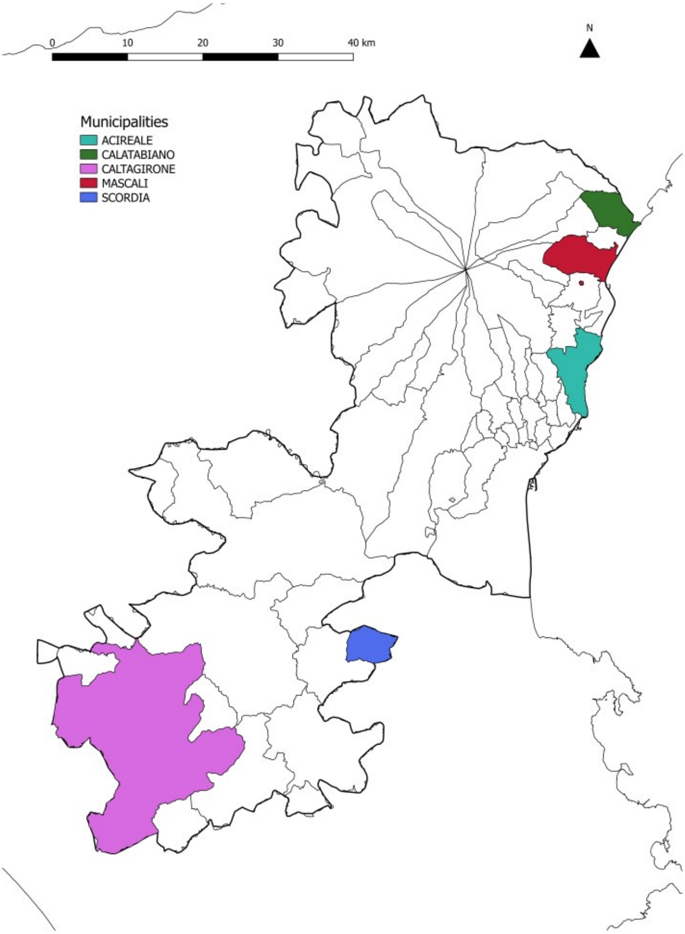


Figure 24. Suitable areas to locate new biogas plants in the province of Catania.

3.4 Quantification of other feedstocks for biogas production

The six most abundant biomass materials in Catania: citrus pulp, olive pomace, whey, poultry litter, cattle manure, and corn silage were used as the feedstocks for biogas production. For each feedstock, farms or processing facilities were located, and the biomass quantity at that entity level was estimated. There are a total of four-hundred farm and food processing operations in Catania with evenly-distributed farms producing cattle and crops, plus major poultry operations in eastern Catania, and intensive citrus-processing operations in four locations across the province (Figure 25). These farm and food processing operations generate 209,200 tons per year of biomass in Catania for potential biogas production, including 62,000 tons of citrus pulp (17% TS) from six citrus processing facilities, 23,300 tons of olive pomace (45% TS) from seventy-nine olive processing facilities, 90,500 tons of cattle manure (12% TS) from two-hundred-thirteen cattle farms, 6,803 tons of poultry manure (32% TS) from twenty-one chicken farms, 5,180 tons of whey (6% TS) from twenty-six dairy processing facility, and 21,372 tons of silage (35% TS) from fifty-five crop farms.

The quantity of biomass feedstocks is summarized in Table 17. Detailed biomass production for individual farms and food processing facilities are presented in Table S1.

Among the six feedstocks, cattle manure represents the highest total overall biomass production while citrus pulp has the highest average biomass production per facility of over 10,300 tons/facility/year. Cattle manure and citrus pulp count for 73% of the total available biomass in Catania. The coefficients of relative variations (CRV) of different feedstock also indicate that citrus pulp production had the largest variation (49% of CRV) between different processing facilities, and olive pomace had the smallest variation (3% of CRV). Four citrus processing facilities have a biomass productivity over 5,000 ton/facility/year (Table S1), which is much larger than other operations (the next largest farm operation is cattle farms with an average biomass production of almost 2,960 ton/farm/year). The citrus pulp and cattle manure provide a good feedstock foundation on which to build these regional biogas plants. Therefore, considering the total biomass production, facility number, and CRV, citrus pulp was selected as the main biomass material to determine the location of regional biogas plants.

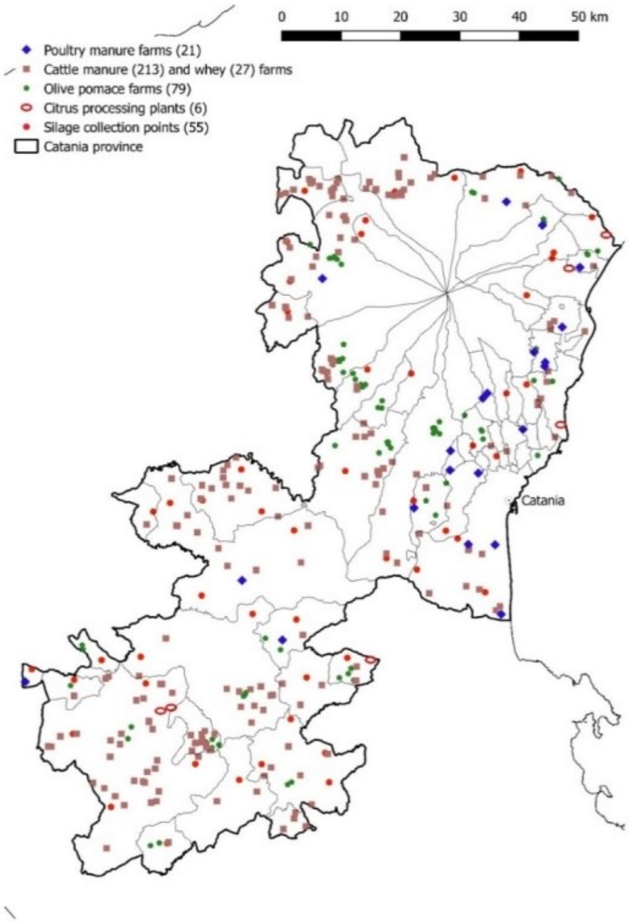


Figure 25. Locations of farms and crop processing facilities in Catania, Italy* : There are 400 farms and food processing facilities in Catania, including poultry, cattle, and crop farms as well as dairy, olive, and citrus processing facilities.

Table 17. Available biomass feedstocks in Catania, Italy.

Feedstock	Numbers of farms or facilities	Total biomass production (Ton/year)	Average biomass production per facility (Ton/facility/year)	Smallest biomass production per farm or facility (Ton/facility/year)	Largest biomass production per farm or facility (Ton/facility/year)	Standard deviation of biomass production per farm or facility	CRV % *	Data source
Citrus pulp	6	62032.7	10338.8	240.0	30000.0	11222.2	48.5	Survey
Olive pomace	79	23295.1	294.9	90.0	650.0	80.9	3.1	Survey
Cattle manure	213	90498.0	424.9	49.8	2963.1	469.8	7.6	Literature
Whey	26	5179.6	199.2	34.6	502.4	131.4	13.2	Literature
Poultry manure	21	6803.1	324.0	0.4	1751.6	491.7	33.9	Literature
Silage	55	21371.9	388.6	0.7	738.8	284.1	10.0	Calculation

*: The Coefficient of Relative Variation (CRV) is the ratio of the standard deviation of biomass production per facility to the average biomass production per facility, and expressed as a percentage.

3.5 Characterization of feedstocks

Each feedstock was characterized, by adopting the methodologies as described in Section 2.4. Each analysis was duplicates and the results were listed in Table 18.

Table 18. Characteristics of seed and individual feedstocks.

	Seed (Liquid filtrate)	Cattle manure (CM)	Poultry litter (PL)	Whey (WH)	Corn silage (CS)	Citrus pulp (CP)	Olive pomace (OP, Phase 2)	Olive pomace (OP, Phase 3)
DM (%) ^{a}	3.40 ± 0.02	12.31 ± 0.15	32.36 ± 4.00	5.89 ± 0.04	35.24 ± 0.55	17.41 ±0.74	32.95 ± 0.14	51.53 ± 0.91
VS (%) ^{a}	2.26 ± 0.01	10.72 ± 0.16	19.66 ± 2.19	5.26 ± 0.04	33.84 ± 0.50	16.72 ± 0.71	28.64 ± 0.20	48.89 ± 0.75
TN (%, DM) ^{b}	4.35 ± 0.06	3.32 ± 0.01	5.11 ± 0.08	-	1.20 ± 0.01	1.58 ± 0.04	1.74 ± 0.04	1.76 ± 0.02
TP (g/kg wet) ^{b}	0.14 ± 0.00	2.32 ± 0.11	92.75 ± 4.55	7.05 ± 0.17	-	-	0.83 ± 0.08	3.96 ± 0.14
C (%, DM) ^{b}	44.56 ± 0.09	40.41 ± 0.02	28.24 ± 0.09	-	43.89 ± 0.08	49.51 ± 0.04	48.21 ± 0.08	53.59 ± 0.10
Lipid (% DM)	-	-	-	-	-	-	1.94 ± 0.07	6.82 ± 1.65
C/N ratio ^{b}	10.24 ± 0.12	12.17 ± 0.03	5.53 ± 0.10	24.10	36.58 ± 0.24	31.35± 0.82	27.72 ± 0.59	30.53 ± 0.21

a Data are the average of three replicates with standard errors.

b Data are the average of two replicates with standard errors.

c. "-" means not detectable.

3.6 Maximizing biogas production by BMP and semi-continuous anaerobic digestion

3.6.1 Biochemical Methane Potential of mixed feedstocks

The BMP test indicates that all six FMs were the suitable feedstock to generate biogas (Figure 26 and Figure 27).

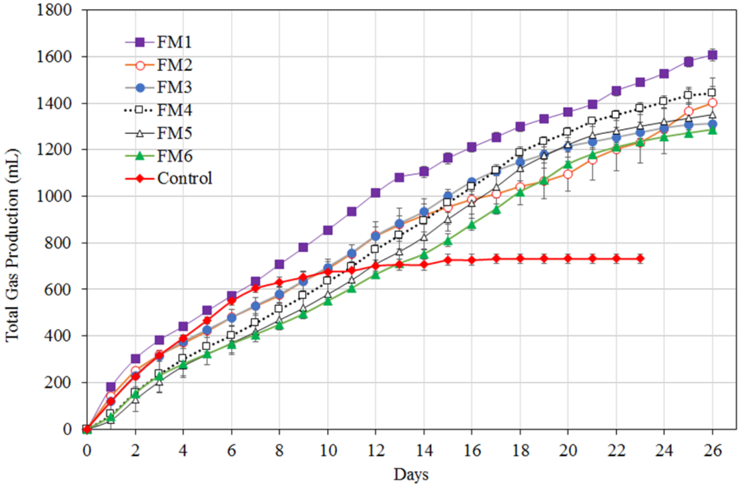


Figure 26. Accumulated biogas of the BMP test [a]

[a] Data are the average of two replicates with standard error.

The C:N ratios of FMs were between 17 to 20 (Table 8), which were all in the preferred C:N ratios for AD (Sievers et al., 1978; Khalid et al., 2011; Speece 1996). The pH of all testing reactors were stabilized at approximately 8 at the end of the testing (Table 19). The BMPs of FM1, FM2, FM3, FM4, FM5, and FM6 were 1,118, 904, 932, 1,085, 893, and

920 mL methane/g VS loading, respectively, which all demonstrated a good potential for methane production. Among the six FMs, the FM1 with 44% (w/w) CP and the FM4 with 18% (w/w) CP and 27% (w/w) OP had slightly higher BMP than other four FMs.

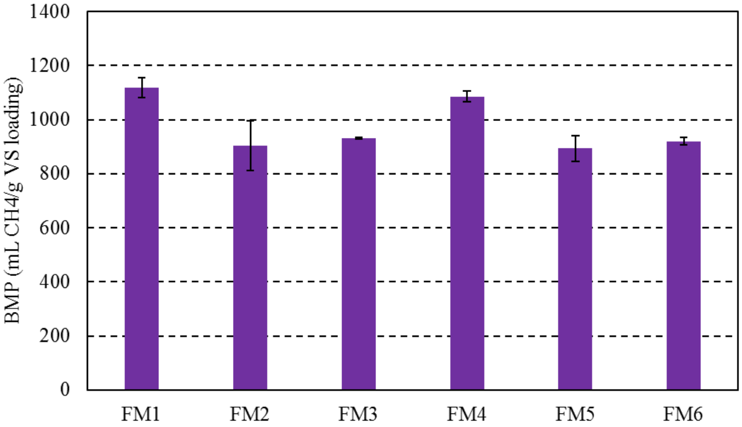


Figure 27. BMP of different FMs*
*: The data are the average of two replicates.

However, Tukey pairwise comparison concluded that there were no significantly (P>0.05) differences on BMP among six FMs. The data also demonstrate that all 6 FMs had the VS reduction at approximately 60% without significant difference between each other (P>0.05), and were much higher than the control (25%) (Figure 28). The BMP and VS reduction data indicate that all six FMs have similar methane production potential, which means these ratios are suitable to be used to prepare the feed for biogas plants.

Table 19. Changes of TS, VS, and pH in the reactors before and after the BMP test.

Parameter	FM1	FM2	FM3	FM4	FM5	FM6	Control (Seed)
			Before the BMP test				
DM (%) [a]	2.63 ± 0.01	2.65 ± 0.02	2.59 ± 0.02	2.71 ± 0.09	2.90 ± 0.02	2.47 ± 0.06	2.44 ± 0.03
VS (%) [a]	1.92 ± 0.01	1.96 ± 0.01	1.91 ± 0.02	1.99 ± 0.06	2.15 ± 0.02	1.81 ± 0.06	1.57 ± 0.02
pH	6.95	6.98	7.14	7.23	7.34	7.52	7.26
			After the BMP test				
DM (%) [b]	1.37 ± 0.21	1.33 ± 0.02	1.23 ± 0.02	1.29 ± 0.02	1.38 ± 0.03	1.26 ± 0.05	1.97 ± 0.02
VS (%) [b]	0.80 ± 0.16	0.76 ± 0.01	0.69 ± 0.00	0.74 ± 0.02	0.81 ± 0.03	0.81 ± 0.03	1.17 ± 0.01
pH [b]	8.02 ± 0.01	8.10 ± 0.02	8.02 ± 0.01	8.10 ± 0.07	8.06 ± 0.01	8.07 ± 0.01	8.25 ± 0.01

a Data are the average of three replicates with standard errors.

b Data are the average of two replicates with standard errors.

Different from BMP and VS reduction, methane contents were significantly ($P<0.05$) different from each other among six FMs (Table 20). With increase of OP content in the FMs, the methane content gradually increased from 73% (v/v) of FM1 to 76% (v/v) of FM6 ($p<0.05$).

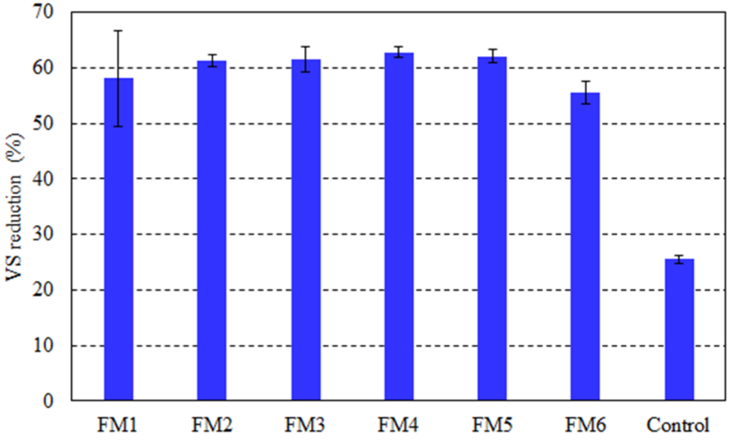


Figure 28. VS reduction during the BMP test [a]

[a] Data are the average of two replicates.

Lipid contents in OP (1.94% lipids in OP2 and 6.82% lipids in OP3) may play a role influencing changes of the methane content.

It is well known that under anaerobic conditions, lipids are first hydrolyzed to glycerol and free long chain fatty acids (LCFAs) by acidogenic bacteria; the glycerol is then converted to acetate by acidogens, and the LCFAs are degraded to acetate and hydrogen through the beta-oxidation pathway (syntrophic acetogenesis) (Long et al., 2012; Weng and Jeris, 1976).

Table 20. Biogas composition of different FMs from the BMP test.

	Methane (% v/v)	Carbon dioxide (% v/v)	Hydrogen sulfide (ppm)
Control	75.51 ± 0.18	24.50 ± 0.18	458.42 ± 86.58
FM1	73.15 ± 0.08	27.14 ± 0.08	385.50 ± 65.57
FM2	72.86 ± 0.19	25.78 ± 0.19	391.93 ± 71.92
FM3	74.22 ± 0.12	25.78 ± 0.12	224.43 ± 60.68
FM4	75.12 ± 0.06	24.88 ± 0.06	352.12 ± 6.07
FM5	76.16 ± 0.06	23.84 ± 0.06	302.40
FM6	76.07 ± 0.07	23.93 ± 0.07	211.28

a Data are the average of two replicates with standard error.

Both glycerol and LCFA degradations proceed rapidly in AD, resulting in relatively high acetate and hydrogen contents (Angelidaki and Ahering, 1992). Methanogens then turn acetate into methane by both splitting acetates into methane and carbon dioxide (hydrogenotrophic methanogens) and converting carbon dioxide and hydrogen to methane (hydrogenatrophic methanogens). With increase of acetate and hydrogen contents in the reactors from the FMs with high OP, hydrogenatrophic methanogens may out-compete hydrogenotrophic methanogens, and lead to higher percentage of methane in the biogas. To explicitly explain the relationship among feedstocks and hydrogenatrophic and hydrgenotrophic methanogens, an in-depth study on dynamic changes of microbial communities during anaerobic digestion of multiple feedstocks is needed.

3.6.2 Selected FMs for semi-continuous anaerobic digestion

The BMP test concluded that all six FMs are suitable as feedstocks for biogas plants. Considering the feedstock availability of citrus pulp and olive pomace in Sicily, Italy (Valenti et al., 2017c, 2017d), FM1, FM2, and FM3 were selected to run the semi-continuous anaerobic digestion to evaluate the performance of the digestion of multiple feedstock.

The characteristics of FM1, FM2, and FM3 for the semi-continuous digestion were listed in Table 21.

Table 21. Characteristics of the selected FMs for semi-continuous anaerobic digestion. [a, b]

	FM1	FM2	FM3
DM (%) [c]	4.97 ± 0.00	4.88 ± 0.00	5.15 ± 0.00
VS (%) [c]	4.01 ± 0.00	3.92 ± 0.00	4.09 ± 0.00
COD (g/L) [c]	44.06 ± 0.89	44.57 ± 0.38	49.36 ± 2.87
TN (g/L) [c]	4.36 ± 0.06	4.32 ± 0.01	4.49 ± 0.22
C:N ratio [c]	18.60 ± 0.00	19.60 ± 0.02	20.40 ± 0.04
pH	7.28	7.29	7.3

[a] The selection is based on the amount of the available feedstock in Sicily.

[b] The mixing ratios of the FMs are the same with those prepared in the BMP test.

[c] Data are the average of two replicates with standard errors.

C:N ratios of three mixtures without adding the seed were 19, 20, and 20, which were in the preferred C:N ratio range of AD. Figure 29 presents the accumulated biogas production of three FMs. Each FM shows a lag phase of biogas production, where the microbial communities adjusted to the new environmental conditions. During the lag phase, pH of individual digestions were continuously dropping, and NaOH had to be added to bring pH back to the desired digestion pH of approximately 6.8. After the lag phase, all digestions were under the stabilized culture and no pH adjustment was needed. The lag phases of FM2 and FM3 were similar, which were around 25 days (one HRT). The digestion performance of FM1 was significantly ($P<0.05$) different from FM2 and FM3. A lag phase of 65 days (2.6 HRTs) was taken to reach the stabilized culture. In order to compare the digestion performance between three FMs, three stages were defined to describe the entire digestion (Figure 29).

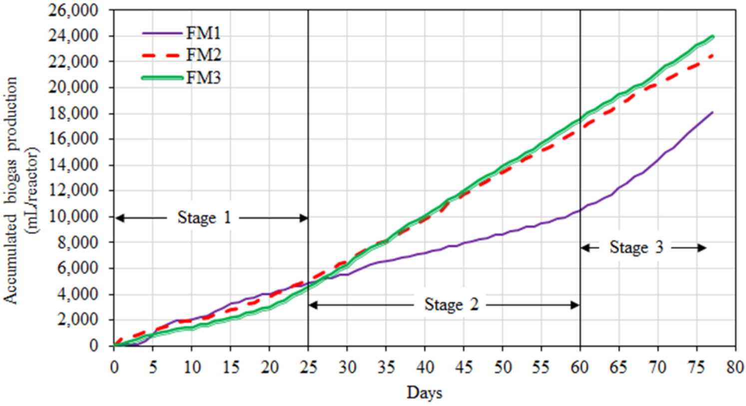


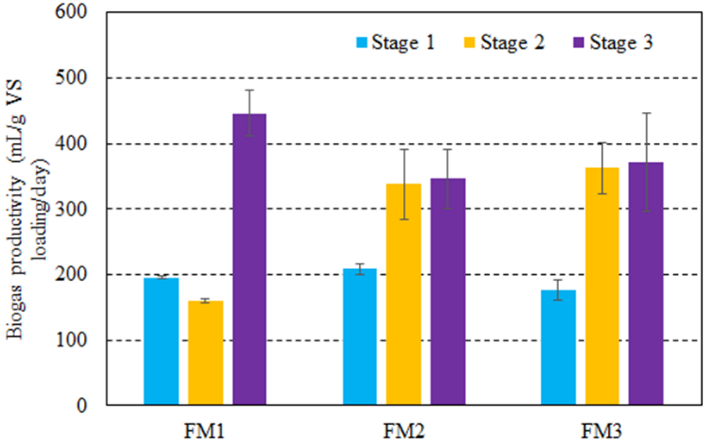
Figure 29. Accumulated biogas production of the selected FMs from the semi-continuous anaerobic digestion.

Stage 1 was based on the lag phase of FM2 and FM3. Stage 2 was based on the lag phase of FM1. In Stage 1, all three cultures were not stabilized. FM1 and FM2 had slightly higher biogas productivities of 195 and 209 mL/g VS loading/day, respectively, than 177 mL/g VS loading/day from FM3 (Figure 30(1)). While, methane contents of FM2 and M3 were 57% and 61%, much higher than 40% of FM1 (Figure 30(2)). Once FM2 and FM3 transferred into the stabilized culture condition in Stage 2, the biogas productivities of them improved and reached 338 and 362 mL/g VS loading/day with no significant ($P>0.05$) difference each other, and maintained the similar biogas productivities for the rest of the digestion period (Figure 30(1)). FM1 in Stage 2 is still in the lag phase and with a low biogas productivity of 160 mL methane/g VS loading/day (Figure 30(1)). After 60 days of the lag phase, FM1 finally reached the stabilized culture condition in Stage 3.

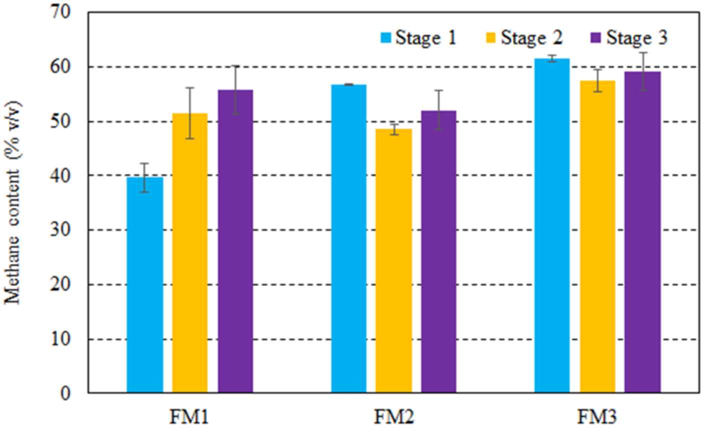
The biogas productivity dramatically increased to 446 mL/g VS loading/day with a methane content of 56% (Figure 30), which was much higher than the biogas productivities of FM2 and FM3 (346 and 371 mL/g VS loading/day, respectively).

Under the stabilized culture condition, FM1 with the highest CP content demonstrated much better performance on biogas production that FM2 and FM3.

The semi-continuous culture concluded that even though the highest biogas productivity was achieved by FM1, the digestion of FM1 requires the stabilization time 2.6 times longer than other FMs with lower CP contents (Table 22). A long start-up stage needs to be considered once running the large-scale, continuous digestion on such combination of multiple feedstocks. Meanwhile, methane composition data for the semi-continuous digestion generally followed the trend found in the BMP test, methane contents in the feed with higher OP contents are slightly but significantly ($P<0.05$) higher than the feed only with CP (Figure 30(2)) (Figure 31).



(1)



(2)

Figure 30. Changes of biogas productivity and methane content during the semi-continuous anaerobic digestion. (1) Biogas productivity and (2) Methane content.

Table 22. Average biogas and methane productivities of semi-continuous anaerobic digestion in Stage 3 regarding the TS loading.

	FM1	FM2	FM3
Biogas productivity (P, L/kg dry FM loading/day)	361.59	277.12	293.37
Methane productivity (L methane/kg dry FM loading/day)	188.03	135.79	167.22

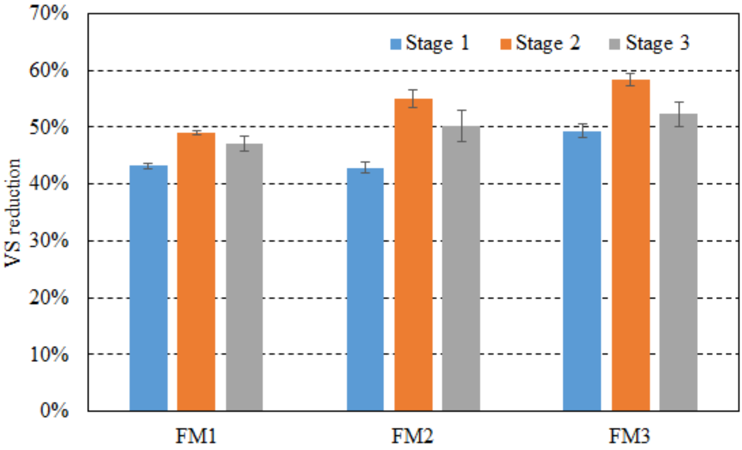


Figure 31. VS reduction during the semi-continuous anaerobic digestion.

[a] Data are the average of two replicates with standard errors.

3.6.3 Mass and energy balance

The mass and energy balance was conducted to compare the digestion performance with different FMs (Table 23). Methane production of FM1, FM2, and FM3 under the stabilized cultivation condition (Stage 3) were 146, 107, and 135 g/kg dry feed, respectively. FM1 had higher methane production than FM2 and FM3. Based on the amount of methane generated and local environmental conditions, the energy balance analysis concluded that with implementation of a CHP unit, net electricity outputs of FM1, FM2, and FM3 were 0.61, 0.45, and 0.56 kWh-e/kg dry feed, respectively, and corresponding net heat outputs were 0.94, 0.69, and 0.86 Kwh-e/kg dry feed. The energy generation efficiencies (net energy output/methane energy × 100) of the studied digestions were relatively high at 65%, 57%, and 65% for FM1, FM2, and FM3, respectively. Even though different mixing ratios led to different energy generation efficiencies, all tested FMs showed the efficiencies more than 55%. The mass and energy balance clearly demonstrates that anaerobic digestion can handle major agricultural residues and biomass available in Sicily to generate renewable energy.

Table 23. Mass and energy balance of anaerobic digestion of the selected FMs.

	FM1	FM2	FM3
Mass balance			
Methane production (M, g/kg dry FM loading) [a]	146.05	107.25	134.66
Energy balance [b]			
Heat input (W_{heat}, kWh-e/kg dry FM) [c]	-0.40	-0.29	-0.37
Electricity input ($W_{electricity}$, kWh-e/kg dry FM) [d]	-0.06	0.04	0.06
Energy output as heat (E_{heat}, kWh-e/kg dry FM) [e]	1.34	0.98	1.23
Energy output as electricity ($E_{electricity}$, kWh-e/kg dry FM) [f]	0.67	0.49	0.62
Net energy output			
Net heat output (kWh-e/kg dry FM) [g]	0.94	0.69	0.86
Net electricity output (kWh-e/kg dry FM) [h]	0.61	0.45	0.56

[a] Eq. 15 was used to calculate the methane production.
[b] Negative numbers mean energy inputs, and positive numbers mean energy outputs.
[c] Eq. 18 was used to calculate the heat input.
[d] Eq. 19 was used to calculate the electricity input.
[e] Eq. 16 was used to calculate the energy output as heat.
[f] Eq. 17 was used to calculate the energy output as electricity.
[g] The net heat output = E_{heat} - W_{heat}
[h] The net electricity output = $E_{electricity}$ - $W_{electricity}$

3.7 Development of biogas plants in Sicily

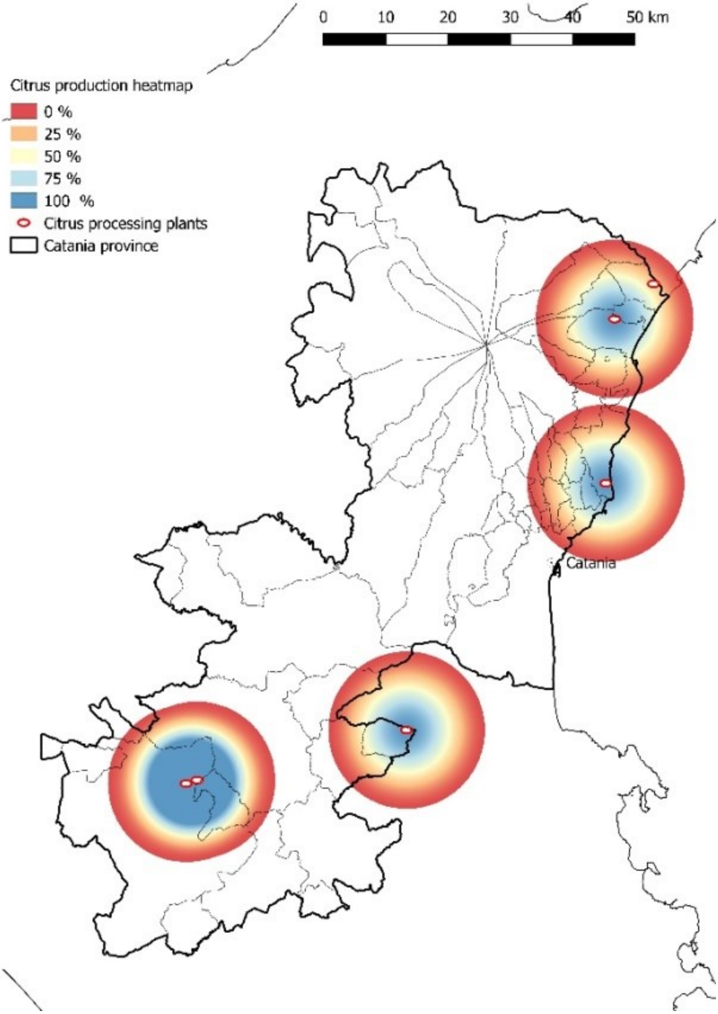
3.7.1 Selected sites for biogas plants

The heatmap based on citrus pulp production obtained from the surveys was used to facilitate locating the biogas plants (Valenti et al., 2016). The heatmap hilghited four central locations representing the most concentrated regional citrus production were identified (Figure 32a). All four locations are near citrus processing facilities in corresponding municipalities (Figure 32b). This result confirms the possible localisation of biogas plants in the geographical areas showed in Figure 24.

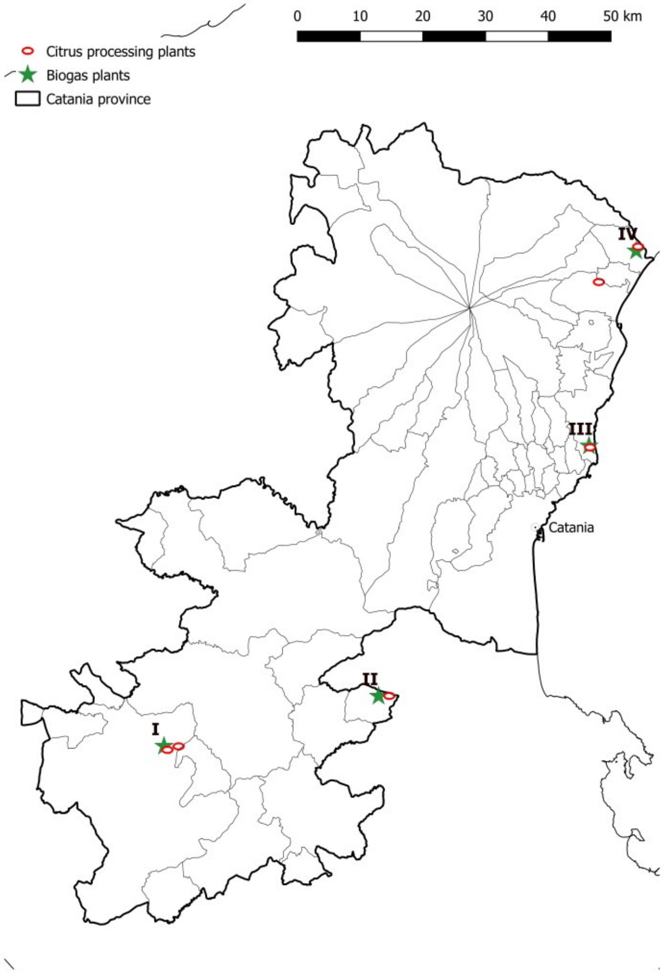
Two citrus processing facilities in the Caltagirone municipality are 3.00 and 1.31 km from the location of biogas plant I. Biogas plant II is 2.91 km from the citrus processing facility in Scordia municipality. The distance between biogas plant III and the citrus processing facility in Acireale municipality is 0.26 km. Two processing facilities in neighbouring municipalities of Calatabiano and Mascali are 1.22 and 7.83 km from biogas plant IV (in Calatabiano). Therefore, these four locations were determined as the sites for regional biogas plants that would treat all six feedstocks in corresponding regions. With these determined biogas plant locations, a buffer zone analysis was conducted to determine the boundaries of individual biogas plants (Figure 33).

Areas around individual biogas plants with a central zone of 10 km radius and the areas with seven incremental 5 km radii from 10 to 45 km were set to determine the biomass collection boundaries for individual plants.

For the farms and processing facilities in intersecting zones of adjacent biogas plants, the transportation distances to different biogas plants were calculated using the road graph plugin tool. The shortest transportation distance was the criterion used to determine which biogas plant receives feedstocks from the farms or processing facilities in the intersection zones (Table S1). After determining the boundaries of the collection areas, the number of farms and facilities and the quantity of feedstocks for individual biogas plants are estimated (Table 24).


0
10
20
30
40
50 km
Citrus production heatmap
0 %
25 %
50 %
75 %
100 %
Citrus processing plants
Catania province
Catania

(a)



(b)

Figure 32. Selected locations of biogas plants. (a) Covered area of the biogas plants based on citrus pulp production, (b) Location of biogas plants.

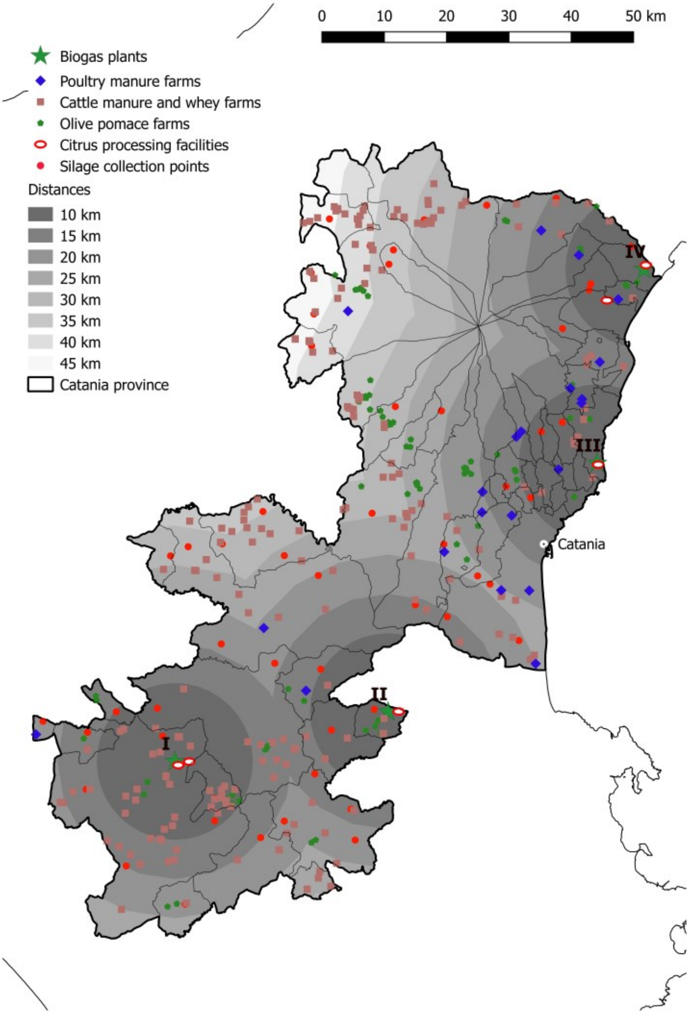


Figure 33. Distribution of farms and processing facilities in buffer zones of individual biogas plants.

Table 24. Farm and facility numbers and feedstock quantity for individual biogas plants.

Biogas plant	Location	Citrus pulp		Olive pomace		Cattle manure		Whey		Poultry manure		Silage		Total biomass amount (Ton/year)
		Number of facilities	Biomass amount (Ton/year)	Number of facilities	Biomass amount (Ton/year)	Number of farms	Biomass amount (Ton/year)	Number of facilities	Biomass amount (Ton/year)	Number of farms	Biomass amount (Ton/year)	Number of farms	Biomass amount (Ton/year)	
I	Caltagirone	2	37,425	14	4,129	73	22,181	11	2,009	1	6	16	6,901	72,650
II	Scordia	1	2,208	11	3,151	44	15,945	4	791	5	3,213	15	6,726	32,208
III	Acireale	1	5,360	42	12,763	45	17,507	6	1,028	10	3,335	10	1,861	46,718
IV	Mascali	2	17,040	14	3,844	51	34,866	5	1,351	5	250	14	5,884	59,212

Biogas plants I, II, III, and IV handle 72,700, 32,200, 46,700, and 59,200 tons/year of biomass, respectively. Among the four biogas plants, biogas plant I located in Caltagirone municipality is the largest, and the main feedstocks are citrus pulp (37,400 ton/year) and cattle manure (22,200 ton/year) that account for 82% of the total biomass that the plant receives. Biogas plant IV is the second largest plant where the main feedstocks are also cattle manure and citrus pulp, except that the plant receives more cattle manure (34,900 ton/year) than citrus pulp (17,000 ton/year). The other two plants have cattle manure as the largest feedstock (15,900 ton/year for biogas plant II and 17,500 ton/year for biogas plant III. Silage (6,730 ton/year) and olive pomace (12,800 ton/year) are the second largest feedstocks for the plants II and III, respectively.

Annual transportation mileages for individual biogas plants were calculated based on the shortest transportation distances from individual farms and processing facilities to biogas plants determined by the Road Graph plugin tool considering the turn restrictions for truck movement.

The resulting transportation routes for individual biomass feedstocks are presented in Figure 34. The annual number of truckloads required to deliver feedstocks to biogas plants I, II, III, and IV are 2,420, 1,070, 1,560, and 1,970, respectively, meaning that the corresponding daily truckloads are 10, 4, 6, and 8 (Assuming that biomass deliveries take place five days a week and fifty weeks per year). The annual round-trip transportation mileages considering both biomass delivery and liquid digestate removal for plants I-IV are 51,300, 45,200, 71,600, and 127,700 km (Table 25). Among these four plants, plant IV has the longest round-trip transportation mileage due to the fact that Mount Etna is located in the region, significantly increasing average transportation distances. The transportation mileages were used to calculate the transportation costs in the following techno-economic analysis.

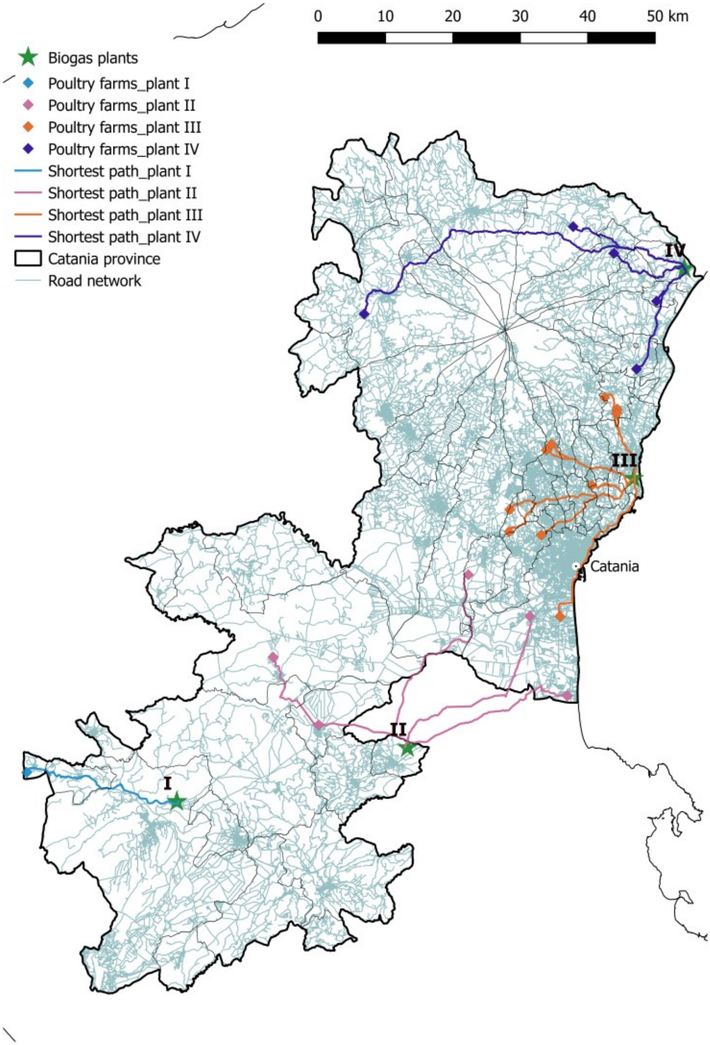


Figure 34 (a) Poultry farms shortest paths.

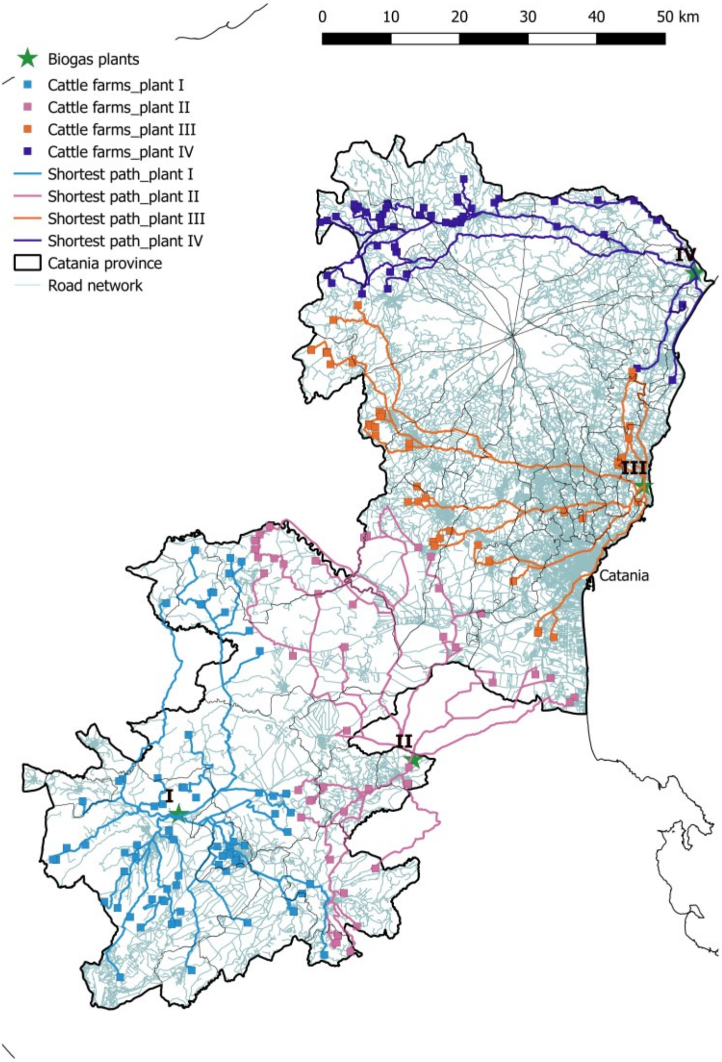


Figure 34. (b) Cattle farms shortest paths.

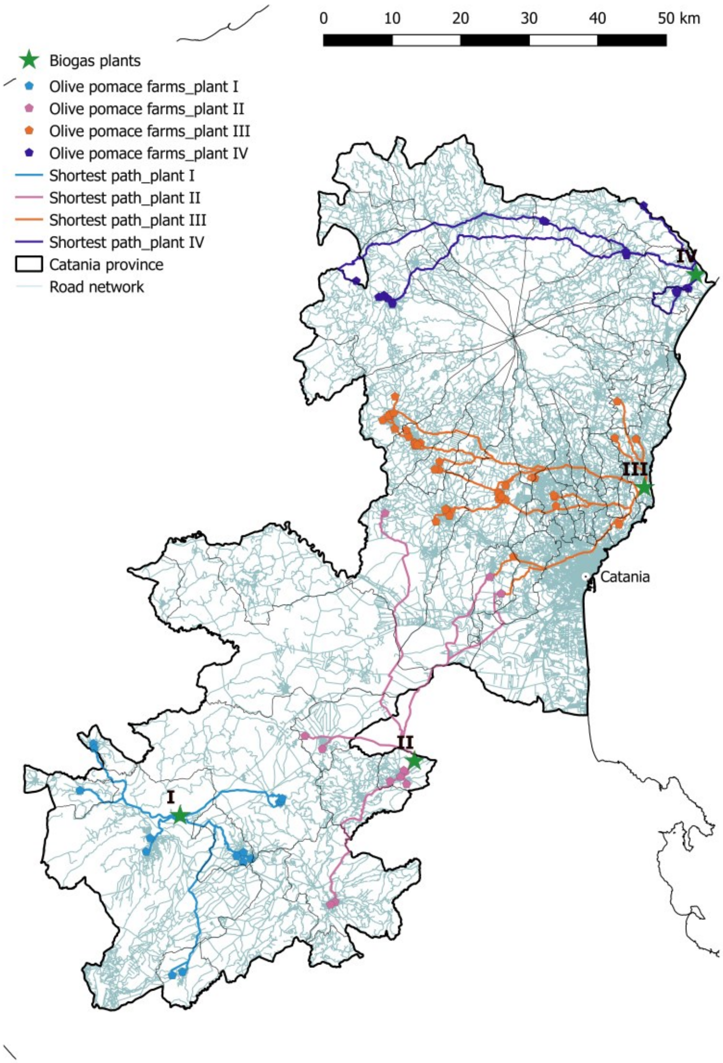


Figure 34. (c) Olive farms shortest paths.

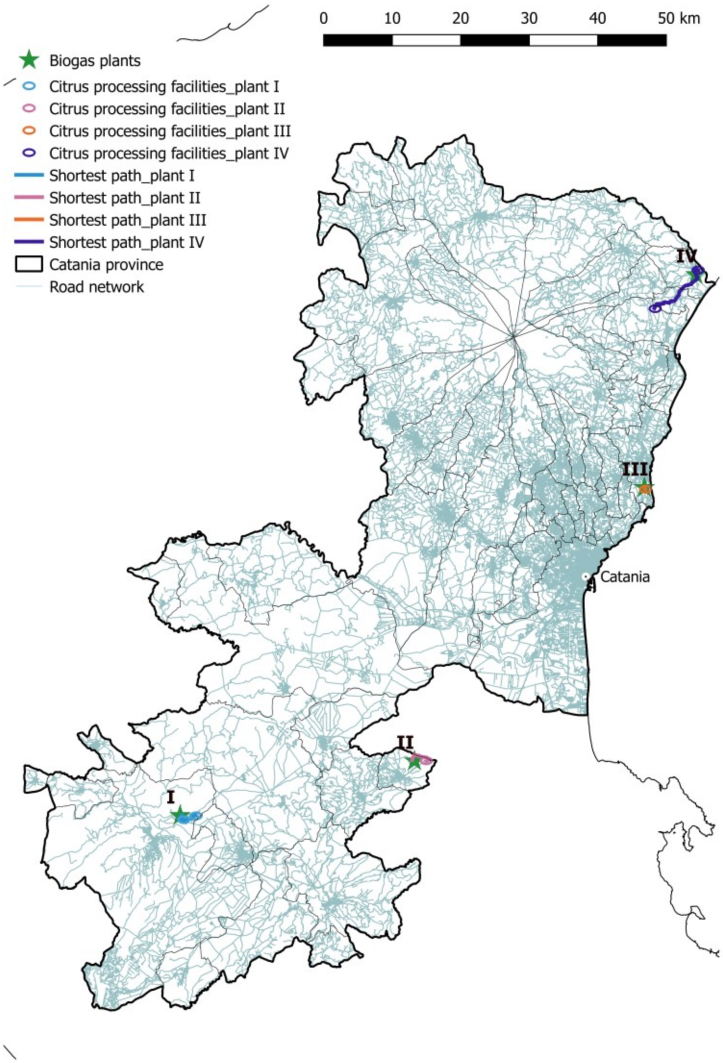


Figure 34.(d) Citrus farms shortest paths.

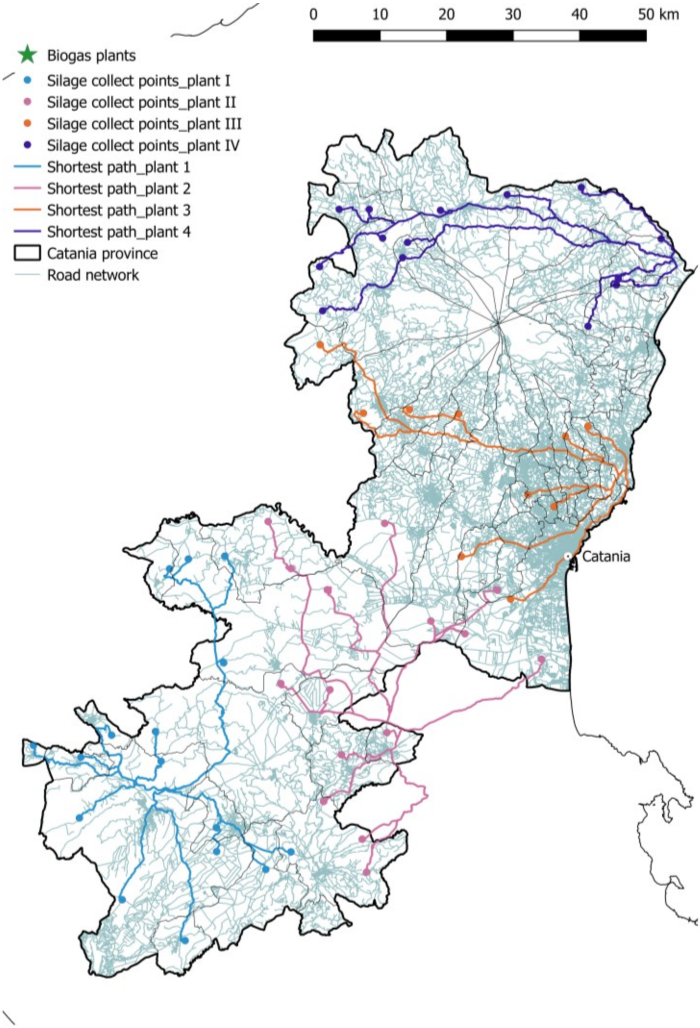


Figure 34.(e) Silage collection points shortest paths

Figure 34. Transportation distances of different feedstocks to regional plants.

Table 25. Annual transportation mileage for individual biogas plants.

Biogas plant	Annual truckload number (one-way) [a]	Annual round-trip transportation mileage (km)
I	2,422	51,290
II	1,074	45,158
III	1,557	71,557
IV	1,974	127,697

a. Truckload numbers are the number of trucks required to deliver all six feedstocks to the assigned biogas plants. The full load of a truck is 30 ton.

b. The round-trip transportation mileage is the sum of mileages to deliver all six feedstock to the biogas plants and transfer the effluent from the biogas plants back to farms as fertilizer.

3.7.2 Technical and economic feasibility

3.7.2.1 Mass and energy balance

The amount of biogas and effluent digestate generated from these biogas plants was calculated from the quantity and VS content of the six feedstocks (Table 26). The total VS in the feedstock are 13,000, 6,420, 9,550, and 10,460 ton/year for biogas plants I, II, III, and IV, respectively. With an average biogas productivity of 0.89 m^3/kg VS reduced and an average VS reduction of 50%, plants I, II, III, and IV generate 5,778,000, 2,858,000, 4,249,000, and 4,657,000 m^3/year biogas, respectively. After the liquid/solid separation of the digestion effluent, the corresponding liquid digestate amounts with 4% TS are 119,000, 62,400, 92,300, and 97,500 ton/year. The corresponding solid digestate amounts with 25% TS are 8,700, 5,700, 8,300, and 7,600 ton/year.

Based on the quantity of biogas produced and methane content, the sizes of individual biogas plants and the corresponding amounts of electricity and heat generated were then estimated (Table 27). Three biogas plants (I, III, and IV) have electrical capacities of approximately 1 MW-e. Plant I has an electricity-production capacity of 1.2 MW-e and is the largest biogas power plant in Catania. It generates 7 GWh-e electricity and 12 GWh-e heat annually. Plant IV is the second largest biogas power plant with a capacity of 1 MW-e, followed by plants III and IV with electricity-production capacities of 0.9 and 0.6 MW-e, respectively.

According to the mass and energy balance analysis, a biogas production system with four regional biogas plants can fully utilize six major biomass feedstocks (a total of 210,000 ton/year) from agricultural and food processing operations in Catania in order to generate 17,542,000 m^3/year biogas. With a total electrical production capacity of 3.8 MW-e, the four regional biogas plants can then convert the biogas into 23.9 GWh-e electricity and 36.8 GWh-e heat per year. The biogas electricity can satisfy 29% of the electricity demand of the agricultural sector in Catania (84.1 GWh-e/year) (Terna, 2016). In addition, the liquid and solid digestates are considered as useful by-products by Italian Norm D.M. 5046/2016 and can be used as fertilizer and soil amendments by local farms.

3.7.2.2 Economic analysis

Economic viability is obviously critical to a regional biogas power generation system in Sicily.

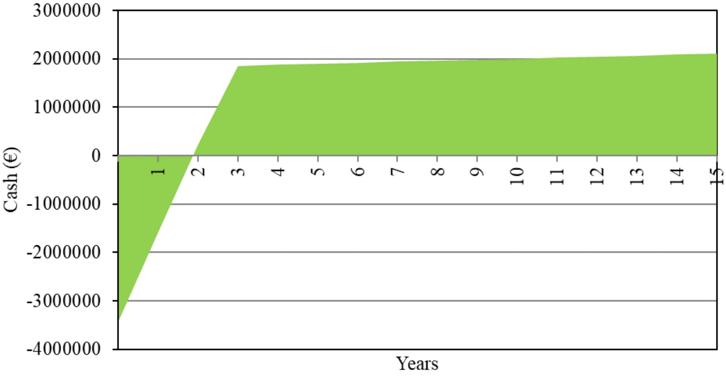
Table 28 is a detailed economic analysis for these four biogas power plants. The CapEx of for building the power plants is €3,439,000, €2,041,000, €2,738,000, and €2,930,000 for plants I-IV, respectively. Among three units, the digester is the most expensive unit for all four plants, more than 75% of total CapEx is required to construct the digesters. The annual OpEx of the biogas power plants includes transportation, digester operation, and CHP operation, which are €537,000,

€420,000, €411,000, and €660,000 for plants I-IV, respectively. As for the revenues of the biogas plants, the heat energy was not considered as a revenue stream in this study due to the difficult of capturing thermal energy. The liquid digestate is transported back to the farms as a fertilizer for crop lands. Liquid digestate is considered to be within the boundary of the biogas production system, and is not considered as a direct revenue stream.

Thus electricity and solid digestate are the revenue streams assumed for the biogas plants. The renewable electricity price in Italy is €0.28/kWh, so that the annual revenues from selling the renewable electricity are €2,209,000, €1,092,000, €1,624,000, and €1,780,000 for plants I-IV, respectively. The corresponding annual revenues from selling the solid digestate are €173,000, €114,000, €166,000, and €152,000. After deducting the annual OpEx, the annual net revenues are €1,845,000, €787,000, €1,379,000, and €1,272,000 for plants I-IV, respectively. Based on the data of CapEx, OpEx, and revenue, a cash flow analysis was further conducted to determine the payback period (Figure 35).

The high value of renewable electricity enables the biogas plants to quickly pay back the capital investment, and generates steady revenues afterwards. All four plants have payback periods of less than 2.5 years.

Besides good economic performance, the regional biogas power generation system also addresses the disposal of these agricultural wastes and residues. For instance, EU Directive 2008/98/EC mandates that citrus wastes and other food processing wastes must be pretreated before landfilling, which adds a significant technical and economic burden on producers.


3000000
2000000
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0
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Cash (€)
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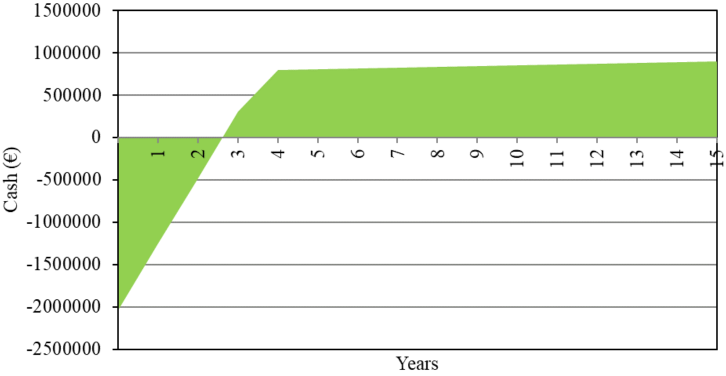
Years

(a)


1500000
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Cash (€)
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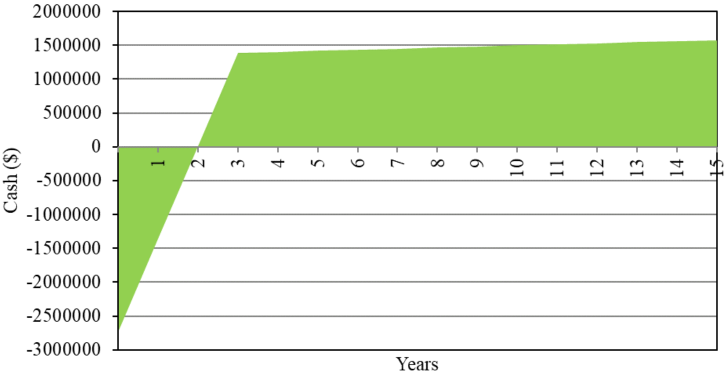
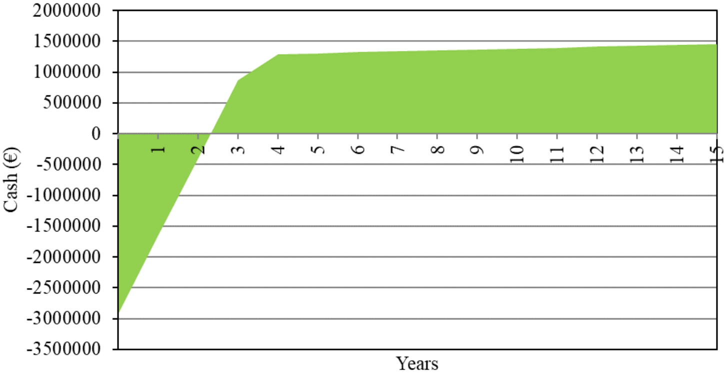
(b)



(c)



(d)

Figure 35. Cash flow analysis of individual biogas power plants. (a). Plant I; (b) Plant II; (c). Plant III; (d). Plant No. IV.

Using the wastes as the feedstock for biogas production leads to a win-win solution for the food processing waste disposal and renewable energy production. In addition, animal wastes are typically used as fertilizers for direct field application.

While phosphorus and some nitrogen in the animal wastes actually promotes crop growth, most of the carbon and nitrogen in the wastes are emitted as atmospheric greenhouse gases in Sicily’s warm climate (Sommer et al., 2004). Using the biogas plant to convert most of the VS in the manure into biogas and applying the digestates with a much lower VS content as fertilizer and soil amendment can significantly reduce the greenhouse gas emissions of animal agriculture. Therefore, regional biogas power generation system appears to be a technically sound, environmentally friendly, and economically feasible solution for Sicilian region.

Table 26. Mass balance of individual biogas plants.

Biogas plant	Feedstock type	Feedstock amount (kg/year) × 1000	TS (%) [a]	VS (%) [b]	Total TS in the feedstock (kg/year) [c] ×1000	Total VS in the feedstock (kg/year) [d] ×1000	Biogas production (m^3/year) [e]	Digestion effluent amount (kg/year) [f] ×1000	Liquid digestate amount (kg/year) [g] ×1000	Solid digestate amount (kg/year) [h] ×1000
I	Citrus pulp	37,425	17	17	13,420	12,984	5,778,027	127,706	119,042	8,664
	Olive pomace	4,129	45	42						
	Cattle manure	22,181	12	11						
	Whey	2,009	6	5						
	Poultry manure	6	32	20						
	Silage	6,901	35	34						
II	Citrus pulp	2,208	17	17	7,136	6,421	2,857,665	68,153	62,442	5,712
	Olive pomace	3,151	45	42						
	Cattle manure	15,945	12	11						
	Whey	791	6	5						
	Poultry manure	3,213	32	20						
	Silage	6,726	35	34						
III	Citrus pulp	5,360	17	17	10,536	9,549	4,249,114	100,581	92,305	8,276
	Olive pomace	12,763	45	42						
	Cattle manure	17,507	12	11						
	Whey	1,028	6	5						
	Poultry manure	3,335	32	20						
	Silage	1,861	35	34						
IV	Citrus pulp	17,040	17	17	11,031	10,465	4,656,769	105,077	97,480	7,598
	Olive pomace	3,844	45	42						
	Cattle manure	34,866	12	11						
	Whey	1,351	6	5						
	Poultry manure	250	32	20						
	Silage	5,884	35	34						

a. TS is the amount of total solids in raw feedsdtocks.
b. VS is the amount of volatile solids in raw feedstocks.
c. Total TS is the sum of the TS of individual feedstocks.
d. Total VS is the sum of the VS of individual feedstocks.
e. Biogas production was calculated based on Equation 20.
f. Digestion effluent amount was calculated based on Equation 21.
g. Solid digestate amount was calculated based on Equation 22.
h. Liquid digestate amount was calculated based on Equation 23.

Table 27. Energy balance of individual biogas plants.

Biogas plant	Engine size (kW-e) [a]	Net electricity generation (kWh-e/year) [b]	Net heat generation (kWh-e/year) [c]
I	1,238	7,887,638	12,134,638
II	612	3,901,025	6,001,577
III	911	5,800,505	8,923,853
IV	998	6,356,998	9,779,997

a. The size of the gas engine in the CHP was determined using Equation 24.
b. The net electricity generation was calculated using Equation 25.
c. The net heat generation was calculated using Equation 26.

Table 28. Economic analysis.

	Plant I	Plant II	Plant III	Plant IV
CapEx (€)				
Anaerobic digester (€) [a]	2,666,036	1,540,430	2,098,316	2,253,556
Biogas cleaning (€) [b]	180,775	141,139	163,472	168,630
CHP (€) [c]	592,129	359,592	476,276	508,210
OpEx (€/year)				
Silage cost (€/year) [d]	172,525	168,150	46,525	147,100
Transportation cost (€/year) [e]	123,609	108,831	172,452	307,750
Anaerobic digester (€/year) [f]	137,558	81,646	109,523	117,216
CHP (€/year) [g]	103,168	61,235	82,142	87,912
Revenue				
Electricity (€/year) [h]	2,208,539	1,092,287	1,624,141	1,779,959
Solid digestate (€/year) [i]	173,280	114,240	165,520	151,960
Net revenue (€/year) [j]	1,844,959	786,665	1,379,019	1,271,942
Payback period (year) [k]	1.87	2.38	2.00	2.32

a. The CapEx for the anaerobic digester is calculated by Equation 27.
b. The CapEx for the biogas cleaning is calculated by Equation 29.
c. The CapEx for the CHP is calculated by Equation 28.
d. The OpEx for the corn silage is calculated by Equation 31.
e. The OpEx for the transportation cost is calculated by Equation 32.
f. The OpEx for the anaerobic digester is calculated by Equation 33.
g. The OpEx for the CHP is calculated by Equation 34.
h. The revenue from electricity is calculated by Equation 36.
i. The revenue from solid digestate is calculated by Equation 37.
j. Net revenue is calculated using the revenue to subtract OpEx.
k. The payback period is calculated using the annual depreciation rates from MARCRS and inflation rate (Figure 35).

3.7.2.3 Economic sensitivity analysis

In addition, an economic sensitivity analysis showed the impacts of revenue streams and operational costs on the payback period of the biogas plants, and provided a guidance to further optimize the biogas plant operations and improve their economic performance (Table 29). Besides the big impact of electricity revenue on the economic performance for all four biogas plants, individual plants had different economic responses to different unit operations. For instance, biogas plant II is the smallest one among the four biogas plants (Figure 36). Transportation and corn silage costs are the major expenses to the plant, and have much more significant impacts on the economic performance than them on other three bigger biogas plants. 25% changes on transportation and corn silage costs influence the payback period of biogas plant II by 14% and 16%, respectively (Figure S 1; Figure S 2; Figure S 3; Figure S 4).

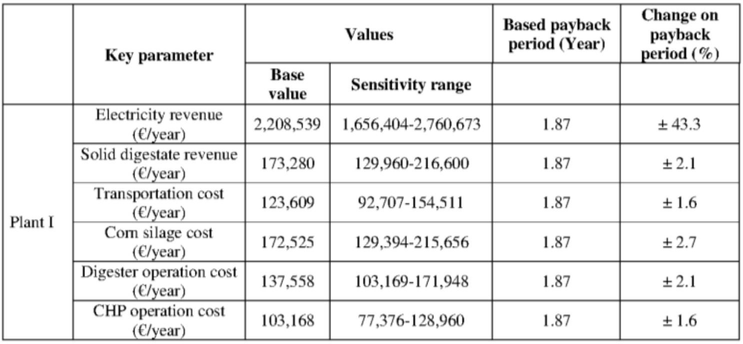
The plant I is the biggest one, located in Caltagirone municipality. The sensitivity analysis demonstrated (Table 29) that the highest influence of the 25% changes costs on payback period was around 3% for corn silage cost because of the highest amount of this feedstock. Moreover, this plant is the only one located in a central position, so the 25% transportation cost changes did not have a big influence on the payback period, only 1.6% change.

As regard the plant III and IV, the results of sensitivity analysis reported in Table 29, showed that the 25% changes on costs influenced th payback period of both two plants by around same percentages with regard solid digestate revenue, the digester operation cost, and CHP operation cost. Instead, as regard corn silage costs, the plant III payback period is influenced by only 0.5% due to the fact that among the located biogas plants, this plant had the smallest amount of corn silage. Furthermore, transportation costs in plant IV had highest significant impact on the economic performance then the other plants. In detail, the payback period change is influenced by 6.5%, because of the orography of the area. In fact, plant IV is located nearest to Etna volcano, so the kms needed during logistics phase to provide the feedstocks to this biogas plant are higher than that carried out by the other plants.

The economic sensitivity analysis clearly demonstrates that, after establishment of the regional biogas plants according to feedstock availability and transportation, some customized adjustments on operations at local level could be carried out to further improve the economic performance of individual biogas plants, such as reducing corn silage usages for plants I and IV, and improving quality of solid digestate for plant III to increase the solid digestate revenue.

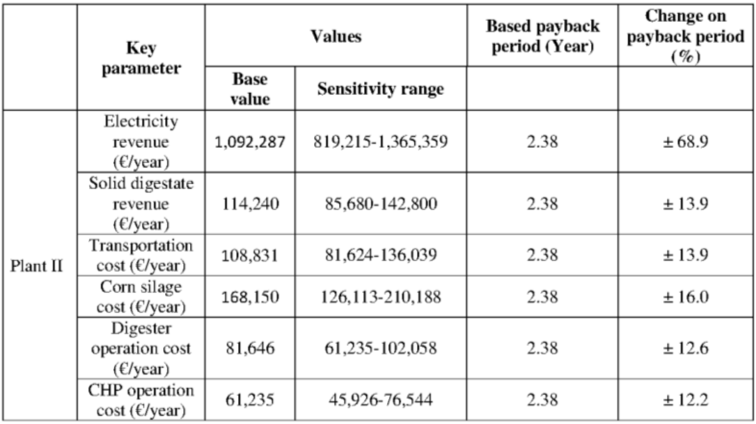
Table 29. Sensitivity analysis of key parameters on the payback period of the biogas plants [a]. (a) Plant I; (b) Plant II; (c) Plant III; (d) Plant IV.

[a] All values are adjusted by ±25% of their base values.



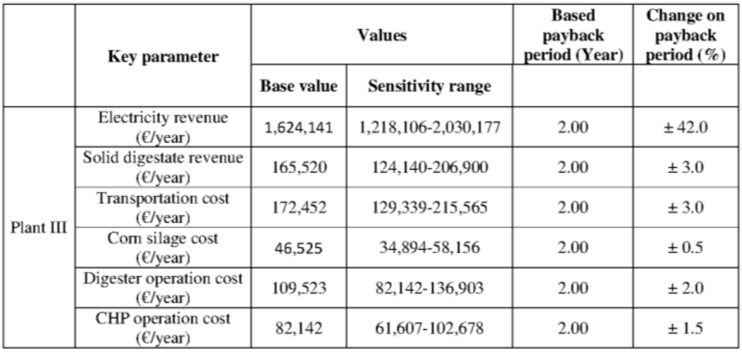
	Key parameter	Values		Based payback period (Year)	Change on payback period (%)
		Base value	Sensitivity range		
Plant I	Electricity revenue (€/year)	2,208,539	1,656,404-2,760,673	1.87	± 43.3
	Solid digestate revenue (€/year)	173,280	129,960-216,600	1.87	± 2.1
	Transportation cost (€/year)	123,609	92,707-154,511	1.87	± 1.6
	Corn silage cost (€/year)	172,525	129,394-215,656	1.87	± 2.7
	Digester operation cost (€/year)	137,558	103,169-171,948	1.87	± 2.1
	CHP operation cost (€/year)	103,168	77,376-128,960	1.87	± 1.6

(a)



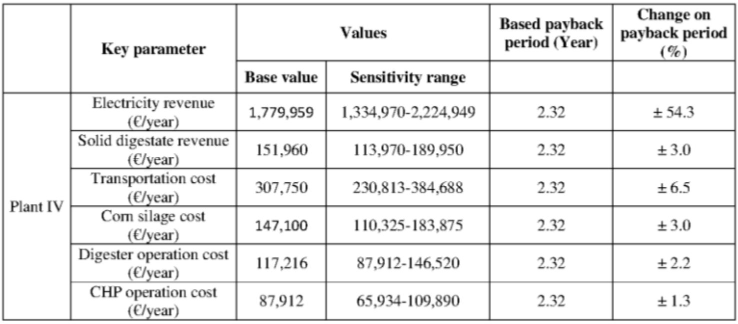
	Key parameter	Values		Based payback period (Year)	Change on payback period (%)
		Base value	Sensitivity range		
Plant II	Electricity revenue (€/year)	1,092,287	819,215-1,365,359	2.38	± 68.9
	Solid digestate revenue (€/year)	114,240	85,680-142,800	2.38	± 13.9
	Transportation cost (€/year)	108,831	81,624-136,039	2.38	± 13.9
	Corn silage cost (€/year)	168,150	126,113-210,188	2.38	± 16.0
	Digester operation cost (€/year)	81,646	61,235-102,058	2.38	± 12.6
	CHP operation cost (€/year)	61,235	45,926-76,544	2.38	± 12.2

(b)



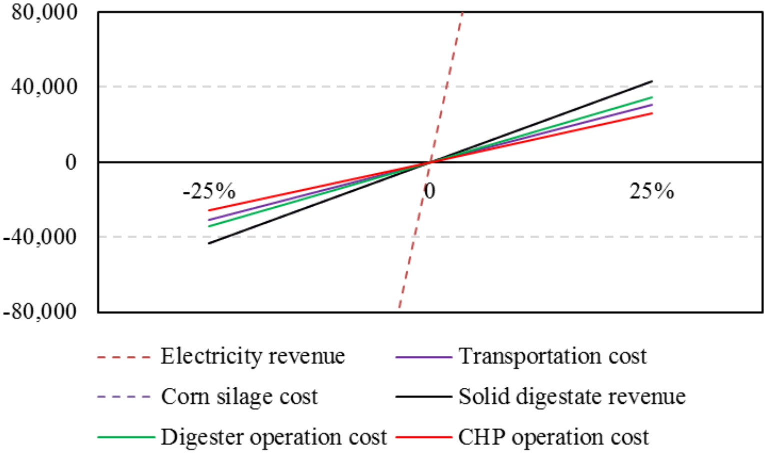
	Key parameter	Values		Based payback period (Year)	Change on payback period (%)
		Base value	Sensitivity range		
Plant III	Electricity revenue (€/year)	1,624,141	1,218,106-2,030,177	2.00	± 42.0
	Solid digestate revenue (€/year)	165,520	124,140-206,900	2.00	± 3.0
	Transportation cost (€/year)	172,452	129,339-215,565	2.00	± 3.0
	Corn silage cost (€/year)	46,525	34,894-58,156	2.00	± 0.5
	Digester operation cost (€/year)	109,523	82,142-136,903	2.00	± 2.0
	CHP operation cost (€/year)	82,142	61,607-102,678	2.00	± 1.5

(c)

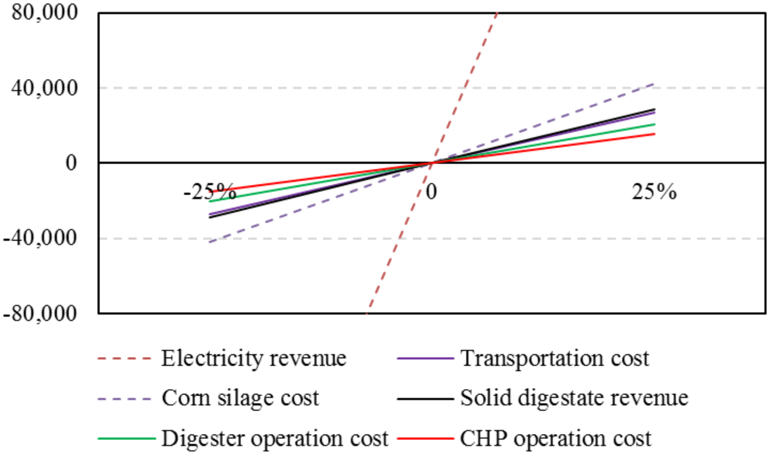


	Key parameter	Values		Based payback period (Year)	Change on payback period (%)
		Base value	Sensitivity range		
Plant IV	Electricity revenue (€/year)	1,779,959	1,334,970-2,224,949	2.32	± 54.3
	Solid digestate revenue (€/year)	151,960	113,970-189,950	2.32	± 3.0
	Transportation cost (€/year)	307,750	230,813-384,688	2.32	± 6.5
	Corn silage cost (€/year)	147,100	110,325-183,875	2.32	± 3.0
	Digester operation cost (€/year)	117,216	87,912-146,520	2.32	± 2.2
	CHP operation cost (€/year)	87,912	65,934-109,890	2.32	± 1.3

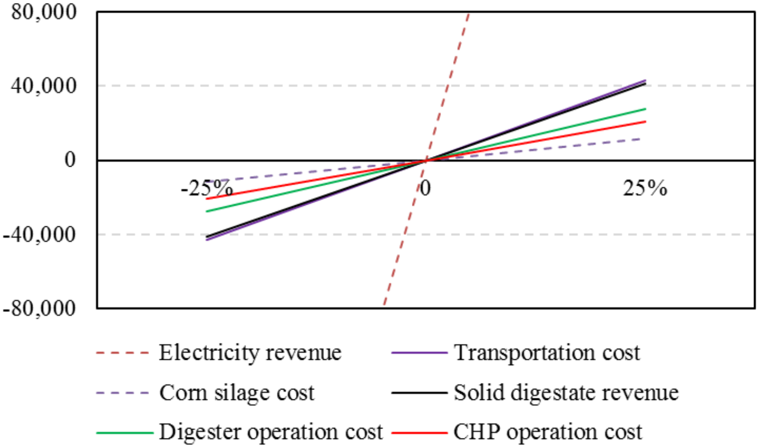
(d)


80,000
40,000
0
-40,000
-80,000
-25%
0
25%
Electricity revenue
Corn silage cost
Digester operation cost
Transportation cost
Solid digestate revenue
CHP operation cost

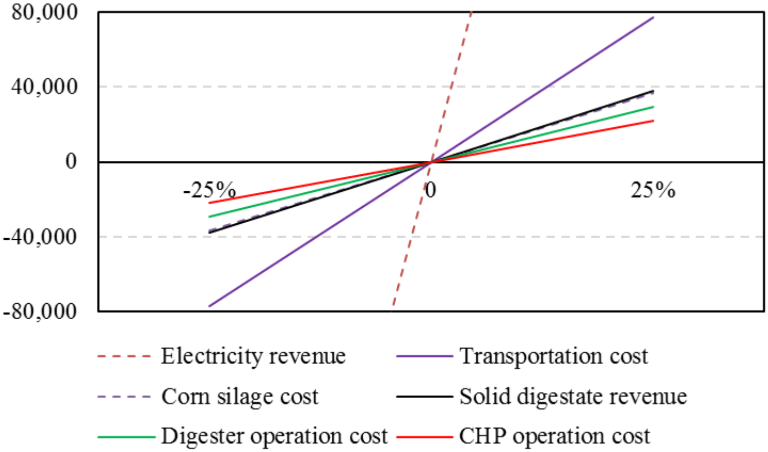
(a)


80,000
40,000
0
-40,000
-80,000
-25%
0
25%
Electricity revenue
Corn silage cost
Digester operation cost
Transportation cost
Solid digestate revenue
CHP operation cost

(b)



(c)



(d)

Figure 36. Economic sensitivity analysis. (a). Plant I; (b) Plant II; (c). Plant III; (d). Plant No. IV.

4 Discussion

4.1 Feedstock's availability

Regarding the evaluation of potential biomass and bioenergy availability, some research studies (Cai et al., 2008) (Robert et al., 2015) only used statistical data to carry out their investigations. Different from this approach, our study was based on both statistical and territorial information to estimate citrus pulp, olive pomace availability in Catania, Sicily. Such an approach has been largely used also in other research fields, which aims at evaluating the effects of agricultural activities on the environment (Arcidiacono and Porto, 2010; 2012; Benini et al., 2010; Gobin et al., 2004). A similar methodology was defined to estimate the biomass resource and its potential for bioenergy utilization in China (Yanli et al., 2010) and Finland (Hohn et al., 2014). In the study focused on China, the amount of the main biomass resources for possible energy use and their energy utilisation potential were analysed based on statistical data, yet through the elaboration of thematic maps to evaluate the geographic distributions. Those thematic maps were produced by the computation of biomass distribution, an evaluation index of the methane potential yield for each biomass typology was estimated through conversion factors (Yanli et al., 2010). In the Finland study, the authors analysed spatial distribution and amount of potential biomass feedstock for biogas production, both using statistics and by interviewing major industrial waste producers (Hohn et el., 2014). The differences between that these studies and this thesis was that the by-products/wastes availability, biomass distribution, and biomethane production were all linked and systematically analysed in our study.

4.2 Multiple feedstocks co-digestion performance

In this study, BMP and AD analyses were performed to evaluate the multiple feedstocks co-digestion feasibility. BMP and anaerobic co-digestion of different organic residues has been widely investigated to enhance AD performance of biogas production and total solids reduction. Most common co-digestion situation is that a main basic feedstock (e.g., animal manure or sewage sludge) is mixed with a minor amount of a secondary feedstock, as reported by Aboudi et al., 2017, Kurahashi et al.,2017, Zhang et al., 2017 and Lehtomaki et al., 2007. The multiple feedstocks co-digestion was carried out only in a few studies (Tasnim et al., 2017; Callaghan et al., 2002; Muradin and Foltynowicz, 2014. In detail the research by Tasnim et al. ran a co-digestion on mixed cow manure, sewage sludge, and water hyacinth that had better gas production than the co-digestion of cow manure and kitchen wastes (Tasnim et al., 2017). Three feedstocks, cattle manure, chicken manure, and fruit/vegetable wastes were used by Callaghan et al. to optimize a co-digestion process (Callaghan et al., 2002). Muradin and Foltynowicz studied the economic performance of a commercial biogas plant receiving nine organic residues (corn silage, potato pulp, spent vinessa waste, fruit and vegetable pomace, cereals, plat tissue waste, municipal sludge, and soya oil) (Muradin and Foltynowicz, 2014). All these studies demonstrated successful biogas production from multiple organic residues.

Considering the needs to analyze other biomass suitable for anaerobic digestion and to solve the dedicated energy crops issues, more and more biogas plants intend to use multiple feedstocks to improve their digestion performance, and require lab-scale testing approaches to determine the feasibility of such operations. Therefore, this study aimed at investigating the multiple feedstocks co-digestion, by adopting an innovative mix of six feedstocks (CP, OP, CM, PL, WH, and corn silage (CS)) available in Sicily and previously localized in the study area with spatial analysis.

A combined BMP and semi-continuous AD testing approach was applied to evaluate the technical feasibility of co-digestion of six feedstocks (CP, OP, CM, PL, WH, and CS). The BMP tests investigated six FMs with different mixing ratios and showed that all FMs had potential to be used as feedstocks for biogas production. The semi-continuous AD on selected FMs based on the available amounts of different feedstocks in Sicily further verified the technical feasibility of co-digestion of multiple feedstocks with different mixing ratios, which provides a solution to convert diverse agricultural residues in Sicily into bioenergy.

4.3 Feasibility of a regional power generation system

The GIS methodology, widely investigated in literature to estimate the biomass resource, has been intensively used to develop biogas production systems at local, regional, and national levels. The methodology was also integrated to multiple social, technical, and environmental criteria to identify the most suitable biogas production locations (Franco et al., 2015), and also to plan size and number of biogas plants in southern Finland as reported by Höhn et al., 2014.

In this study, a GIS-based modeling approach was applied to develop an optimized biogas power generation system in the Catania province of Sicily based on the type and quality of feedstocks, the location of farms and processing facilities, and the road network. It was also conducted a technical and economic analysis to determine the bioenergy production and economic performance of the system. Four biogas power plants in the system with a power capacity ranging from 0.6 to 1.2 MW are localised in Catania from north to south to best meet biomass transportation and logistics requirements. The system handles a total of 211,000 ton/year biomass and generates 23.9 GWh-e/year electricity to satisfy about 29% of the total agricultural electricity demand in the province, providing a win-win-win solution for renewable energy, the environment, and rural community.

This study also provides a modeling platform that can be extended to other provinces in Sicily, so that a comprehensive biogas power generation system using multiple biomass feedstocks for all of Sicily can be delineated in the near future.

4.4 *Future works*

This work aimed at investigating technical and economic aspects of establishing a sustainable biogas production system in Sicily. It used a multidisciplinary approach to develop a Gis-based techno-economic assessment, and demonstrated that the resulted system appears to be a technically sound, environmentally friendly, and economically feasible solution for Sicilian region. In the future, studies on environmental impacts of the resulted system need to be investigated such as life cycle analysis. Two scenarios should be compared, the co-digestion system with biogas production using the six matrices/by-products vs. the other treatment systems (i.e., land application for both poultry and cattle manure, landfill dispose of citrus pulp, burning and then land application for olive pomace and feeding animal for silage an whey).

A for the co-digestion performance, an in-depth study on dynamic changes of microbial communities during anaerobic digestion of multiple feedstocks needs to be carried out to explicitly explain the relationship between feedstocks and microbial communities.

5 Conclusions

The main goal of the research activity was to investigate the feasibility of establishing a sustainable biogas sector in Sicily. It was achieved through the definition of a GIS-based model to find suitable locations of new biogas plants and by analysing the selected feedstocks to maximize the biogas production of the chosen diet for anaerobic digestion.

Firstly, in this study, a methodology for the computation of a spatial index that describes the level of citrus pulp and olive pomace potential production was defined and implemented. This methodology was applied to a case study highly representative of the Italian citrus and olive production.

The methodology application allowed the identification of citrus pulp and olive pomace producing areas at different territorial levels, specifically provinces and municipalities in relation to the available databases, though the methodology is suitable to be utilised with lower territorial levels.

The data collection, which was also carried out by specific surveys, and the related elaborations, made it possible to reach the objectives of this study since they were suitable to compute and map the citrus and olive production areas and the citrus pulp and olive pomace at different levels in the whole study area. Moreover, in this phase, it was demonstrated that the selection of the areas eligible for biogas plants location was mainly influenced by the density of the citrus producing areas which ranged from 5% to 19% among the classes of municipalities analysed. In fact, the density of the olive producing areas resulted always equal to about 3% among the same classes.

Then, since anaerobic digesters for biogas production need a blend of different matrices, the GIS-based modeling approach was applied to develop an optimized biogas power generation system in the Catania province of Sicily based on the type and quality of feedstocks, location of farms and processing facilities, and the road network.

At the same time, the selected feedstocks were analysed to characterize them and combined in suitable diets for anaerobic digestion. Each diet was analysed with BMP tests and then in semi-continuous anaerobic digestion to select the diet which maximize the biogas production.

Consequently, a technical and economic analysis was conducted to determine the bioenergy production and economic performance of the system. Four biogas power plants in the system with a power capacity ranging from 0.6 to 1.2 MW are distributed in Catania from north to south to best meet biomass transportation and logistics requirements.

The system handles a total of almost 211,000 ton/year biomass and generates 23.9 GWh-e/year electricity to satisfy about 29% of the total agricultural electricity demand in the province, providing a win-win-win solution for renewable energy, the environment, and rural community.

This study also provides a modeling platform that can be extended to other provinces in Sicily, so that a comprehensive biogas power generation system by using multiple biomass feedstocks for all of Sicily can be delineated in the near future. In this context, the research activity that I developed and completed during my PhD is tightly connected to the most up-to-date applications of both GIS model and combined BMP and semi-continuous AD testing approach.

The thesis provided new knowledge and make advances in the biogas production area by addressing the most crucial issues of feedstocks supply logistics and anaerobic digestion of multiple feedstocks.

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6 Supplemental materials

6.1 Statistical analysis

R code and results for Figure 27

```
# read the dataset into an R variable using the .csv file

BMPcomparison <-read.csv("C:/Users/francesca/Desktop/BMPpape
r/R-code/forFigure27.csv", head=T)

#display the data

BMPcomparison

tapply(X = BMPcomparison$BMP, INDEX = list(BMPcomparison$mix
ture), FUN = mean)

anova(lm(BMP ~ mixture, BMPcomparison))

#pairwise.t.test(BMPcomparison$mixture, BMPcomparison$gas, p
.adj = "bonferroni")

TukeyHSD(aov(BMP~mixture, BMPcomparison))
```

BMP comparison:
Data:

mixture	R mixture	BMP
FM1	a	1080.7293
FM1	a	1154.3770
FM2	b	996.8996
FM2	b	811.6596
FM3	c	935.8067
FM3	c	928.1332
FM4	d	1104.9272
FM4	d	1065.4683
FM5	e	940.6478
FM5	e	845.9658
FM6	f	905.8756
FM6	f	934.9436

BMP average

a	b	c	d	e	f
1117.5531	904.2796	931.9699	1085.1978	893.3068	920.4096

ANOVA analysis

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
mixture	5	97941	19588.2	4.5943	0.04529
Residuals	6	25582	4263.6		

Tukey analysis

	diff	lwr	upr	p adj
b-a	-213.27353	-473.14302	46.59595	0.1087850
c-a	-185.58318	-445.45266	74.28631	0.1749428
d-a	-32.35536	-292.22485	227.51413	0.9944775
e-a	-224.24633	-484.11582	35.62315	0.0902786
f-a	-197.14351	-457.01300	62.72598	0.1434177
c-b	27.69036	-232.17913	287.55984	0.9973012
d-b	180.91817	-78.95131	440.78766	0.1895255
e-b	-10.97280	-270.84229	248.89669	0.9999694
f-b	16.13002	-243.73947	275.99951	0.9997967
d-c	153.22782	-106.64167	413.09730	0.3026713
e-c	-38.66316	-298.53264	221.20633	0.9877926
f-c	-11.56033	-271.42982	248.30915	0.9999604
e-d	-191.89097	-451.76046	67.97851	0.1569692
f-d	-164.78815	-424.65764	95.08134	0.2494729
f-e	27.10282	-232.76666	286.97231	0.9975579

R code and results for Figure 30

```
# read the dataset into an R variable using the .csv file

BiogasProductivity <-read.csv("C:/Users/francesca/Desktop/BM
Ppaper/R-code/forFigure30.csv", head=T)

#display the data

BiogasProductivity

anova(lm(gas ~ FM + stage, BiogasProductivity))

TukeyHSD(aov(gas~stage+FM, BiogasProductivity))

anova(lm(CH4 ~ FM + stage, BiogasProductivity))

TukeyHSD(aov(CH4~stage+FM, BiogasProductivity))
```

Biogas Productivity Data:

mixture	stage	R mixture	gas	CH4
FM1	I	a	193.24	42.34
FM1	II	a	158.03	56.24
FM1	III	a	480.86	51.25
FM1	I	a	197.27	36.99
FM1	II	a	162.19	46.71
FM1	III	a	411.97	60.19
FM2	I	b	217.43	56.95
FM2	II	b	391.92	47.49
FM2	III	b	391.96	48.38
FM2	I	b	200.45	56.69
FM2	II	b	285.01	49.50
FM2	III	b	300.84	55.59
FM3	I	c	192.86	62.18
FM3	II	c	400.98	59.45
FM3	III	c	446.71	62.54
FM3	I	c	160.47	60.89
FM3	II	c	323.86	55.42
FM3	III	c	295.99	55.69

ANOVA analysis (gas)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
FM	2	4567	2283	0.3557	0.707296
Stage	2	113474	56737	8.8380	0.003771
Residuals	13	83455	6420		

Tukey analysis (gas-stage)

	diff	lwr	upr	p adj
II-I	93.37833	-28.76532	215.5220	0.1469282
III-I	194.43500	72.29134	316.5787	0.0027621
III-II	101.05667	-21.08699	223.2003	0.1114030

Tukey analysis (gas-FM)

	diff	lwr	upr	p adj
b-a	30.675000	-91.46866	152.8187	0.7883759
c-a	36.218333	-85.92532	158.3620	0.7196257
c-b	5.543333	-116.60032	127.6870	0.9921193

ANOVA analysis (CH4)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
FM	2	336.89	168.446	4.4975	0.03277
Stage	2	36.99	18.496	0.4938	0.62128
Residuals	13	486.89	37.453		

Tukey analysis (CH4-stage)

	diff	lwr	upr	p adj
II-I	-0.205000	-9.534537	9.124537	0.9981461
III-I	2.933333	-6.396204	12.262870	0.6916137
III-II	3.138333	-6.191204	12.467870	0.6568560

Tukey analysis (CH4-FM)

	diff	lwr	upr	p adj
b-a	3.480000	-5.849537	12.80954	0.5987674
c-a	10.408333	1.078796	19.73787	0.0286006
c-b	6.928333	-2.401204	16.25787	0.1613927

R code and results for Table 20

```
# read the dataset into an R variable using the .csv file

GasComposition  <-read.csv("C:/Users/francesca/Desktop/BMPpap
er/R-code/forTable20.csv", head=T)

#display the data

GasComposition

tapply(X = GasComposition$CH4, INDEX = list(GasComposition$m
ixture), FUN = mean)

anova(lm(CH4 ~ mixture, GasComposition))

TukeyHSD(aov(CH4~mixture, GasComposition))

#-------------------

tapply(X = GasComposition$CO2, INDEX = list(GasComposition$m
ixture), FUN = mean)

anova(lm(CO2 ~ mixture, GasComposition))

TukeyHSD(aov(CO2~mixture, GasComposition))

#-------------------

tapply(X = GasComposition$H2S, INDEX = list(GasComposition$m
ixture), FUN = mean)

anova(lm(H2S ~ mixture, GasComposition))

TukeyHSD(aov(H2S~mixture, GasComposition))
```

Gas Composition Data:

mixture	R mixture	CH4	CO2	H2S
FM1	a	73.07	26.93	319.93
FM1	a	73.23	26.77	451.07
FM2	b	72.66	27.34	320.02
FM2	b	73.04	26.96	463.85
FM3	c	74.10	25.90	163.75
FM3	c	74.34	25.66	285.11
FM4	d	75.06	24.94	358.19
FM4	d	75.18	24.82	346.05
FM5	e	76.22	23.78	NA
FM5	e	76.10	23.90	302.40
FM6	f	76.00	24.00	NA
FM6	f	76.14	23.86	211.28

Gas Composition- CH4 average

mixture	a	b	c	d	e	f
CH4 average	73.15	72.85	74.22	75.12	76.16	76.07

ANOVA analysis (CH4-mixture)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
mixture	5	20.348	4.0697	176.94	1.991e-06
Residuals	6	0.138	0.0230		

Tukey analysis (CH4-mixture)

	diff	lwr	upr	p adj
b-a	-0.30	-0.9035736	0.3035736	0.4438284
c-a	1.07	0.4664264	1.6735736	0.0031452
d-a	1.97	1.3664264	2.5735736	0.0001048
e-a	3.01	2.4064264	3.6135736	0.0000072
f-a	2.92	2.3164264	3.5235736	0.0000087
c-b	1.37	0.7664264	1.9735736	0.0008185
d-b	2.27	1.6664264	2.8735736	0.0000455
e-b	3.31	2.7064264	3.9135736	0.0000042
f-b	3.22	2.6164264	3.8235736	0.0000048
d-c	0.90	0.2964264	1.5035736	0.0077257
e-c	1.94	1.3364264	2.5435736	0.0001144
f-c	1.85	1.2464264	2.4535736	0.0001501
e-d	1.04	0.4364264	1.6435736	0.0036563
f-d	0.95	0.3464264	1.5535736	0.0058614
f-e	-0.09	-0.6935736	0.5135736	0.9876732

Gas Composition- CO2 average

mixture	a	b	c	d	e	f
CO2 average	26.85	27.15	25.78	24.88	23.84	23.93

ANOVA analysis (CO2-mixture)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
mixture	5	20.348	4.0697	176.94	1.991e-06
Residuals	6	0.138	0.0230		

Tukey analysis (CO2-mixture)

	diff	lwr	upr	p adj
b-a	0.30	-0.3035736	0.9035736	0.4438284
c-a	-1.07	-1.6735736	-0.4664264	0.0031452
d-a	-1.97	-2.5735736	-1.3664264	0.0001048
e-a	-3.01	-3.6135736	-2.4064264	0.0000072
f-a	-2.92	-3.5235736	-2.3164264	0.0000087
c-b	-1.37	-1.9735736	-0.7664264	0.0008185
d-b	-2.27	-2.8735736	-1.6664264	0.0000455
e-b	-3.31	-3.9135736	-2.7064264	0.0000042
f-b	-3.22	-3.8235736	-2.6164264	0.0000048
d-c	-0.90	-1.5035736	-0.2964264	0.0077257
e-c	-1.94	-2.5435736	-1.3364264	0.0001144
f-c	-1.85	-2.4535736	-1.2464264	0.0001501
e-d	-1.04	-1.6435736	-0.4364264	0.0036563
f-d	-0.95	-1.5535736	-0.3464264	0.0058614
f-e	0.09	-0.5135736	0.6935736	0.9876732

Gas Composition- H2S average

mixture	a	b	c	d	e	f
H2S average	385.500	391.935	224.430	352.120	NA	NA

ANOVA analysis (H2S-mixture)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
mixture	5	51343	10269	1.557	0.3444
Residuals	4	26380	6595		

Tukey analysis (H2S-mixture)

	diff	lwr	upr	p adj
b-a	6.435	-378.6761	391.5461	0.9999991
c-a	-161.070	-546.1811	224.0411	0.4713338
d-a	-33.380	-418.4911	351.7311	0.9972434
e-a	-83.100	-554.7628	388.5628	0.9449665
f-a	-174.220	-645.8828	297.4428	0.5683613
c-b	-167.505	-552.6161	217.6061	0.4410124
d-b	-39.815	-424.9261	345.2961	0.9938655
e-b	-89.535	-561.1978	382.1278	0.9280022
f-b	-180.655	-652.3178	291.0078	0.5401288
d-c	127.690	-257.4211	512.8011	0.6499942
e-c	77.970	-393.6928	549.6328	0.9566411
f-c	-13.150	-484.8128	458.5128	0.9999886
e-d	-49.720	-521.3828	421.9428	0.9933115
f-d	-140.840	-612.5028	330.8228	0.7229929
f-e	-91.120	-635.7493	453.5093	0.9546207

R code and results for Figure 28

```
# read the dataset into an R variable using the .csv file

VSreduction  <-read.csv("C:/Users/francesca/Desktop/BMPpaper/
R-code/forFigure28.csv", head=T)

#display the data

VSreduction

tapply(X = VSreduction$VS, INDEX = list(VSreduction$mixture)
, FUN = mean)

anova(lm(VS ~ mixture, VSreduction))

TukeyHSD(aov(VS~mixture, VSreduction))
```

VS reduction
Data:

mixture	R mixture	VS
FM1	a	49.47917
FM1	a	66.66667
FM2	b	60.20408
FM2	b	62.24490
FM3	c	63.87435
FM3	c	59.16230
FM4	d	61.80905
FM4	d	63.81910
FM5	e	63.25581
FM5	e	60.93023
FM6	f	57.45856
FM6	f	53.59116
Control	g	26.11465
Control	g	24.8407

VS reduction average

R mixture	a	b	c	d	e	f	g
VS average	58.073	61.225	61.518	62.814	62.093	55.525	25.478

ANOVA analysis (VS-mixture)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
mixture	6	2146.9	357.82	14.403	0.001264
Residuals	7	173.9	24.84		

Tukey analysis (VS-mixture)

	diff	lwr	upr	p adj
b-a	3.1515731	-16.60545	22.90859	0.9929657
c-a	3.4454079	-16.31161	23.20243	0.9889314
d-a	4.7411537	-15.01587	24.49817	0.9504670
e-a	4.0201066	-15.73691	23.77713	0.9765375
f-a	-2.5480548	-22.30507	17.20896	0.9977190
g-a	-32.5952097	-52.35223	-12.83819	0.0034302
c-b	0.2938348	-19.46318	20.05085	1.0000000
d-b	1.5895806	-18.16744	21.34660	0.9998390
e-b	0.8685335	-18.88849	20.62555	0.9999953
f-b	-5.6996279	-25.45665	14.05739	0.8951218
g-b	-35.7467828	-55.50380	-15.98976	0.0019677
d-c	1.2957458	-18.46127	21.05277	0.9999509
e-c	0.5746987	-19.18232	20.33172	0.9999996
f-c	-5.9934627	-25.75048	13.76356	0.8735210
g-c	-36.0406176	-55.79764	-16.28360	0.0018717
e-d	-0.7210471	-20.47807	19.03597	0.9999985
f-d	-7.2892085	-27.04623	12.46781	0.7578900
g-d	-37.3363633	-57.09338	-17.57934	0.0015068
f-e	-6.5681614	-26.32518	13.18886	0.8258145
g-e	-36.6153162	-56.37234	-16.85830	0.0016989
g-f	-30.0471549	-49.80417	-10.29014	0.0055275

R code and results for Figure 31

```
# read the dataset into an R variable using the .csv file

VSreduction  <-read.csv("C:/Users/francesca/Desktop/BMPpaper/
R-code/forFigure31.csv", head=T)

#display the data

VSreduction

anova(lm(VS ~ FM + stage, VSreduction))

TukeyHSD(aov(VS~stage+FM, VSreduction))

#---------------------

anova(lm(VS ~ stageFM, VSreduction))

TukeyHSD(aov(VS~stageFM, VSreduction))
```

VS reduction
Data:

FMs	stage	R FM	VS	StageFM
FM1	I	a	43.66	Ia
FM1	II	a	48.59	IIa
FM1	III	a	48.50	IIIa
FM1	I	a	42.66	Ia
FM1	II	a	49.40	IIa
FM1	III	a	45.70	IIIa
FM2	I	b	41.82	Ib
FM2	II	b	56.58	IIb
FM2	III	b	52.94	IIIb
FM2	I	b	43.83	Ib
FM2	II	b	53.40	IIb
FM2	III	b	47.51	IIIb
FM3	I	c	50.57	Ic
FM3	II	c	59.46	IIc
FM3	III	c	54.45	IIIc
FM3	I	c	48.08	Ic
FM3	II	c	57.16	IIc
FM3	III	c	50.03	IIIc

ANOVA analysis (VS-FM + stage)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
FM	2	142.762	71.381	13.472	0.0006781
stage	2	242.988	121.494	22.929	5.456e-05
Residuals	13	68.883	5.299		

Tukey analysis (VS-stage)

	diff	lwr	upr	p adj
II-I	8.995000	5.485879	12.5041211	0.0000369
III-I	4.751667	1.242546	8.2607878	0.0088457
III-II	-4.243333	-7.752454	-0.7342122	0.0180741

Tukey analysis (VS-FM)

	diff	lwr	upr	p adj
b-a	2.928333	-0.5807878	6.437454	0.1078944
c-a	6.873333	3.3642122	10.382454	0.0004909
c-b	3.945000	0.4358789	7.454121	0.0274273

ANOVA analysis (VS-stageFM)

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
stageFM	8	412.55	51.569	11.03	0.0007884
Residuals	9	42.08	4.676		

Tukey analysis (VS-stageFM)

	diff	lwr	upr	p adj
Ib-Ia	-0.335	-8.8891993	8.2191993	1.0000000
Ic-Ia	6.165	-2.3891993	14.7191993	0.2197791
IIa-Ia	5.835	-2.7191993	14.3891993	0.2664351
IIb-Ia	11.830	3.2758007	20.3841993	0.0069537
IIc-Ia	15.150	6.5958007	23.7041993	0.0011891
IIIa-Ia	3.940	-4.6141993	12.4941993	0.6712994
IIIb-Ia	7.065	-1.4891993	15.6191993	0.1271454
IIIc-Ia	9.080	0.5258007	17.6341993	0.0360056
Ic-Ib	6.500	-2.0541993	15.0541993	0.1798286
IIa-Ib	6.170	-2.3841993	14.7241993	0.2191296
IIb-Ib	12.165	3.6108007	20.7191993	0.0057531
IIc-Ib	15.485	6.9308007	24.0391993	0.0010086
IIIa-Ib	4.275	-4.2791993	12.8291993	0.5882874
IIIb-Ib	7.400	-1.1541993	15.9541993	0.1031943
IIIc-Ib	9.415	0.8608007	17.9691993	0.0292572
IIa-Ic	-0.330	-8.8841993	8.2241993	1.0000000
IIb-Ic	5.665	-2.8891993	14.2191993	0.2934929
IIc-Ic	8.985	0.4308007	17.5391993	0.0381983
IIIa-Ic	-2.225	-10.7791993	6.3291993	0.9721106
IIIb-Ic	0.900	-7.6541993	9.4541993	0.9999370
IIIc-Ic	2.915	-5.6391993	11.4691993	0.8921758
IIb-IIa	5.995	-2.5591993	14.5491993	0.2428672
IIc-IIa	9.315	0.7608007	17.8691993	0.0311222
IIIa-IIa	-1.895	-10.4491993	6.6591993	0.9890618
IIIb-IIa	1.230	-7.3241993	9.7841993	0.9993817
IIIc-IIa	3.245	-5.3091993	11.7991993	0.8313620
IIc-IIb	3.320	-5.2341993	11.8741993	0.8158145
IIIa-IIb	-7.890	-16.4441993	0.6641993	0.0758865
IIIb-IIb	-4.765	-13.3191993	3.7891993	0.4714092
IIIc-IIb	-2.750	-11.3041993	5.8041993	0.9173071
IIIa-IIc	-11.210	-19.7641993	-2.6558007	0.0099415
IIIb-IIc	-8.085	-16.6391993	0.4691993	0.0671316
IIIc-IIc	-6.070	-14.6241993	2.4841993	0.2324378
IIIb-IIIa	3.125	-5.4291993	11.6791993	0.8549873
IIIc-IIIa	5.140	-3.4141993	13.6941993	0.3904278
IIIc-IIIb	2.015	-6.5391993	10.5691993	0.9841924

6.2 *Figures and tables*

Table S 1 Biomass production and locations of individual farms and food processing facilities.

Biomass	Farm No.	Biomass amount (Tons/year)	Biogas plant	Annual transportation mileage to the assigned biogas plant (km)	Transportation route No.
Citrus pulp					
	1	30,000.00	I	1,312.93	1
	2	2207.70	II	215.10	2
	3	7,425.00	I	743.15	3
	4	16,800	IV	682.18	4
	5	240.00	IV	62.63	5
	6	5,360.00	III	47.25	6
Cattle manure					
	1	49.80	III	4.81	42
	5	49.80	III	19.87	2
	6	49.80	III	13.48	1
	8	49.80	III	11.75	5
	9	49.80	III	11.73	4
	10	49.80	III	80.30	22
	11	49.80	III	76.09	27
	12	49.80	III	82.82	26
	13	49.80	III	75.24	20
	14	49.80	III	74.25	19
	15	49.80	III	75.05	21
	16	58.10	III	79.39	24
	17	2,963.10	III	3,936.61	23
	21	2008.60	III	1,884.41	38
	22	58.10	II	37.25	41
	23	58.10	II	37.08	40
	26	58.10	II	53.93	39
	31	58.10	III	64.66	29
	32	58.10	III	65.18	28
	34	58.10	IV	87.05	8
	36	66.40	IV	85.26	10

(continue)

(…)

37	66.40	IV	85.35	11
38	66.40	IV	106.85	5
39	66.40	III	108.60	11
45	74.70	IV	99.58	6
46	74.70	IV	91.37	7
50	74.70	IV	88.73	13
52	74.70	IV	104.75	4
54	74.70	IV	83.74	12
55	83.00	III	156.83	10
60	83.00	I	49.23	13
63	83.00	I	32.88	32
64	83.00	I	27.63	29
65	83.00	I	56.27	7
71	99.60	I	44.92	5
73	99.60	I	50.22	17
75	99.60	I	49.48	25
77	99.60	I	41.24	62
79	99.60	I	57.16	19
93	107.90	I	36.49	22
94	116.20	I	103.27	11
95	116.20	I	57.08	6
96	116.20	I	50.95	36
97	116.20	I	39.82	30
112	132.80	I	83.20	15
114	132.80	I	56.36	4
115	132.80	I	64.70	12
116	132.80	I	82.51	14
118	132.80	I	34.79	1
120	132.80	I	52.23	20
121	132.80	I	41.78	23
123	141.10	I	63.30	37
124	141.10	I	95.02	9
125	141.10	I	83.64	18
128	946.20	I	281.39	3
130	149.40	I	90.33	26
131	149.40	I	95.16	8
132	149.40	I	17.88	38
135	157.70	I	43.20	2
139	157.70	II	210.64	28
141	166.00	II	232.91	25
142	174.30	II	246.36	27
145	174.30	II	231.79	26
146	174.30	II	266.58	29
147	174.30	I	229.49	45

(continue)

(…)

148	174.30	I	239.05	44
149	174.30	II	247.42	31
150	174.30	II	197.33	22
153	182.60	I	239.90	46
157	182.60	IV	77.87	50
158	182.60	IV	87.71	49
159	182.60	IV	123.91	47
160	182.60	IV	108.18	48
161	190.90	IV	54.74	51
162	190.90	IV	143.41	46
163	190.90	II	130.86	44
164	190.90	II	128.12	45
165	190.90	II	139.85	46
167	199.20	III	166.23	44
169	199.20	II	181.61	42
170	199.20	II	144.89	43
174	199.20	III	167.76	45
178	199.20	II	157.98	47
179	207.50	IV	63.55	1
181	207.50	IV	105.15	3
183	207.50	III	108.59	8
184	207.50	III	126.04	9
187	215.80	I	90.14	63
188	215.80	I	93.76	65
193	224.10	I	81.18	69
194	224.10	I	94.38	64
195	224.10	I	90.21	74
196	232.40	I	101.68	67
198	232.40	I	103.85	66
201	240.70	I	96.96	70
205	240.70	I	98.51	68
206	240.70	I	93.16	73
207	249.00	II	272.85	10
209	249.00	I	201.69	58
210	249.00	I	288.11	60
211	249.00	I	181.30	61
212	249.00	II	269.47	9
213	257.30	I	227.09	59
215	257.30	II	318.03	11
216	257.30	I	213.76	57
224	265.60	III	113.15	40
225	282.20	II	109.92	5
226	282.20	II	92.55	4
227	282.20	II	133.41	17

(continue)

(…)

228	282.20	I	167.54	55
229	282.20	I	133.15	52
230	290.50	I	161.30	34
233	290.50	I	142.29	33
234	589.30	I	338.53	54
235	556.10	II	360.81	13
236	298.80	I	151.40	53
237	298.80	II	187.19	16
238	298.80	II	178.40	15
239	298.80	II	181.11	14
241	307.10	I	114.33	50
243	307.10	III	219.08	43
244	307.10	III	240.62	39
245	307.10	II	115.62	18
246	315.40	III	337.35	37
248	415.00	II	494.75	33
249	323.70	III	349.96	31
250	323.70	III	337.29	36
255	332.00	III	340.06	32
258	332.00	III	304.65	34
262	340.30	II	415.41	32
263	340.30	II	480.00	34
264	365.20	III	389.61	30
267	373.50	II	388.34	38
269	381.80	III	432.11	33
281	398.40	I	417.33	47
285	398.40	I	467.90	43
286	406.70	I	456.10	42
287	406.70	I	458.62	41
290	415.00	II	373.64	21
296	423.30	I	447.07	48
297	431.60	II	349.65	19
298	431.60	II	301.79	20
299	431.60	IV	480.82	35
300	439.90	IV	525.96	34
301	464.80	IV	497.15	40
302	473.10	IV	527.62	41
303	473.10	IV	540.16	36
304	473.10	IV	552.00	37
306	473.10	IV	523.84	42
307	473.10	III	848.22	12
308	481.40	III	848.21	13
310	489.70	IV	614.96	30
312	498.00	IV	633.93	33

(continue)

(…)

315	514.60	IV	593.61	38
316	514.60	III	849.25	14
317	522.90	III	846.94	15
318	522.90	III	846.34	16
319	531.20	IV	661.48	39
320	539.50	III	869.98	17
322	547.80	IV	701.33	31
323	547.80	IV	554.20	45
329	564.40	I	308.04	28
331	572.70	III	198.59	41
335	597.60	II	20.24	1
337	630.80	II	83.44	2
338	630.80	II	81.64	3
343	655.70	II	580.02	7
354	813.40	II	606.89	6
360	913.00	II	631.06	12
366	979.40	I	743.82	56
370	1,020.90	I	892.40	10
377	1,045.80	IV	1,821.79	14
378	1,045.80	IV	1,769.53	16
380	1,079.00	IV	1,797.86	18
383	1,153.70	IV	1,843.03	20
386	1,236.70	IV	1,823.18	24
392	1,494.00	IV	2,599.02	15
394	1,568.70	IV	2,575.39	19
396	1,585.30	IV	2,318.66	25
397	1,601.90	IV	2,396.25	27
400	1,693.20	IV	2,708.81	21
404	1,817.70	IV	2,738.89	28
405	1,850.90	IV	2,797.75	29
406	1,892.40	IV	3,180.57	17
407	1,942.20	IV	2,893.09	23
408	66.40	IV	130.14	26
413	58.10	IV	94.23	22
Cattle manure and whey				
4	133.80 / 34.65	III	34.69	3
18	156.10 / 40.42	III	289.87	25
51	200.70 / 51.97	IV	330.58	9
87	289.90 / 75.07	I	136.95	31
91	289.90 / 75.07	I	170.21	24
122	379.10 / 98.16	I	206.15	35
129	401.40 / 103.94	I	168.23	21
134	423.70 / 109.71	I	333.51	27
137	423.70 / 109.71	II	782.14	30

(continue)

(…)

138	423.70 / 109.71	II	656.79	24
140	446.00 / 115.49	II	638.01	23
173	535.20 / 138.58	III	529.48	46
189	215.80 / 150.13	I	130.73	72
202	646.70 / 167.46	I	284.20	71
232	1,940.10 / 502.37	I	1,003.84	51
260	914.30 / 236.75	III	1,141.37	35
261	914.30 / 236.75	III	1,137.92	47
276	1,048.10 / 271.40	I	1,687.25	39
283	892.00 / 230.97	I	1,058.65	49
293	323.70 / 225.20	I	796.93	40
309	1,315.70 / 340.69	III	2,577.80	18
313	1,360.30 / 352.24	IV	2,126.62	32
314	1,382.60 / 358.01	IV	1,876.47	43
324	1,471.80 / 381.11	IV	1,905.97	44
326	802.80 / 207.88	IV	482.51	2
344	1,761.70 / 456.18	II	2,322.34	8
Olive pomace				
1	294.9	III	65.98	1
2	90.00	III	19.28	41
3	160.00	III	32.21	39
4	180.00	III	38.71	40
5	140.00	III	39.54	38
6	380.00	III	490.97	36
7	294.90	III	366.59	31
8	294.90	III	361.66	32
9	294.90	III	364.38	34
10	294.90	III	365.03	33
11	294.90	III	345.97	30
12	294.90	III	360.49	35
13	300.00	III	205.74	10
14	550.00	III	362.21	8
15	294.90	III	199.59	14
16	294.90	III	208.10	11
17	294.90	III	210.86	12
18	294.90	III	206.26	9
19	294.90	III	213.22	13
20	250.00	III	259.95	28
21	170.00	III	200.75	29
22	480.00	III	506.53	25
23	500.00	III	526.48	23
24	135.00	III	158.31	27
25	330.00	III	348.15	26
26	294.90	III	315.51	24

(continue)

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27	294.90	IV	458.31	7
28	294.90	IV	462.10	8
29	202.00	II	253.33	9
30	294.90	IV	468.60	10
31	294.90	IV	463.77	9
32	294.90	IV	538.40	11
33	294.90	I	74.34	11
34	294.90	I	85.58	10
35	315.00	IV	142.17	16
36	294.90	IV	223.62	13
37	294.90	IV	228.38	12
38	180.00	IV	22.42	2
39	130.00	IV	14.77	3
40	294.90	IV	153.34	1
41	294.90	I	124.93	4
42	294.90	I	122.91	7
43	294.90	I	138.05	5
44	294.90	I	131.13	6
45	270.00	IV	99.20	4
46	294.90	IV	110.75	5
47	360.00	III	166.51	3
48	185.00	III	84.09	4
49	294.90	III	131.46	2
50	294.90	I	278.41	9
51	294.90	I	266.13	8
52	294.90	I	142.20	3
53	294.90	I	152.45	2
54	294.90	I	153.84	1
55	294.90	I	181.02	14
56	294.90	I	173.86	13
57	294.90	II	296.56	10
57	294.90	III	251.19	7
58	450.00	III	314.09	6
59	294.90	II	285.32	11
59	294.90	III	245.15	5
60	350.00	III	216.29	42
61	294.90	II	127.22	7
62	294.90	II	140.80	8
63	294.90	III	278.78	18
64	294.90	III	277.85	17
65	294.90	III	279.63	19
66	294.90	III	276.70	15
67	294.90	III	298.95	16
68	294.90	IV	453.29	6

(continue)

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69	294.90	I	143.58	12
70	650.00	III	626.78	22
71	320.00	III	315.87	20
72	294.90	III	292.54	21
73	294.90	III	120.85	37
74	294.90	II	34.29	3
75	294.90	II	38.05	4
76	294.90	II	26.93	5
77	294.90	II	40.78	6
78	294.90	II	270.00	1
79	294.90	II	268.48	2
Poultry manure				
1	5.88	III	0.00	10
2	1,751.56	III	450.77	7
3	214.48	III	64.29	9
4	482.16	III	197.24	8
5	489.34	IV	800.30	3
6	275.20	I	201.26	1
8	84.11	III	46.51	2
9	211.78	III	153.98	1
10	0.82	II	0.00	4
11	0.43	II	0.00	5
12	1,151.11	II	1078.57	3
13	1,341.26	IV	797.95	5
14	30.66	IV	11.71	4
15	43.00	IV	14.61	1
16	54.05	IV	11.29	2
17	417.62	III	283.93	3
18	12.86	III	0.00	6
19	21.50	III	13.56	5
20	14.58	III	0.00	4
21	107.97	II	47.69	1
22	92.75	II	71.59	2
Silage				
1	5.40	III	0.00	10
2	182.10	III	247.66	5
3	433.90	II	251.11	12
4	4.50	III	0.00	6
5	738.80	IV	1389.37	11
6	738.80	IV	1077.44	7
7	738.80	IV	1310.40	10
8	15.70	IV	4.13	1
9	652.40	I	322.17	7
10	652.40	I	285.74	12

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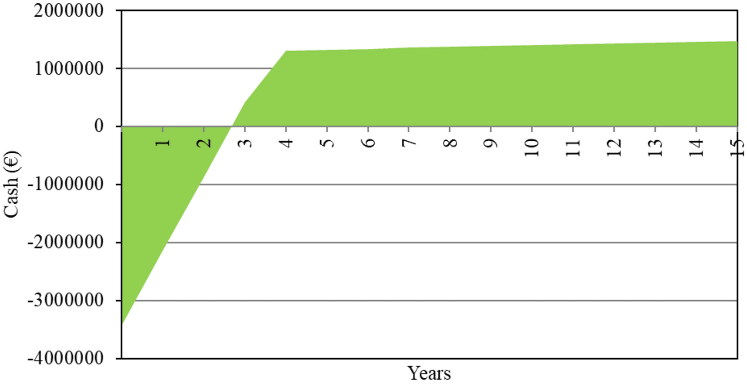
11	652.40	I	351.37	2
12	652.40	I	411.28	6
13	685.80	II	910.52	8
14	685.80	I	875.81	15
15	685.80	II	723.31	9
16	38.50	IV	18.69	2
17	600.00	II	394.47	13
18	600.00	III	482.51	3
19	600.00	II	422.32	15
20	69.30	I	22.89	1
21	22.50	III	12.40	1
22	721.30	I	469.51	4
23	520.80	IV	678.73	9
24	520.80	IV	663.03	8
25	669.60	IV	1073.12	6
26	669.60	IV	978.06	5
27	9.20	IV	0.00	13
28	43.10	I	26.99	5
29	349.60	II	130.63	2
30	413.50	I	237.52	11
31	413.50	II	246.15	7
32	72.60	I	39.37	10
33	25.10	II	27.26	14
34	74.80	III	52.96	4
35	54.10	II	28.19	6
36	276.80	II	281.65	11
37	4.00	IV	0.00	14
38	354.30	I	467.13	13
39	354.30	III	322.28	7
40	538.60	I	716.85	14
41	538.60	I	418.41	16
42	538.60	II	492.00	10
43	609.20	III	981.53	8
44	609.20	IV	676.95	4
45	609.20	IV	544.03	3
46	2.20	I	0.00	8
47	176.80	I	86.20	9
48	0.70	III	0.00	2
49	1.60	IV	0.00	12
50	38.40	II	2.50	1
51	7.50	III	0.00	9
52	674.80	II	347.49	3
53	674.80	I	464.97	3
54	674.80	II	484.37	4
55	674.80	II	572.28	5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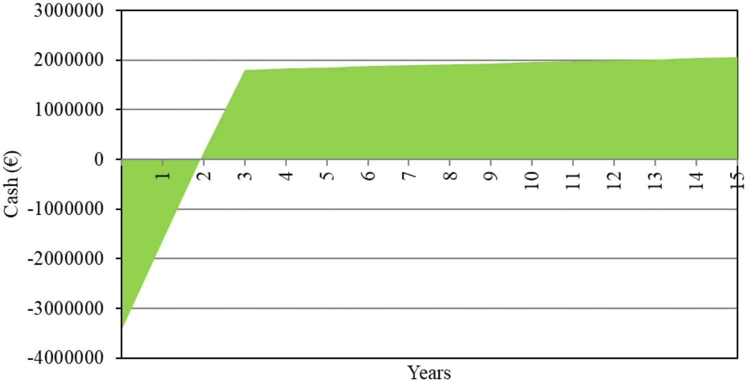
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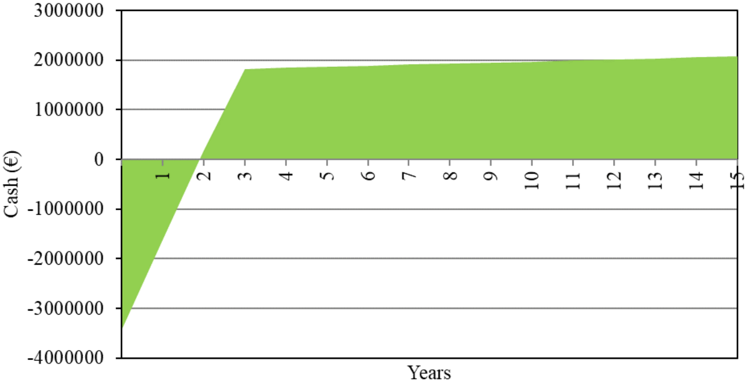
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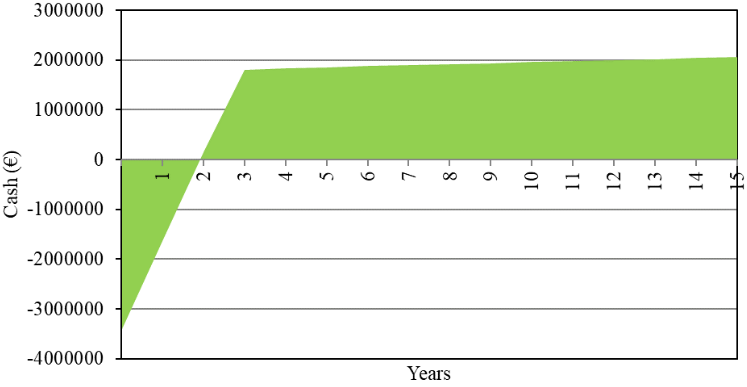
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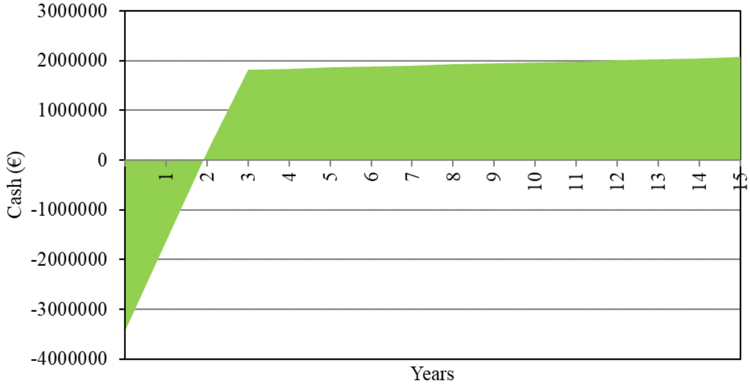

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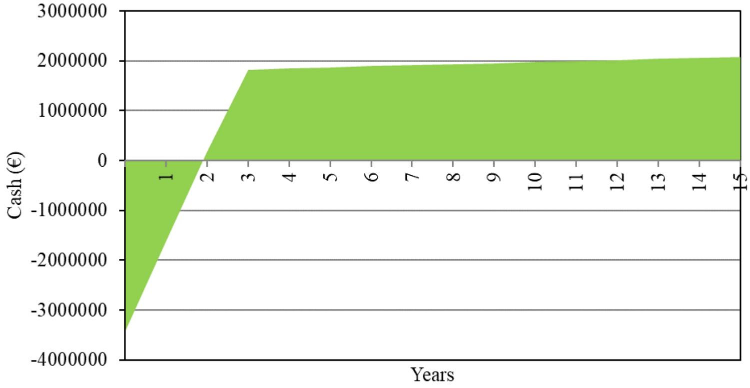
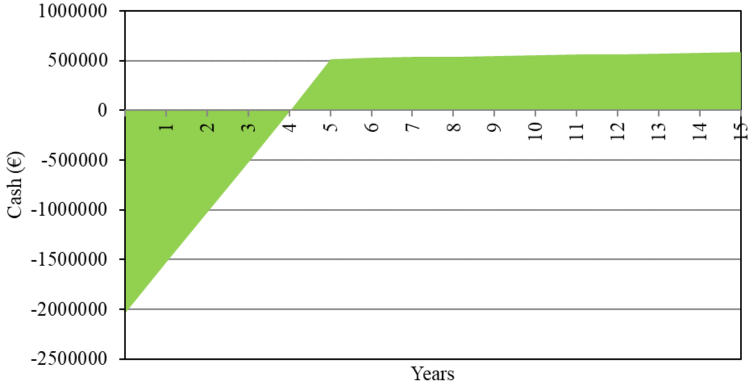


(f)

Figure S 1. Sensitivity analysis on cash flow of Plant I. (a). Electricity revenue; (b). Solid digestate revenue (c). Transportation cost (d) Corn silage cost; (e). Digester operation cost; (f). CHP operation cost.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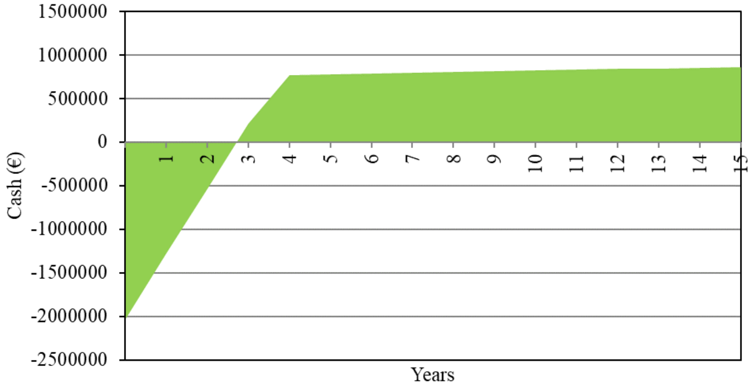
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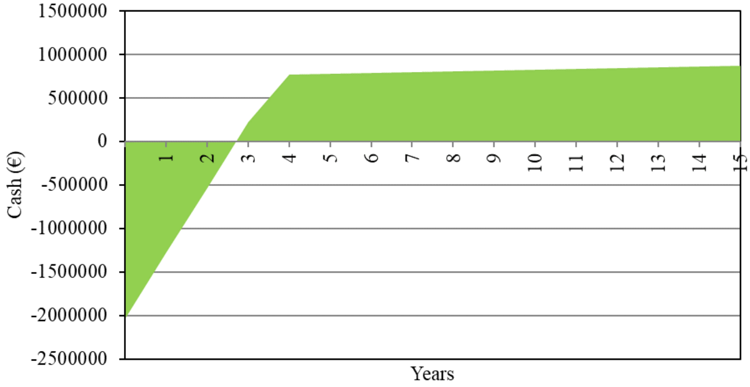
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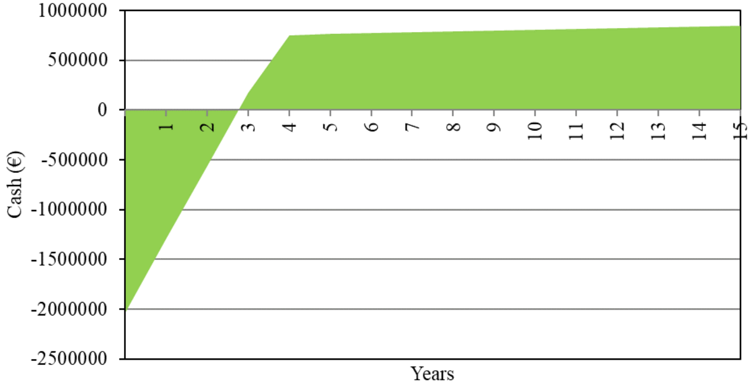
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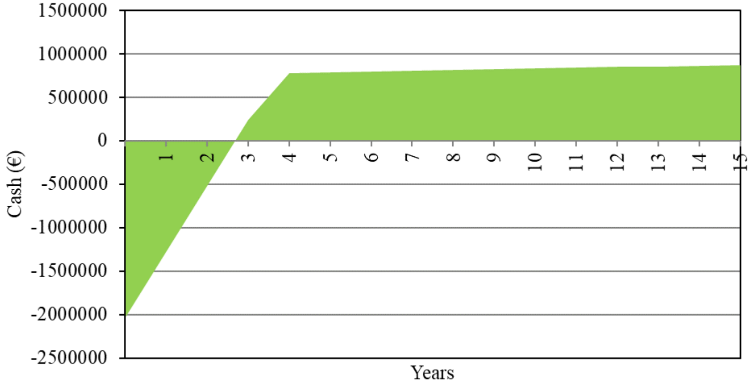

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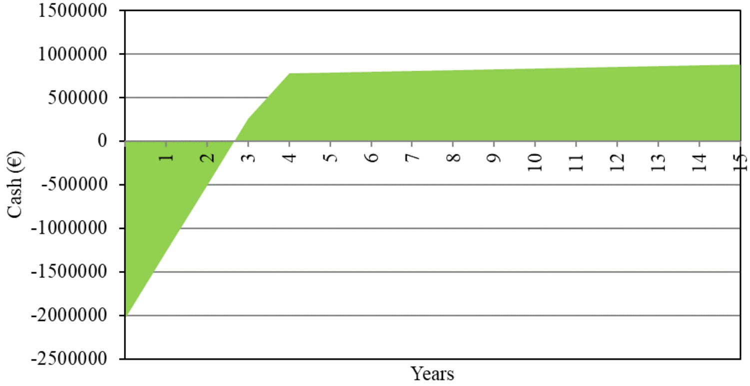
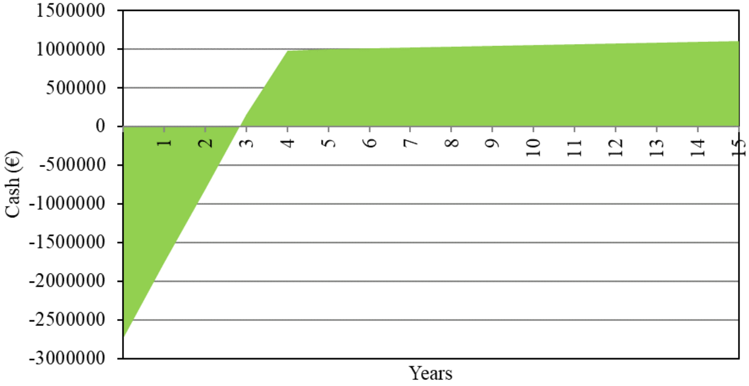


(f)

Figure S 2. Sensitivity analysis on cash flow of Plant II. (a). Electricity revenue; (b). Solid digestate revenue (c). Transportation cost (d) Corn silage cost; (e). Digester operation cost; (f). CHP operation cost.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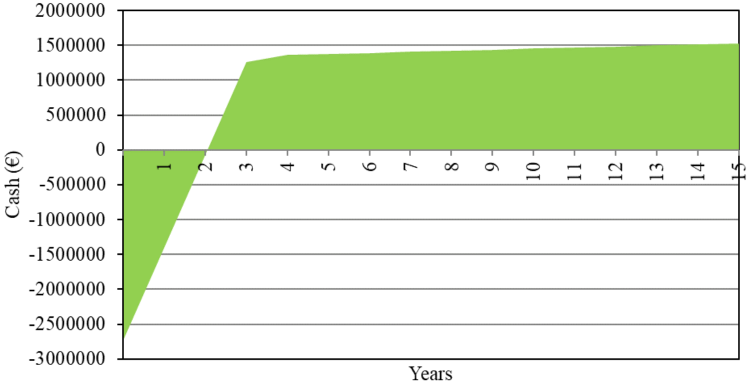
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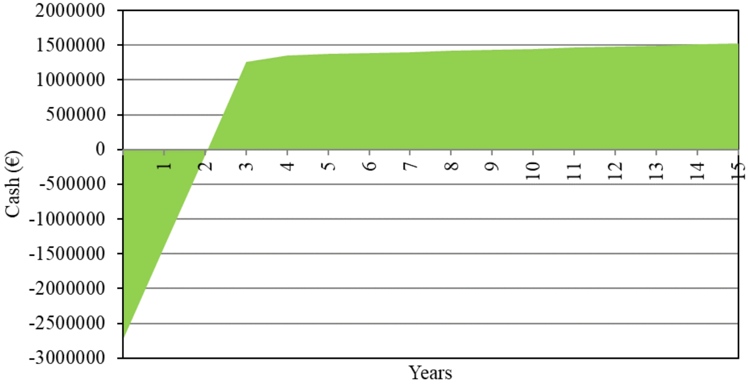
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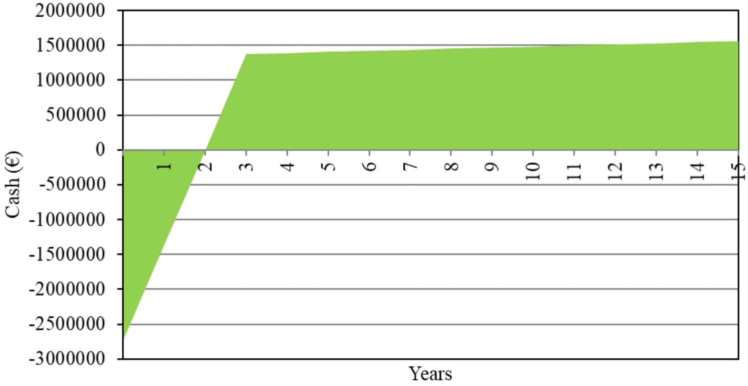
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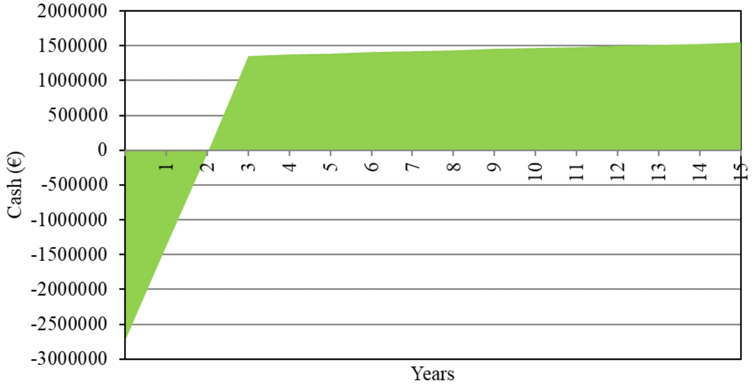

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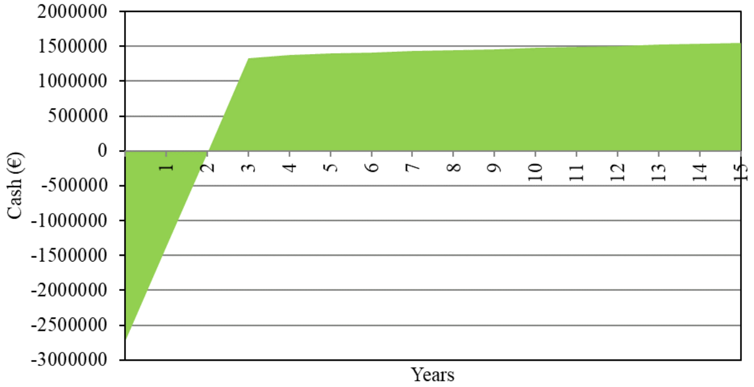
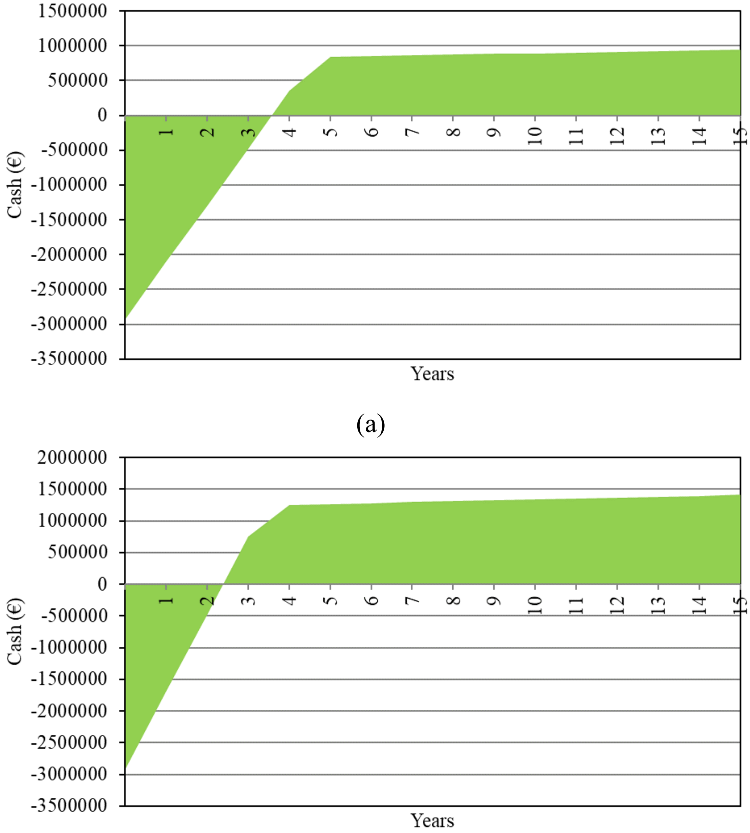


(f)

Figure S 3. Sensitivity analysis on cash flow of Plant III. (a). Electricity revenue; (b). Solid digestate revenue (c). Transportation cost (d) Corn silage cost; (e). Digester operation cost; (f). CHP operation cost.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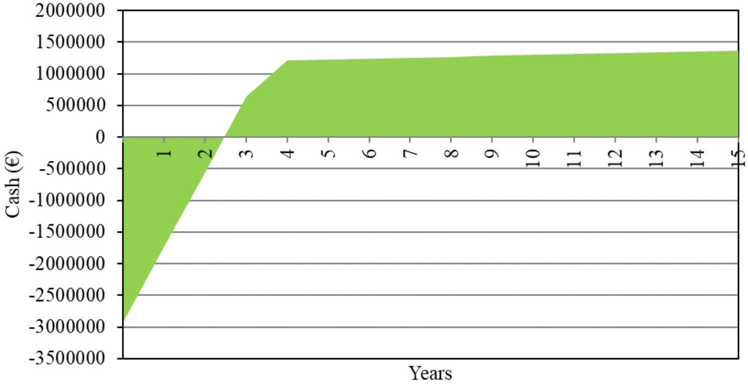
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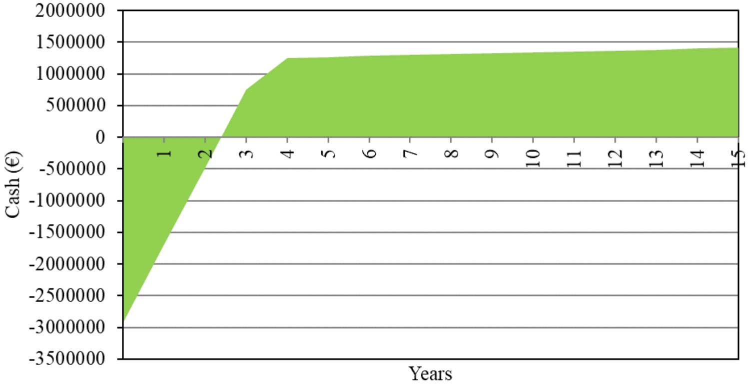
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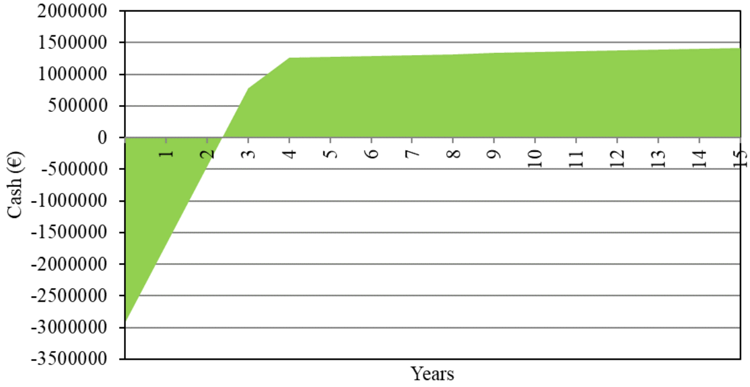

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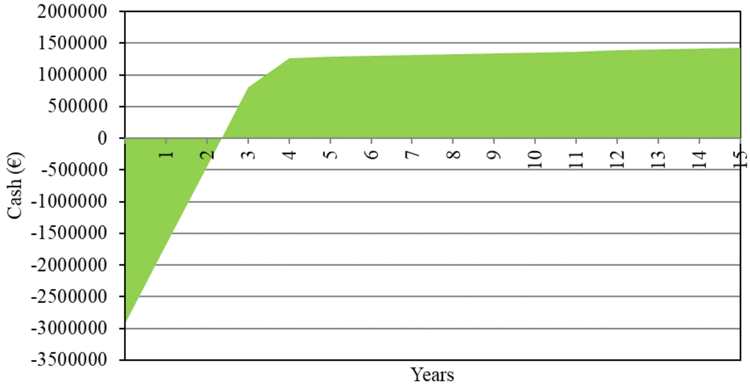

(f)

Figure S 4. Sensitivity analysis on cash flow of Plant IV. (a). Electricity revenue; (b). Solid digestate revenue (c). Transportation cost (d) Corn silage cost; (e). Digester operation cost; (f). CHP operation cost.