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Optimization of Semy-Dry anaerobic digestion for a wider diffusion of the Food Waste treatment for energy recovery

Technical and Economic evaluation

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ABSTRACT

Currently, large plants are the most favoured approach for the anaerobic treatment of the organic fraction of municipal solid waste (OFMSW). However, centralised solutions imply certain limitations which prevent large-scale implementation of the anaerobic digestion (AD) of food waste for energy recovery. As a result, we are digesting less than 5% of organic waste both in Europe and the USA even today. Pursuing the criteria for maximising the balance between profit and impacts, an innovative layout with the ultimate goal of promoting the use of small, easy-to-operate AD plants is proposed. The purpose of the research is to investigate the better way to apply the Semi-Dry approach to the OFMST treatment, with fermenters that can manage to treat the biowaste as it is (feeding with TS>20-25%), with no dilution or any co-substrate addition needed. A source-separated OFMSW (SS-OFMSW) was treated in a mesophilic plug flow reactor by applying an atypical combination of conditions such as high SS-OFMSW solid content (214.5 g·kg-1), high organic loading rate (6.2 kg VS·m-3·d-1), and no dilution or co-substrate addition. A suitable and an efficient mixing system is essential to control the process. Accordingly, the process was stable in a single-stage reactor, in the absence of digestate recirculation, obtaining specific gas production of 0.67 m3·kg-1 VS in terms of biogas and 0.41 m3·kg-1 VS in terms of methane. High reactor volume exploitation and small plant construction were feasible, reaching a gas production rate of 4.5 m3·m-3 d-1. Costs in terms of capital and operating expenditure are estimated, and an economic evaluation is carried on to study the economic sustainability of full-scale installation at different plant sizes.

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1. OVERVIEW OF THE RESEARCH PROJECT

1.1 Industrial PhD – Schmack Biogas Srl

Schmack Biogas is a company born in Germany in 1995 as answer to the increasing interest that EU and the national regulators were starting to give to the Anaerobic Digestion (AD), as a technique able to meet the environmental protection to the needing of new renewable energy solutions. Being between the firsts to focus its business in the sole supply of AD technology, the company is today an international leader in the market, able to offer solution for the anaerobic treatment of any type of biowaste (agro-wastes, Organic Fraction of Municipal Solid Waste OFMSW, wastewater sludges) or energy crops. Schmack Biogas in particular developed cutting-edge solutions for the treatment of solid or highly fibrous materials, making the Semi-Dry approach its main distinctive character. With Schmack Biogas technology, over 450 plants have been installed in 18 countries worldwide, 56 of which in Italy. Its aim strongly orientated in innovation led the company to undertake a partnership with the Ca' Foscari University of Venice and to support an Industrial PhD program, of which the present work is the conclusion.

1.2 Purpose of the Research

In the field of the Organic Fraction of Municipal Solid Waste (OFMSW) treatment, AD usually applies a Dry approach, in which the waste is treated as solid substrate after have mixed with a lignocellulosic fraction. Less diffused but still common, is the Wet approach, where the biowaste is diluted with water and processed in large digesters where Total Solid (TS) content is usually in the range of 5-7%. The purpose of the research is to investigate the best way to apply the Semi-Dry approach to the OFMSWT treatment, with fermenters that can manage to treat the biowaste as it is (feeding with TS>20-25%), with no dilution or any co-substrate addition needed. The ultimate target is to promote the diffusion of smaller and easier-to-manage fermenters, in order to support a worldwide increasing of the worldwide total OFMSW amount treated with for energy recovery and to permit the sustainability of decentralized treatment plants.

1.3 Content of the Research project

The whole research can be divided into four main sections, each of which aimed at a specific goal and preliminary to the next part of the research. The four main sections are schematically summarized in table 1. Each section has its specific conclusions.

INTRODUCTION	Analyse the availability of OFMSW in EU, the fraction currently treated with energy recovery and how much is still potentially available for AD as opportunity for new installations. Analyse strengths and weaknesses of the traditional approaches in AD in term of TS content, mono or co-digestion, single or double phase reactor; and understand if an unusual approach could give a technological improvement.
STUDY OF PRETREATMENT SYSTEMS	Identify the ideal system for OFMSW pre-treatment (purification by inert contamination) to produce a clean but solid organic pulp for a Semi-Dry fermenter
PILOT SCALE EXPERIMENTATION	Understand if the anaerobic process can be sustained at high OLR and by feeding OFMSW with no dilution (high TS content); understand if the steady state is possible with no recirculation in order to make the plant operation easy; calculate the biogas production parameters (Specific Gas production, SGP) and the other process parameters to upgrade the pilot scale results at the full scale
ECONOMIC EVALUATION	Evaluate the economical sustainability for a full scale upgrading with the experimental values from the research. Estimate the Capital Expenditure (CAPEX) and the Operating Expenditure (OPEX) for different scenarios and study how the economical sustainability varies according to the size plant.
CONCLUSIONS	TECHNICAL CONCLUSION: process parameters at steady state with high OLR and highly solid OFMSW fed. ECONOMICAL CONCLUSION: treatment cost per ton of OFMSW according to the plant size, profitability of a full scale Semi-Dry installation, economical sustainability of decentralized plants.

Figure 1: schematic summary of the Research content

2. INTRODUCTION

2.1 State of Art

The Waste Framework Directive (EU Directive 2008/98/EC) introduced in Europe to support the treatment of OFMSW for energy recovery and its subsequent amendments (EU directive 2018/851/EC) have encouraged the widespread use of AD plants in European countries (Murphy and Mckeogh, 2004). Literature on OFMSW treatment capacity and number of installed AD plants in Europe is not up to date, and this lack of updated data has also been reported in other regions (Clarke, 2018). A recent review reported that in 2014, there were 244 AD plants with an overall treatment capacity of 8 million tons of OFMSW across 17 European countries (De Baere et al., 2012). Albeit less specific, more updated data were published by the European Biogas Association (EBA) in their annual reports; according to EBA, in 2016, there were 17,662 plants, a number that had increased by 283% since 2009. Most of these plants are fed with agricultural residues, and agri-waste plants accounted for 70% of 12,496 installed AD units. Based on food waste treatment capacity, there were 688 AD installations fed with generic biowaste (municipal, household, and industrial wastes) in 2016 (European Biogas Association (EBA), 2017). At present, only 5% and 2% of the food waste in Europe and the USA, respectively, are sent for AD treatment (Clarke, 2018).

2.2 Traditional approaches in AD

When OFMSW must be subjected to AD, to select the process configuration the choice is done considering the following three aspects (Hartmann and Ahring, 2006):

1. The actual TS content of the digestate inside the fermenter;
2. The necessity to add any co-substrate to the OFMSW and in case the type of co-substrate added;
3. The process configuration (single-phase versus two-phase).

A brief analysis of typical conditions applied in full-scale AD plants was conducted, with the objective of identifying the benefit of each process condition and the reason they don’t support a real proliferation of AD plants. Based on the results of this analysis, a different approach is proposed, compiling the best operative conditions to facilitate the creation of an efficient and a sustainable AD plant network. Those best operative conditions are then used to design the pilot experiment.

2.2.1 Low Solid vs High Solid Anaerobic Digestion

A common AD process classification is done according to the TS content of the substrate: TS below 10% determines the Wet process (or low-solids, LS) and TS above 15% determines the Dry process (or high-solids, HS) (Hartmann and Ahring, 2006). Wet digestion is the most advanced technology with the benefit of permitting an easy-to-control process, even if it accounts the 40% of the AD installations in Europe, (Panigrahi and Dubey, 2019). Dry digestion, such as the Valorga, Dranco, Kompogas, and Linde (TS > 15%) (Fagbohungbe et al., 2015) processes, account 60% of the European installations and have the key advantage of reduced reactor volume. However, shortcomings of both techniques have been recognised. For instance, LS digesters require dilution, which leads to sedimentation of heavy materials, in addition to a large reactor volume and a very low TS content in the effluent digestate (Kothari et al., 2014) (Rico et al., 2011). HS digestion shows low degradation efficiency and biogas production (Pastor-Poquet et al., 2018) (Fagbohungbe et al., 2015) (Di Maria et al., 2017) (Abbassi-Guendouz et al., 2012) (Le Hyaric et al., 2011) (Veluchamy and Kalamdhad, 2017). The feasibility of using HS content in small-scale digesters for AD has already been investigated and limited methane production was noted (Fagbohungbe et al., 2015). In this context, intermediate working conditions between LS and HS digestion, in the absence of dilution or co-substrate addition, would probably achieve an higher Gas Production Rate (GPR), which is an indicator of highly efficient reactor volume exploitation. Therefore, this approach would be interesting when the target is to build easier AD plants with smaller reactors.

2.2.2 Mono-digestion vs co-digestion

Regarding the co-substrates added, co-digestion with green waste and sewage sludge is largely preferred over mono-digestion to prevent and control toxicity (Tyagi et al., 2018) (Mata-Alvarez et al., 2000) (Siddique and Wahid, 2018) (Mehariya et al., 2018) (Zhang et al., 2018), as well as to optimize the C:N ratio (Bolzonella et al., 2018). Nonetheless, certain negative effects of co-digestion in full-scale plants have been reported (Ortner et al., 2014). Green waste is often not available at the same treatment site as food waste (Davidsson et al., 2007), leading to collateral logistics problems; moreover, co-digestion requires more complex engineering (for pumping, mixing, and so on) because of the addition of the lignocellulosic fraction. Co-digestion with sewage sludge requires an upgrade of the existing wastewater treatment plant, which is often difficult considering financial constraints and policy restrictions. In addition, co-digestion of OFMSW with sewage sludge produces a digestate enriched in heavy metals, rendering its reintroduction into agriculture more difficult than that of pure OFMSW digestate (Cavinato et al., 2013). Hence, although co-digestion is a common condition, when the target is to promote small, easy-to-operate AD plants for OFMSW, mono-digestion should be adopted.

2.2.3 Single-phase vs double-phase

Regarding the process, a two-phase approach is more beneficial for kinetic, biological, and operational reasons (Jo et al., 2018) (Chinellato et al., 2013) (Browne and Murphy, 2014) (Mattioli et al., 2017). A single-phase digestion system would, however, be less expensive and produce a smaller impact on soil consumption, ultimately promoting the use of small AD plants in European countries.

2.3 Condition applied for the pilot experiment

To overcome the limitations of the conventional installations, an uncommon mix of conditions is applied at the pilot scale to investigate if the process could lead to biological stability. This atypical layout involves the following:

1. Semi-dry digestion (to gain the benefits but overcome the limitations of both wet and dry AD)
2. A single-phase reactor (to minimise costs and impacts of digester construction)
3. Mono-digestion of undiluted OFMSW (to avoid the disadvantages of co-digestion)

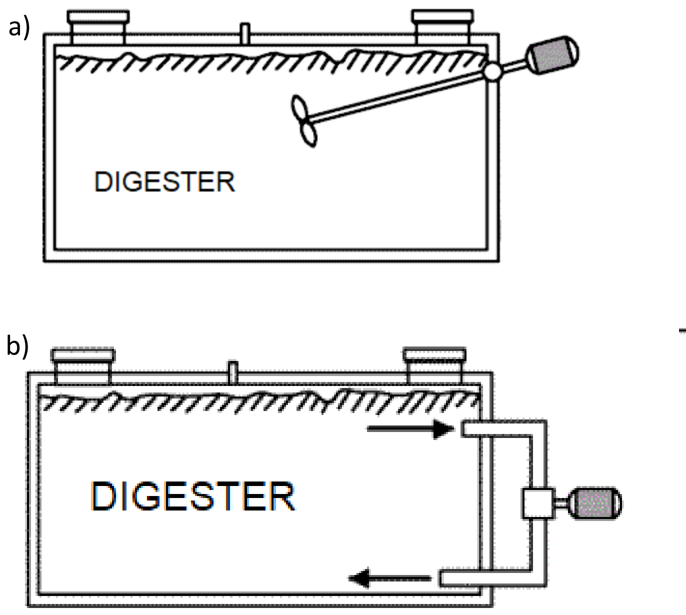


Figure 2: Types of common wet anaerobic digesters: a) submergible mixers, b) hydraulic mixing, c) gas mixing (Energypedia, 2021)

Those conditions are usually never applied together because of mechanical limits of the technology usually applied to AD fermenters. In particular, reference is made to the stirring system. Traditional stirring systems in AD fermenters are three: mixers, gas lifters and pump mixing systems. Figure 2 shows schematically the three different systems. All those systems are unable to handle a digestate where the TS content implies a viscosity too high to assure proper turbulence in the fermenter (above 8-10% of TS they start to be unsuitable) (Karim et al., 2005). For this reason, any choice in plant design has traditionally been limited by the necessity of keeping the TS content in the digestate adequately low (Ward et al., 2008) (Lindmark et al., 2014). The very deep experience made in the last twenty years with biogas plants, where the treatment of energy crops imposed to find a solution for handling very dense materials in the fermenters, has made available new and strong solutions. In this field Schmack Biogas has a strong know-how, as the possibility of treating dense and very fibrous materials has always been a core and distinctive character of the company. The possibility, given by a PFR reactor, to have a long mixer system that runs along the entire length of the fermenter, with paddles that continuously break the surface and almost scrape the bottom avoiding crusts formation, sediment deposition and shady areas not properly mixed, made the applicability of the above conditions concrete. An overview of a PFR reactor for Semi-Dry anaerobic digestion is shown in Figure 3.

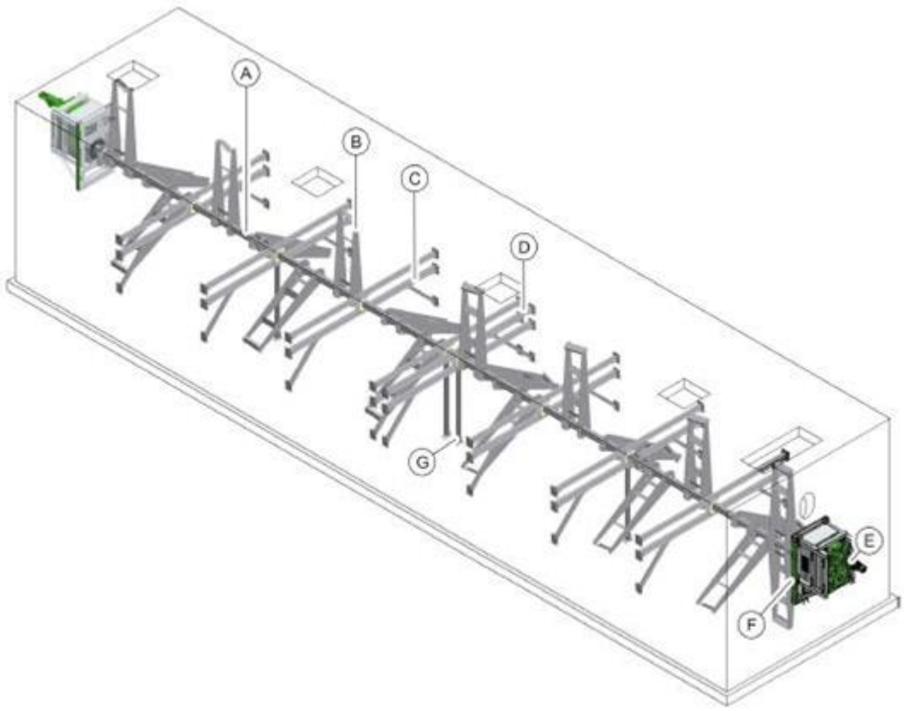


Figure 3: PFR reactor for Semi-Dry anaerobic digestion

3. STUDY OF THE PRETREATMENT SYSTEMS

3.1 Introduction and Purpose of the study

When we deal with OFMSW, with mechanical pre-treatment it is meant a sorting system used to process the organic waste before entering to the fermenter. The operation is only mechanic, and it is operated by a combination of chipping, grinding or milling, depending on the type of system. The scope of the pre-treatment is priorly to remove the non-organic contaminants by means of physic, dimensional, gravimetric and magnetic property, to adjust humidity and produce a homogenized pulp with ideal TS content, according to the type of digestion (Wet or Dry). The size and crystallinity reduction of particles, as for example of lignocellulosic materials, is also an important achievement that increases the specific surface area of the organic particles and leads to a better methane conversion efficiency (Hilkiah Igoni et al., 2008). The choice of the more adequate sorting technology is usually a compromise between stream separation efficiency, TS content and particle size in the effluent material, installation costs, maintenance costs, energy requirement and all the operating costs in general. Between them, the particle size of the output is a very important factor because it implies not only the degradation rate of the organics, but also the viscosity of the effluent, that is the main parameter to influence mixing efficiency in the fermenter (Jiang et al., 2014). Sedimentation problems and floating of non-biodegradable plastics from light fractions able to form a solid blanket, is also another not negligible detail (Ritzkowski et al., 2006).

On the techniques of mechanical-biological pre-treatment of municipal solid waste, literature is quite weak. Some authors studied the variation of the chemical characterization of the OFMSW according to different sorting techniques, but they did not consider particle size (López et al., 2010). Other authors did a granulometric characterization of the organic waste size particles, but the study was conducted as function of the degradation rate (Zhang and Banks, 2013). They also reported the lack of similar comparative studies. Only few comparative studies were found in literature (Giuliano et al., 2011) (Zhang et al., 2019). Other authors did a similar study but they focused only on particles larger than 1 mm (Hansen et al., 2007).

Purpose of this part of the research is to systematically characterize the output material produced by three different mechanical pre-treatment systems, and to understand how the TS and VS are distributed within the granulometric classes. The three pre-treatment systems are chosen between the one widely applied at the full scale. The reject plastic material was also sampled to measure the residual organic contamination and their residual humidity.

3.2 Materials and Methods

3.2.1 Sampling strategy

Samples used for this study were collected from three different OFMSW treating plant, each of them provided with a different sorting system: hammer mill, wet pulper and extrusion press. All the three plants are located in north of Italy and they all treat Source Selected OFMSW (SS-OFMSW). The samples were collected over a period of a year, in three different seasonal conditions: for each plant, four samples were collected in the middle of the winter, four samples in the middle of the summer and the last four sample in midseason conditions. The average environmental temperature is 6-8°C for the coldest season, 24-26°C for the warmest season, and intermediate values for the middle season (ISPRA, 2015). In each season, the four samples were collected one per week over a period of a month, trying to avoid to sample in the same day of the week. The samples were collected in a 4-L vessel from the full-scale pre-treatment machinery under normally operating conditions, and then frozen within the next 2 hours. No details were known about how long the OFMSW was in urban waste lorry before arriving at the treatment facility. The reject plastics were collected and stored in a 6-L plastic bag and kept frozen at -18°C.

3.2.2 Analytical Methods

For a granulometric analysis of the OFMSW, a proper standard method is not available. The problem of defining a standardized procedure to use as descriptor of particle size in solid wastes is well described by other authors, they also give an explanation of the main contributing factors (Von Blottnitz et al., 2002). A reference method (APHA-AWWA-WEF, 1998) is available for wastewaters, but it cannot be considered strictly representative due to the fact that the food waste is much less heterogenous and have much different size particles respect to a typical wastewater sludge. For OFMSW, some authors rather suggested to use an approach similar to the one used for mineral processing, in which the application of semi-empirical knowledge, and of fundamentals, is common and shows great benefits (Von Blottnitz et al., 2002).

According to this premise, for the present research the OFMSW characterization was operated as initially suggested by Laguna et al. (1999) and then adopted by other authors for investigations in similar materials (Laguna et al., 1999) (Mahmoud et al., 2006) (Zhang and Banks, 2013) (Karr and Keinath, 1978) (Zhang et al., 2019). To perform the screening, an automatic shaker (Retsch AS200 Digit) provided with 8 stainless steel sieves with different mesh opening and with a diameter of 200 mm or 100 mm were used. The eight different mesh sizes were 20, 10, 5, 1, 0.5, 0.25, 0.125 and 0.063 mm. The sieves were mounted vertically one on the top of the other in increasing order of mesh opening, the finest at the bottom, the widest at the top. The column of sieves was covered at the top with a disk provided with nozzles for spraying water during the analysis, water came from water tap. At the bottom, the sieves were mounted on a disk provided with a collecting pipe to discharge the percolation water. The separation in granulometric class, according to the different mash sizes, was facilitated by a strong vibration procured by the instrument and held for 30 minutes with abundant effluent water. Before the analysis, the sample was carefully homogenized and divided in two rates. On the first, TS and VS were analysed in the sample as it is (APHA-AWWA-WEF, 1998). The second rate was weighted and then processed in the automatic shaker. After sieving, the particles retained on the different screens were recovered by a backwash using water and collected in aluminium trays for TS and VS analysis. Once the amount of the TS and VS retained on each sieve, was determined, it was possible to calculate by simple difference the total amount of solids lost correspondent to the fraction finer than the 0.063 mm grid. For each class of size, results were hence reported as percentage of the total weight that they represent.

The choice of mesh dimensions was done according to previous experiences. Levine et al. (1991) defined, as important value, a mesh of 0.1 mm because particles under this size are defined supercolloidal: they cannot be considered solubilized but they show a readily degradable behaviour and for this reason they have important repercussions on the process biochemistry (Levine et al., 1991). Giuliano et al. chose the mesh of 0.25 mm as the finest size, and they found almost all the solids under this dimension(Giuliano et al., 2011). Having only few reference experiences, to be able to collect as much information as possible, the mesh sizes were set as above described.

On the reject plastic, no reference studies were found in literature. The analysis was conducted as manual sorting according to ISWA recommendations (ISWA International Solid Waste Association, 2017). The sample was first weighted and then manually sorted, separating the organic residual from all the inert material. Each fraction was weighted in order to quantify the percentage of organic contaminant in the reject material. On the organic fraction TS and VS were also measured in order to obtain a characterization of the quality of the organic compound. On the inert material, only the TS were measured in order to calculate the moisture content.

3.3 Description of the pre-treatment systems

3.3.1 Hammer Mill

Hammermills are a popular type of shredder applied since many years for size reduction of very different materials and for different applications (mainly in the mining industry, food/agricultural industry, waste industry). The core of the system is a radial rotor with hammers attached to the rotor by means of pins. When the rotor is rotating, the hammers are free to swing perpendicular to the rotor, and by inducing impact or shearing forces they produce the waste fragmentation. Input solid waste is generally fed from the top by gravity. Output material is expelled through screens in the drum of a selected size. Input material remains in the hammermill until it is small enough in at least two dimensions to fall through the grate opening. Different openings size of the external grate controls the output material size (Ananth and Shum, 1976) (Kratky and Jirout, 2011).

The Hammer Mill selected for the research is manufactured by Wackerbauer GmbH, (Ampfing, DE), model Type TM 75. The separation mill works with a specially developed patent-protected principle, and special hammers design, that operates mechanical unpacking, grinding, separating and washing of the impurities by one machine. The heavy impurities are mechanically transported to the ejection point, the light fraction of the impurities is separated by air according to a low weight. A 10 mm grid is used to limit the particle size of the grinded material. A simple screw press is integrated in the ejection chute, which squeezes the rest of the liquid out of impurities. This stream of inert material accounts for about 20% of the food waste to the plant (on wet mass). A liquid supply is necessary for the very optimal function of the separation mill, both for allowing efficient separation than for wash the reject inert material. The liquid consumption is self-regulated according to the current consumption of the drive motor. Water consumption depends on solids ad impurities content of the waste and is approximately 1 $m^3 \cdot t^{-1}$ of food waste treated. An electrical 75 kW engine powers the main drive. The milling process capacity is 25 $m^3 \cdot t^{-1}$ of input waste, that is equal to 12-20 $t \cdot h^{-1}$ according to the specific weight of the input waste. Figure 4 shows the mentioned machinery and a detail of the spare hammers.

The Hammer Mill selected is installed into the Rovereto (TN, Italy) Waste Water Treatment Plant (WWTP) that treats 13,000 $m^3 \cdot d^{-1}$ of mixed wastewaters and 140 $m^3 \cdot d^{-1}$ of liquid wastes (landfill leachate, winery wastewaters and septic tanks). The Hammer Mill serves the wet anaerobic line that receives 10 t per day of OFMSW separately collected in the city of Rovereto (Mattioli et al., 2017).

Figure 4: The Hammer Mill that provided the sample for the granulometric analysis and a detail of the spare hammers

3.3.2 Extrusion Press

The Extrusion Press is a sorting system where the waste is physically separated into a wet fraction and a solid fraction by applying a very high pressure. The waste is squeezed into an extrusion chamber by the application of a pressure usually generated by a piston. The liquid-organic fraction is extruded out of from extrusion holes, that are appositely made on the extrusion chamber. The portion of the input waste retained in the chamber constitutes the dry-reject fraction, where all the inerts accumulate (Cesaro et al., 2021). Extruders are not typical size reduction machines, however, due to their abilities they have been often tested for biomass disintegration (Kratky and Jirout, 2011). Respect to the other mechanical food waste pre-treatment systems, due to the high-pressure nature of the process, the press-extrusion promotes not only the reduction of OFMSW particle size but also the solubilisation of the organic material. This is an important feature of the technique, because it is reported to improve the biodegradability of the organic material. Depending on the intensity of the mechanical stress induced by extrusion, the thermal degradation of sugars and amino acids can also occur (Cesaro and Belgiorno, 2014). Other authors even reported the occurring of cellulose, hemicellulose or protein depolymerization (Xu et al., 2016). A schematic representation of the machinery is reported in Figure 5.

Beside the technique is today quite largely applied for Municipal Solid Waste (MSW) treatment, and few studies have deepened the treatment consequences under the chemical-physical point of view (Xu et al., 2016) (Hjorth et al., 2011) (Mu et al., 2018), very little is known about mechanical details of the machines and their full scale experience. This is because these systems are usually patents, and manufacturers usually allow the proliferation of only few technical details (Cesaro and Belgiorno, 2014).

The Extruder Press used for the present research have a treatment capacity of 15-18 $t \cdot h^{-1}$ of OFMSW, according to the degree of impurities. The system requires a liquid addition of 8-10 $m^3 \cdot h^{-1}$ that is produced separately by the exhausted anaerobic digestate with a screw press. The operational pressure varies with the season. On summer, for liquefaction phenomena due to high temperature during transportation, the OFMSW is delivered more liquid and so a lower squeezing pressure is needed. In summer the applied pressure is on average 180-190 bar. During wintertime, the OFMSW is delivered with higher TS content so an higher pressure must be applied to obtain an acceptable separation efficiency. In winter the applied pressure is on average 240 bar. The extrusion holes on the extruding chamber have a size of 10 mm in the lateral sides, and 14 mm in the front side. The machinery is manufactured by VM Press Srl (Ovada, AL, Italy). The Extrusion Press is installed in an anaerobic digestion plant treating OFMSW and agriculture feedstocks. The OFMSW is normally collected in the around area but can be delivered also from long distance that requires up to one or two day for the transportation. The author did not have the authorization to report further details of the mentioned machinery. As example, a screw press produced by another manufacturer is reported in Figure 6.

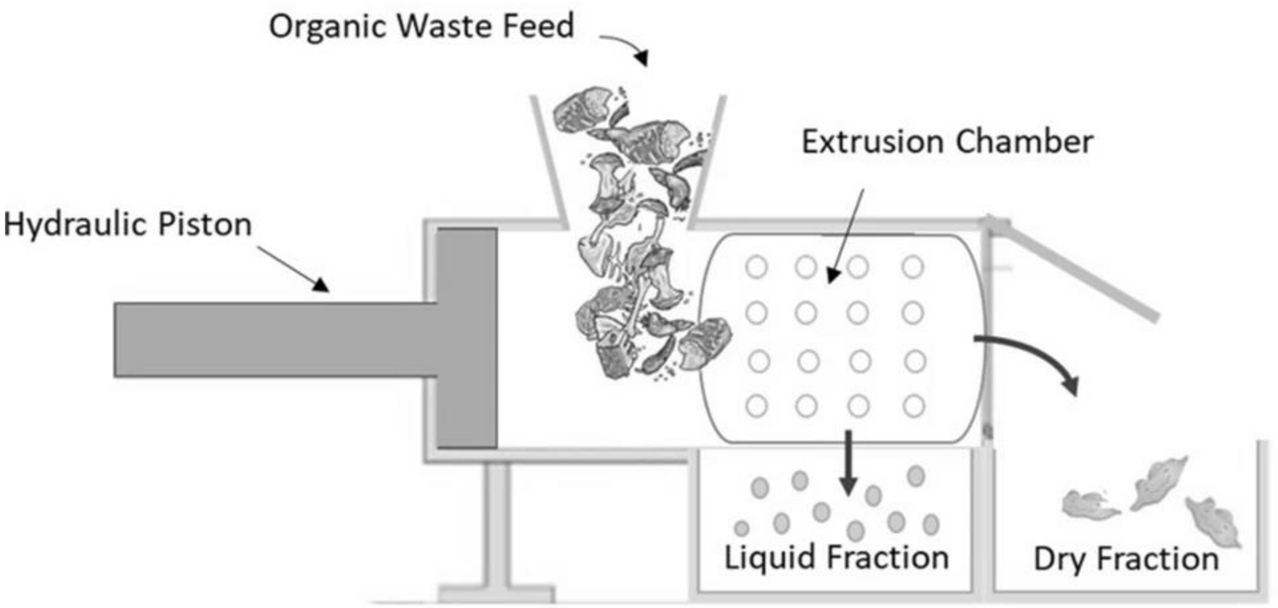


Figure 5: Schematic representation of an Extrusion Press (Cesaro et al., 2021)

Figure 6: Anaergia's Organics Extrusion Press (OREX™), from online manufacturer webpage

3.3.3 Combined System

The combined System selected for the research is a sorting system manufactured by Cesaro Mac Import Srl (Eraclea, VE, Italy). The machine is patented as TIGER DEPACK® and specifically the installed model is the Tiger DSP 25-5. The system is designed for de-packaging, sorting and homogenization of OFMSW sent to anaerobic or aerobic treatment, where the purity of the material is a key factor to assure a closed cycle on the waste treatment process (because of high quality digestate or compost production). The system combined a cochlea with a patented vertical centrifugation process. The cochlea acts as rough “bag opener”, because conveying the waste inside a narrow opening, it involves the coarse fractionation of the larger materials. The food waste is hence delivered at the basis of a vertical rotor. The rotor is run at high-speed rate and is provided with blades and knives with a specific shape and inclination to raise and pulp the food waste. The bladed rotor is installed inside a cylindrical filter with defined mesh opening to allow the spill of the smashed organic fraction and to retain the inert contaminants. The separation of the organics by the inert material is done according to the weight. The heavier fraction (organic fraction), because more susceptible to kinetic energy, is squeezed out from the vertical filter and collected at the bottom of the machine. The lighter fraction (bags, plastics, fabrics etc), due to the upward thrust created by the rotating rotor, is able to reach the upper exit of the vertical filter after have been cleaned by the organic fraction adhered to their surfaces. A small amount of liquid can be added to favour the washing of the light inert materials and adjust the TS on the organic pulp according to its destination.

The selected machine is installed in the Biociclo Srl composting plant of Castiglione delle Stiviere (BS, Italy). The plant serves a catchment area of more than 400,000 inhabitants and treats 32,000 t of OFSW, 12,000 t of garden wastes and 3,000 of wastewater sludges, per year. The food waste (kitchen waste only) is gathered in compostable biowaste bags and comes to this treatment plant every day from locations within 40 km at the most. The Combined System is provided with a 5.5 m^3 loading hopper. The cochlea is powered by a 7.5 kW electrical engine provided with power inverter, the main rotor is powered by a 55 kW engine. The system has an average treatment capacity of 8.5 $t \cdot h^{-1}$ in winter and 14 $t \cdot h^{-1}$ in summer. The difference is due to the higher outside temperature, that in summer affect the food waste during the delivery to the treatment facility implying a certain degree of liquefaction. The machine doesn’t use any external water addiction. Only in wintertime, a liquid fraction is dosed during the sorting operation. As liquid fraction it is used leachate collected from the food waste storage yard, according to a quantity of 3 $m^3 \cdot t^{-1}$ of food waste treated. The vertical filter has a mesh opening of 20 mm. The mentioned Combined System is shown in Figure 7.

Figure 7: The Combined System that provided the sample for the granulometric analysis and a detail of the vertical filter and the loading cochlea

3.4 Results and Discussion

The results obtained by the output streams analysis of the three different sorting machineries, can be divided in three sections. At first, the characterization of the organic pulp is done according to the TS and VS content depending on the different sorting system, as it is an important information to characterize the waste fed to the digester. The granulometric characterization is then considered, to analyse how the different techniques break up the organic materials. Lastly, results and observations on the reject inerts are presented to evaluate the organic contamination rate of the stream that is normally landfilled.

3.4.1 TS and VS characterization - Seasonality

Results obtained by the monitoring campaign of the sorting systems are presented in Table 1 and shown in Figure 8. Results show both the annual average than the seasonal average, per each sorting machine, according to section 3.2.1. Classical Standard Deviation (SD) and percentage Standard Deviation (%SD) are also calculated. To understand if there is any seasonal variation on the quality of the output stream, an analysis of the SD must be done.

Table 1: Annual and season average of the particle size analysis conducted on three different sorting systems

		Annual AVERAGE	**SD**	**SD%**	Cold season	SD	SD%	Middle season	SD	SD%	Warm season	SD	SD%
Extrusion Press	TS%	**30.4%**	**±2.7%**	**8.9%**	33.1%	±2.2%	6.5%	30.7%	±1.0%	3.4%	27.4%	±1.5%	5.5%
	VS%	**24.0%**	**±2.8%**	**11.8%**	26.8%	±2.7%	10.0%	23.9%	±1.9%	7.9%	21.3%	±0.9%	4.2%
	VS/TS%	**78.7%**	**±3.0%**	**3.8%**	80.8%	±3.0%	3.8%	77.9%	±3.6%	4.7%	77.7%	±1.4%	1.8%
Hammer Mill	TS%	**8.9%**	**±1.3%**	**15.2%**	9.5%	±1.2%	12.1%	7.5%	±1.2%	15.4%	9.5%	±0.9%	10.0%
	VS%	**7.6%**	**±1.1%**	**14.6%**	8.3%	±1.0%	12.2%	6.5%	±1.0%	15.3%	8.0%	±0.7%	9.0%
	VS/TS%	**86.0%**	**±2.5%**	**2.9%**	87.1%	±1.7%	2.0%	86.9%	±0.1%	0.1%	84.5%	±3.5%	4.1%
Combined System	TS%	**27.2%**	**±2.8%**	**10.2%**	26.3%	±0.6%	2.4%	28.0%	±4.1%	14.6%	27.2%	±2.7%	9.9%
	VS%	**21.5%**	**±2.7%**	**12.7%**	20.2%	±1.3%	6.4%	23.2%	±3.5%	15.2%	20.8%	±2.2%	10.5%
	VS/TS%	**78.9%**	**±5.7%**	**7.2%**	76.5%	±3.1%	4.0%	83.0%	±4.2%	5.1%	76.6%	±7.0%	9.2%

On the TS basis, the SD calculated on the averages of each season, respectively for cold, middle and warm season, are: ±2.2%, ±1.0% and ±1.5% (Extrusion Press), ±1.2%, ±1.2% and ±0.9% (Hammer Mill) and ±0.6%, ±4.1% and ±2.7% (Combined System). On the VS basis, the SD calculated on the averages of each season, respectively for cold, middle and warm season, are: ±2.7%, ±1.9% and ±0.9% (Extrusion Press), ±1.0%, ±1.0% and ±0.7% (Hammer Mill) and 1.3%, 3.5% and 2.2% (Combined System). On the %VS/TS ratio, the SD calculated on the averages of each season, respectively for cold, middle and warm season, are: ±3.0%, ±3.6% and ±1.4% (Extrusion Press), ±1.7%, ±0.1% and ±3.5% (Hammer Mill) and ±3.1%, ±4.2% and ±7.0% (Combined System). Even if considering the unavoidable rumour derived by a manual procedure as noticed by other authors (Von Blottnitz et al., 2002), those values always are lower than 10% of the relative average. This testifies that there is no significative variability on the organic pulp quality within the same season. No reference studies are found in literature to compare the results.

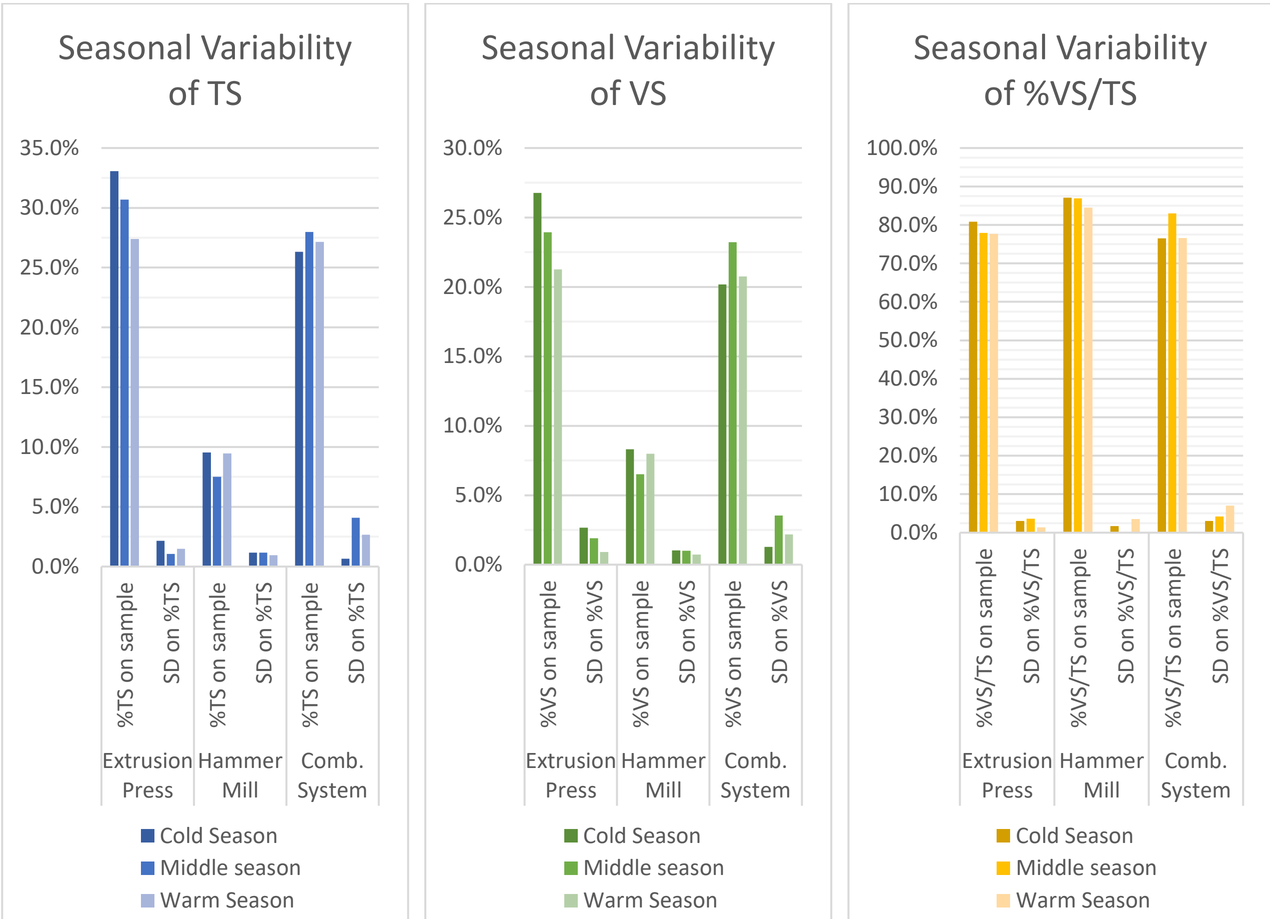


Figure 8: Comparative results of Extrusion Press, Hammer MIll and Combined System, as annual and seasonal average and dived by %TS, %VS and VS/TS

As well as being low, the SD calculated for the different seasons are also quite similar to each other, the relative average values both for TS, VS and %VS/TS are also similar. This testifies, for all the sorting systems, the absence of significative variation on the organic pulp as the environmental temperature changes: both in term of variability and characterization, it is homogeneous along the all year independently by the season. The absence of statistical variation of household wastes depending on the season, agrees with what reported by other authors (Edjabou et al., 2018) (Edjabou et al., 2018) (Denafas et al., 2014). An exception is observed only for the Extrusion Press, for which it can be seen a decreased TS content as long as we pass from winter to summer. Passing from each season to the warmest one, the TS lowering is of about 10%. The same behaviour is observed for VS content. If the variation cannot be attributed to different eating habits of citizens, it is probably due to a biological degradation (hydrolytic liquefaction) that the organic waste undergoes, with the seasonal temperature increasing, in the lorry during the delivery to the treatment facility. The Extrusion Press, as reported in section 3.3.2, is installed in the only treatment site where part of the organic waste is delivered from far away. The absence of seasonal variability is testified also by the VS/TS ratio. As visible in Figure 8 and Table 1, the percentage of organic matter in the TS is very stable along the whole year for every type of sorting system. The %SD on the annual %VS/TS average is 3.8%, 2.9% and 7.2% respectively for Extrusion Press, Hammer Mill and Combined System. A low variation in the VS/TS ratio means that the inert component of the organic pulp is stable along the whole year, and that is attributable to two factors: seasonal homogeneity of food waste composition, and stability of the cleaning efficiency of the sorting system.

To compare the effect of sorting cleaning and homogenization to the organic waste fed to the digesters, data in Figure 9 are plotted. The figure compares and shows the TS, VS and VS/TS as annual average of all the samples, per each sorting type. The Extrusion Press and the Combined System shows a similar behaviour, producing an organic pulp with 30.4% and 27.2% of TS respectively. VS content in TS is the 78.7% and 78.9% in Extrusion Press and the Combines System respectively. They seem to be very similar under the point of view of sorting efficiency, so the choice between the better system must be done according to other factors as for example CAPEX or OPEX. Respect to the other, the Hammer Mill technique shows instead a different behaviour: TS are significantly lower with an annual average of 8.9% and the volatile fraction of the TS is significantly higher explaining the 86.0% of the TS. The higher humidity content found in Hammer Mill samples may be related to the higher quantity of water needed to efficiently remove the inerts from the food waste in this type of technique. The high degree of cleanness is by the way testifies by the higher percentage of VS content found in the Hammer Mill samples respect to the other two sorting solutions. It must however be noticed that the Hammer Mill is installed in a plant with Wet digesters technology, and the food waste dilution observed may respond to this detail.

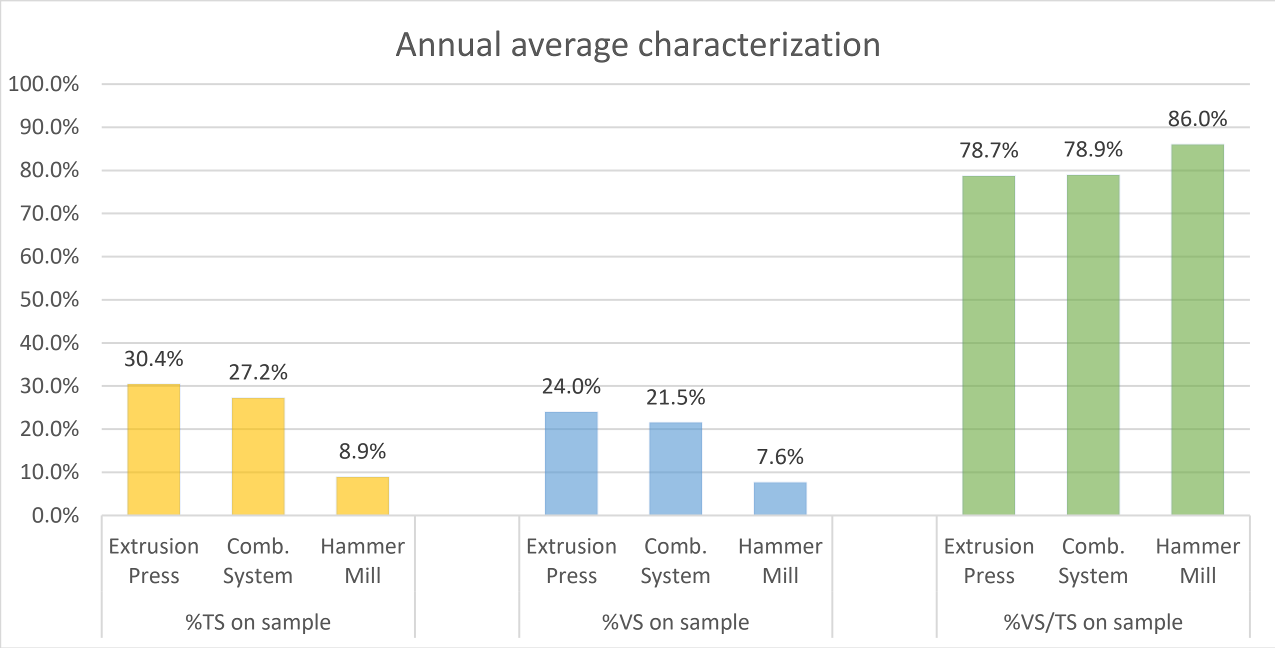


Figure 9: Comparison of the annual average characterization of the three different sorting system on %TS, %VS and VS/TS

3.4.2 Granulometric profile

About the granulometric study, a proper statistical analysis to evaluate any seasonal variation on the particle size distribution, was not actually done. Table 2 reports the average annual values for each machinery, both for TS and VS, with all the relatives SD and %SD values. In Figure 10, the %SD calculated on the annual average, is plotted according to the particle size for each sorting technique. For Hammer Mill, for particles wider than 20 mm, the %SD in zero because no TS are accounted for this dimensional class. By observing Figure 10, it is evident that the %SD is ubiquitously quite high, with an average on all the samples higher than 40%. Peaks of %SD higher than 100% is even evaluated for the widest particles. This means that the variability of the samples is really high. This high variation is however not due to inhomogeneity of the samples during the year, but by a low reproducibility of the technique due to the procedure. How observed already by other authors, the manual collecting of very small particles from a very thin mesh, is the very limiting step of the procedure (Mahmoud et al., 2006) (Von Blottnitz et al., 2002) (Carrasco and Gao, 2019) (Zhang and Banks, 2013) (Laguna et al., 1999).

Table 2: Average annual values for each machinery, both for TS and VS, with all the relatives SD and %SD values

Mesh opening (mm)		Extrusion Press	SD	SD%	Hammer Mill	SD	SD%	Combined System	SD	SD%
>20	**TS%**	**5.2%**	±4.9%	93.9%	**0.0%**			**1.1%**	±2.6%	222.6%
	VS%	**0.7%**	±0.6%	94.5%	**0.0%**			**0.1%**	±0.3%	246.2%
10	**TS%**	**5.8%**	±3.8%	65.4%	**1.1%**	±0.8%	71.0%	**10.0%**	±9.0%	89.6%
	VS%	**0.9%**	±1.0%	109.5%	**0.1%**	±0.1%	66.8%	**2.0%**	±3.3%	162.4%
5	**TS%**	**8.7%**	±1.8%	21.2%	**6.3%**	±2.3%	35.8%	**11.5%**	±3.0%	25.7%
	VS%	**2.0%**	±1.0%	47.7%	**0.4%**	±0.2%	46.3%	**3.5%**	±2.2%	64.2%
1	**TS%**	**13.9%**	±2.2%	15.5%	**18.8%**	±5.9%	31.6%	**18.9%**	±5.9%	31.1%
	VS%	**4.7%**	±1.2%	25.7%	**3.1%**	±1.7%	53.4%	**6.5%**	±2.6%	39.6%
0.5	**TS%**	**4.2%**	±0.8%	19.7%	**4.3%**	±2.2%	50.9%	**5.3%**	±1.9%	35.5%
	VS%	**0.8%**	±0.3%	35.4%	**0.7%**	±0.5%	73.7%	**1.2%**	±0.6%	47.4%
0.25	**TS%**	**3.3%**	±0.4%	11.6%	**5.0%**	±2.4%	47.4%	**3.4%**	±1.2%	35.4%
	VS%	**0.6%**	±0.3%	51.5%	**0.7%**	±0.5%	74.6%	**0.7%**	±0.4%	55.6%
0.125	**TS%**	**3.9%**	±1.8%	46.2%	**3.0%**	±0.6%	19.2%	**2.1%**	±0.7%	30.8%
	VS%	**0.7%**	±0.3%	41.7%	**0.5%**	±0.3%	62.1%	**0.4%**	±0.2%	51.2%
0.063	**TS%**	**3.0%**	±2.3%	74.2%	**1.3%**	±1.1%	88.5%	**2.9%**	±3.3%	111.8%
	VS%	**0.6%**	±0.5%	77.3%	**0.2%**	±0.2%	83.8%	**0.4%**	±0.4%	94.6%
0.063>	**TS%**	**51.8%**	±8.0%	15.5%	**60.3%**	±8.7%	14.5%	**44.6%**	±8.7%	19.4%
	VS%	**88.9%**	±2.8%	3.1%	**94.2%**	±2.9%	3.1%	**85.1%**	±5.1%	6.0%

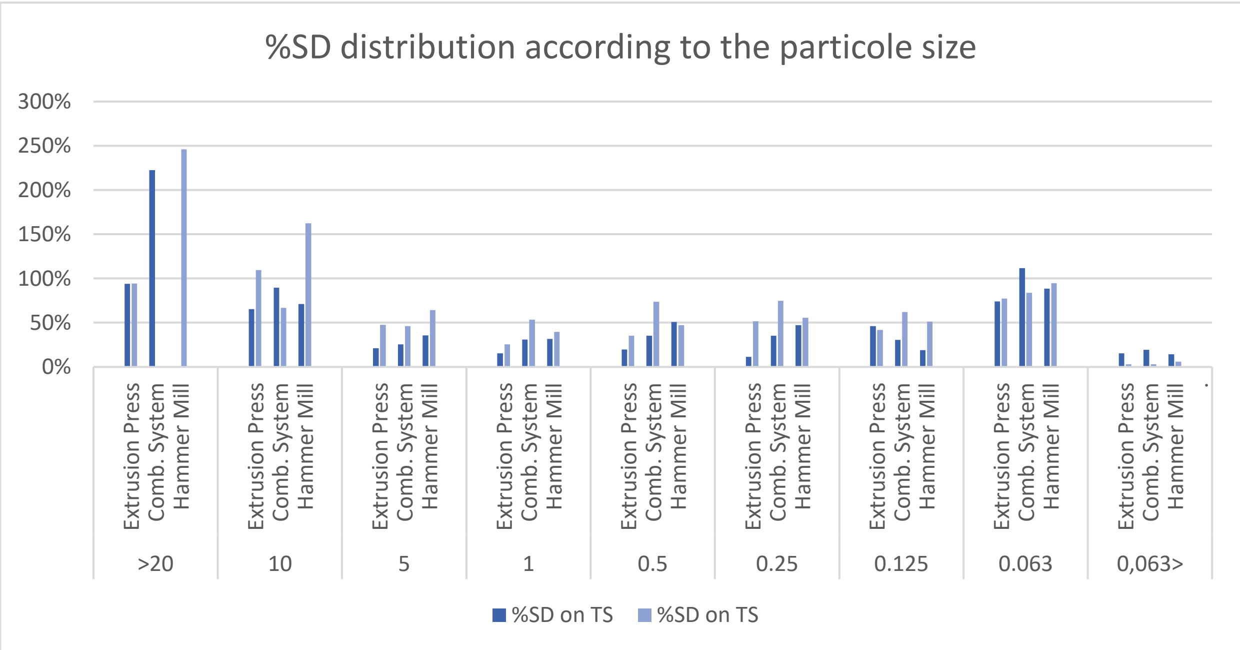


Figure 10: The %SD calculated on the annual average plotted according to the particle size, for each sorting technique

Only for VS under 0.063 mm, the %SD is very low (3.1%, 3.1%, 6.0%), explained by the fact that those values are calculated by difference (see section 3.2.2). The huge variation above 10 mm is explained by the fact that the particles in these classes are likely to be of very different nature (plastics, metals, shields, bones etc), implying a very high variability in their TS or VS according to the specific weight (Jansen et al., 2004). Despite this, some important information can still be derived from the annual averages.

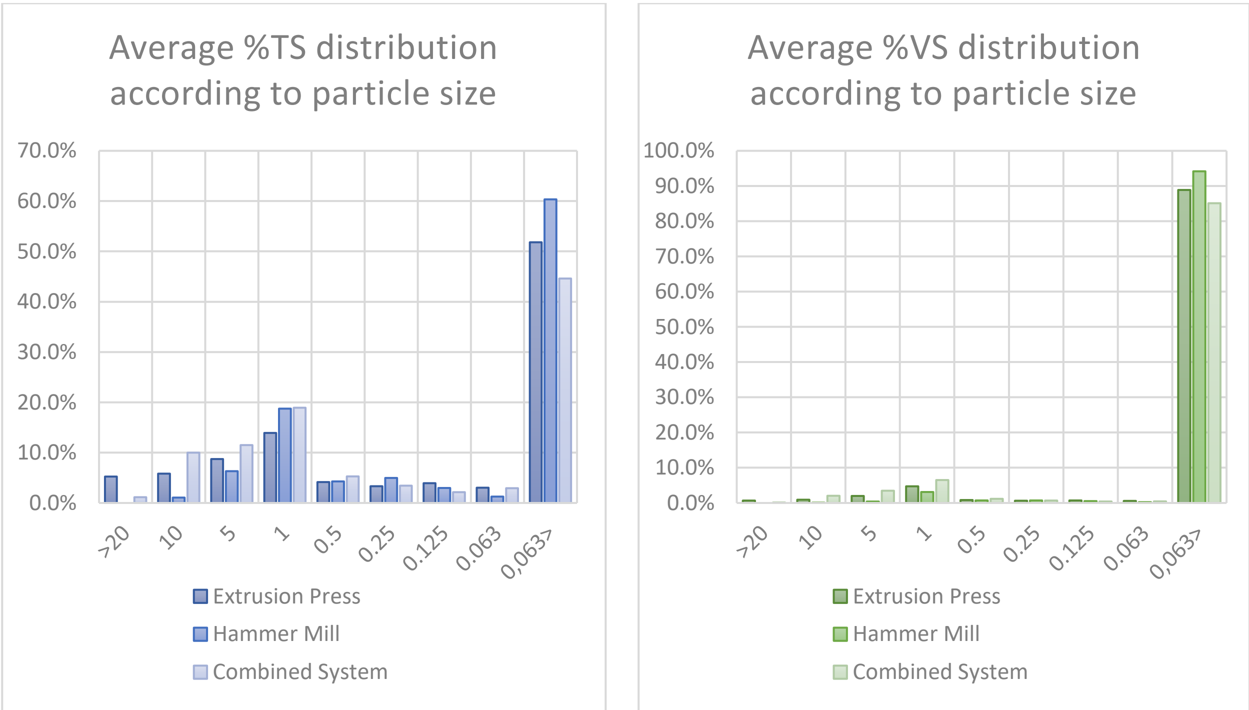


Figure 11: Average granulometric distribution according to particle size, separately for TS and VS, for the three sorting systems

The average annual distribution, according to particle size, is plotted in Figure 11. It is clearly visible that particles under 0.063 mm are the most abundant fractions. A better visual comparison of the TS and VS distribution above or below 0.063 mm is given in Figure 12, where it is possible to see that, on average, 52% of the TS and 89% of the VS are of supercolloidal nature. Similar results are found by Giuliano et al. (2011) who counted 70% of the TS and 69% of the VS below the finest mesh size of 0.25 mm; the finest fraction is however always the most abundant also in the other literature references (Karr and Keinath, 1978) (Carrasco and Gao, 2019) (Giuliano et al., 2011). It must be remembered that the sorting systems does not use any addiction of wastewater sludge but, in case, just a little addition of tap water. There is hence not any external contamination of fine particles solids, and all the VS detected come from the food waste itself. This observation is quite important because it proves that the three sorting methods are capable of high degree of demolition, and that the organic pulp sent to the fermenter is very readily degradable, offering important implications to the choice of the Hydraulic Retention Time (HRT) of the fermenter and for the biological process control.

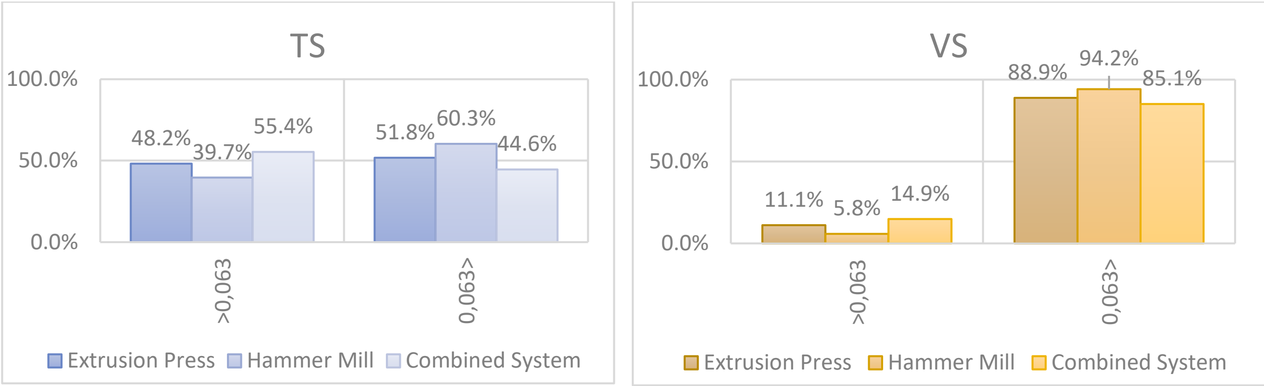


Figure 12: Cumulative particles distribution above and below the size of 0.063 mm, separately for TS and VS and for all the three sorting systems

The Figure 11, show also that it is possible to distinguish three classes according to size distribution: one below 0.063 mm already discussed, an intermediate class with sizes between 0.063 and 1 mm, and a class of compounds with dimension wider than 1 mm. The data matrix, cleaned by the data of the finest fraction, was transformed and referred to 100% in order to better understand how the particles wider than 0.063 distributes according to their size. Results are shown in Figure 13. It is possible to observe, for all the sorting system, an intermediate class of middle-size particles with dimension between 0.063 and 1 mm. This class represents only the 14.5%, 16.4% and 6.9% of total TS and 2.8%, 2.7% and 1.3% of total VS for the Extrusion Press, Hammer Mill and the Combined System respectively. Another cluster is recognized for the particles above 1 mm, that explain the 35.9%, 34.4% and 56.8% of the TS and the 11.0%, 5.9% and 17.4% for the Extrusion Press, Hammer Mill and the Combined System respectively. A normal distribution can be observed for the Hammer Mill: particles are mostly abundant in the granulometric class between 1 and 5 mm; the widest particles (>20mm) are totally absent, then they close they are to 1 mm the most abundant they are, showing that the Hammer Mill is capable of assuring high demolition plus high homogeneity of the output pulp. It must be also noticed that the Hammer Mill is the only technique to produce a conspicuous fraction of particles between 1 mm and 0.063 mm. This is clearly visible in Figure 13. This fractions explains in the Hammer Mill the 38% of the total particles with size above 0.063 mm, compared to the 25% for the Extrusion Press and 18%

for the Combined System. This is a very important observation because it consists in the fraction that tends to behave and precipitate as sand in the digester, leading to sediment problems in the pipes or excessive abrasion on the rotating part of the plant (mixers, propellers, pumps etc). The Hammer Mill ability to produce finer particles could also be related to the higher moisture content in the processed food waste, factor that was found significative in other experiences (Zhang et al., 2019). The Combined System, instead, almost doesn't produce particles with size bigger than 20 mm, but they are spread quite homogeneously between 1 and 20 mm. The Extrusion Press is the sorting system, between the others, more capable of leaving quite big clasts in the output organic stream, wider also of 20 mm. The tendency of the particle size to distribute in three classes, with a macro limit of 1 mm, and a micro limit below the supercolloidal width, seems to be a common behaviour as very similarly found by other authors (Giuliano et al., 2011).

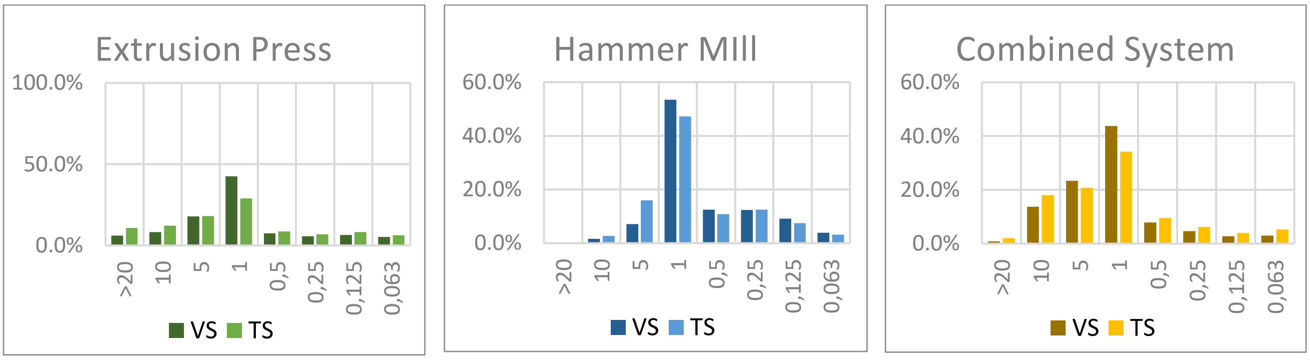


Figure 13: Particles with size wider than 0.063 mm and their percentual distribution in the granulometric classes

3.4.3 Contamination of the reject inert residuals

On the inert residual rejected by the sorting machine, stream that is usually landfilled, the organic contamination was assessed to further quantify the efficiency of the separation system. The annual average values are reported in Table 3 and important data are plotted in Figure 14. The machinery that shows higher cleanliness efficiency is the Combined System, that produce a reject stream with 50% of inerts and 50% of organic contaminant. The Extrusion Press and the Hammer Mill show very similar behaviour between each other and lower cleanliness efficiency: the organic fraction in the reject material is 68% and 66% respectively. These values are more optimistic compared to the ones reported in previous studies, where organic matter consisted on more of the 90% of the total wet weight (Hansen et al., 2007).

Table 3: Results of the manual sorting and classification made on the reject material collected over a year from the three sorting systems

mesh opening (mm)		Extrusion Press	SD	SD%	Hammer Mill	SD	SD%	Combined System	SD	SD%
>20	**TS%**	**5.2%**	±4.9%	93.9%	**0.0%**			**1.1%**	±2.6%	222.6%
	VS%	**0.7%**	±0.6%	94.5%	**0.0%**			**0.1%**	±0.3%	246.2%
10	**TS%**	**5.8%**	±3.8%	65.4%	**1.1%**	±0.8%	71.0%	**10.0%**	±9.0%	89.6%
	VS%	**0.9%**	±1.0%	109.5%	**0.1%**	±0.1%	66.8%	**2.0%**	±3.3%	162.4%
5	**TS%**	**8.7%**	±1.8%	21.2%	**6.3%**	±2.3%	35.8%	**11.5%**	±3.0%	25.7%
	VS%	**2.0%**	±1.0%	47.7%	**0.4%**	±0.2%	46.3%	**3.5%**	±2.2%	64.2%
1	**TS%**	**13.9%**	±2.2%	15.5%	**18.8%**	±5.9%	31.6%	**18.9%**	±5.9%	31.1%
	VS%	**4.7%**	±1.2%	25.7%	**3.1%**	±1.7%	53.4%	**6.5%**	±2.6%	39.6%
0.5	**TS%**	**4.2%**	±0.8%	19.7%	**4.3%**	±2.2%	50.9%	**5.3%**	±1.9%	35.5%
	VS%	**0.8%**	±0.3%	35.4%	**0.7%**	±0.5%	73.7%	**1.2%**	±0.6%	47.4%
0.25	**TS%**	**3.3%**	±0.4%	11.6%	**5.0%**	±2.4%	47.4%	**3.4%**	±1.2%	35.4%
	VS%	**0.6%**	±0.3%	51.5%	**0.7%**	±0.5%	74.6%	**0.7%**	±0.4%	55.6%
0.125	**TS%**	**3.9%**	±1.8%	46.2%	**3.0%**	±0.6%	19.2%	**2.1%**	±0.7%	30.8%
	VS%	**0.7%**	±0.3%	41.7%	**0.5%**	±0.3%	62.1%	**0.4%**	±0.2%	51.2%
0.063	**TS%**	**3.0%**	±2.3%	74.2%	**1.3%**	±1.1%	88.5%	**2.9%**	±3.3%	111.8%
	VS%	**0.6%**	±0.5%	77.3%	**0.2%**	±0.2%	83.8%	**0.4%**	±0.4%	94.6%
0.063>	**TS%**	**51.8%**	±8.0%	15.5%	**60.3%**	±8.7%	14.5%	**44.6%**	±8.7%	19.4%
	VS%	**88.9%**	±2.8%	3.1%	**94.2%**	±2.9%	3.1%	**85.1%**	±5.1%	6.0%

Average %SD is 18.2%, 34.1% and 28.9% respectively for Extrusion Press, Hammer Mill and Combined System. According to this observation, the Extrusion Press seems to be the technique capable of higher constancy in the quality of the reject stream. It must be however noticed that, for practical reasons, the analysis was conducted on samples collected in a bag and so not of huge volume. The nature of the inert fraction in the reject material is of being made up of contaminants (plastic bags, tin cans, small kitchen tools etc) of relatively big dimensions, so a sample inevitably involves in high variability. This is also a reason why the evaluation of a seasonal quality variation, on only four samples, has no sense in this case. The inert fraction produced by the Hammer Mill and the Combined System have a moisture content of 60% and 57% respectively, while the Extrusion Press releases an inert fraction sensibly drier with only 42% of humidity. The relative %SD is about 15% for the three techniques, value quite low if considered the high difficult on sampling and analysing a representative fraction of the reject material. It must be noticed that the fraction accounted as humidity is probably organic matter that remained adhered to the surface of the material during the manual sorting (see section 3.2.2). The organic fraction separated by the inerts in the reject material, shows a very high content of VS, that is 79%, 89% and 86% respectively for Extrusion Press, Hammer Mill and Combined System, and a %SD always lower than 10%. These values are aligned with the VS content of the sorted organic pulp.

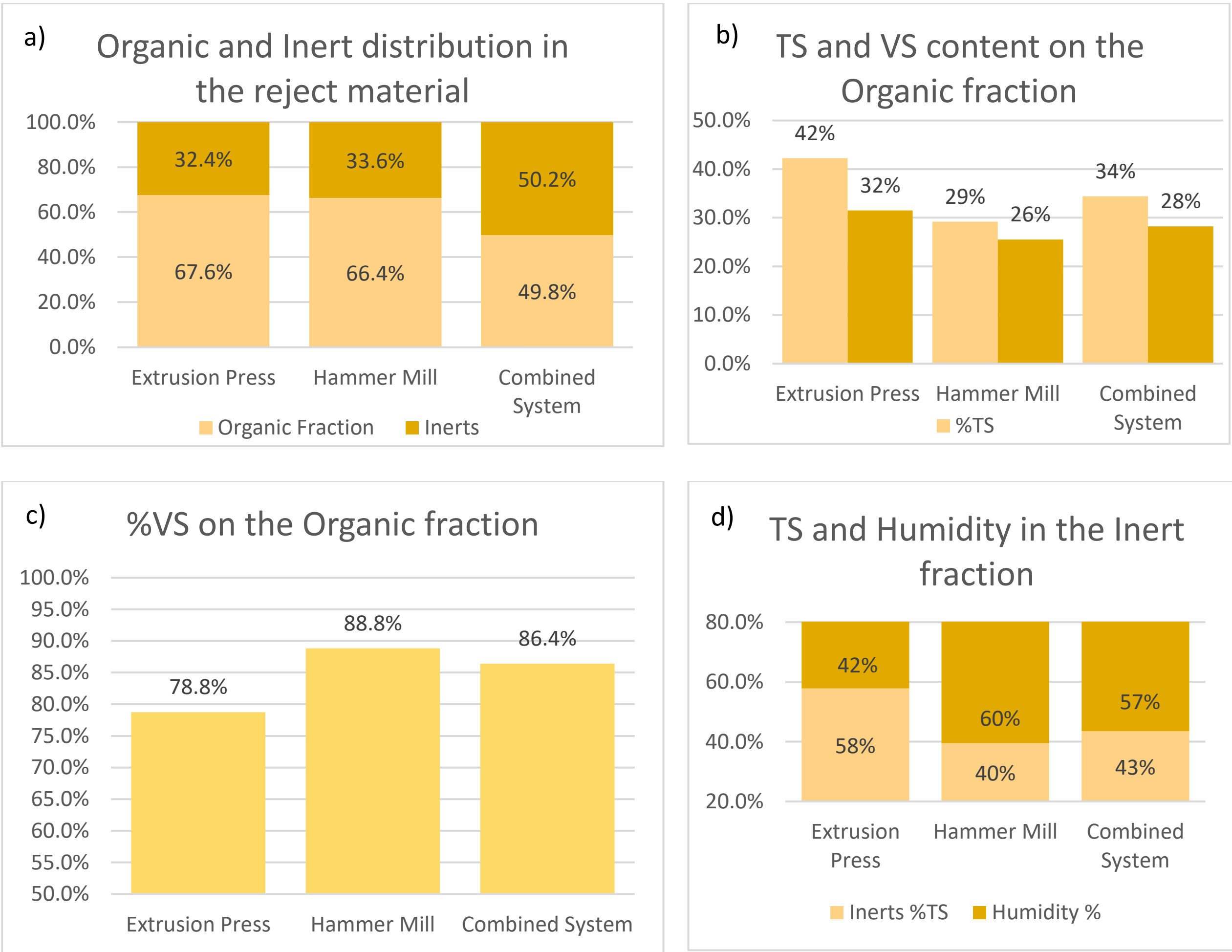


Figure 14: Results of the manual sorting and classification made on the reject material collected over a year from the three sorting systems

3.5 Conclusions

The Extrusion Press, Hammer Mill and the Combined System studied, can all be considered high demolition sorting techniques. Most of the particles produced are below 0.063 mm. In this granulometric fractions, particles have supercolloidal nature and they have important repercussion on the viscosity of the digestate (they actually do not imply any real overload to the mixing systems) and on the degradability (particles are very easily available for microorganisms). TS under 0.063 mm are on average the 52% of the total; VS under 0.063 mm are on average the 90% of the total.

The tested sorting systems shown a high homogenization efficiency: no significative seasonal variation have been detected on the organic pulp sent to the digester, so a full-scale digester can be managed all the yearlong with the same approach without any risk of seasonal variability. Only the Extrusion Press shown a decrease in TS, that shown a lowering of 10% passing from a season to the other as the temperature increases. This is however probably due to a degradation phenomenon occurred during the OFMSW transportation from the collection point to the treatment facility.

The Hammer Mill is the technique that was able to better remove the inerts: VS in the organic pulp accounted for 86% of the total compared to the 79% for both the Extrusion Press and the Combined System.

The Hammer Mill is the sorting system that produced the more liquid organic pulp, where TS are 8.9% on a mass basis. TS on the Combined system are 27.2% with high degree of cleanliness, TS on the Extrusion Press are 30.4% with a certain degree of contamination. It must be however noticed that the tested Hammer Mill was serving a Wet anaerobic digester and maybe a so low TS content is a target condition for the plant. In any case, under these conditions, the technique is able of the highest inert removal efficiency.

Compared to the others, the Hammer Mill is the technique that produce the more homogeneous pulp in term of particle size. The particles with size above 0.063 mm show a normal distribution tendency around the size of 1 mm. Although big clasts with size wider than 20 mm are totally absent, a conspicuous fraction of clasts between 0.063 mm and 1 mm implies a concrete predisposition to sedimentation.

The Extrusion Press is the technique that showed the highest production of particles with size above 20 mm. It is important to consider that this fraction, if constituted by plastics, gives high risk of dangerous floating layer formation.

4. PILOT SCALE EXPERIMENTATION

4.1 Purpose of the experimental pilot scale study

According to section 1.2, the purpose of the research is to evaluate the possibility of simplifying the anaerobic digestion plant design, for allowing a costs reduction in order to stimulate a capillary diffusion of the SS-OFMSW anaerobic treatment for energy recovery. To achieve this goal, a layout with the following conditions have been selected:

1. Semi-dry digestion in a PFR reactor;
2. A single-phase reactor;
3. Mono-digestion of undiluted OFMSW.

The purpose of this part of the research is to run, at the pilot scale, a continuous test to understand if the anaerobic process can be sustained at high OLR and by feeding OFMSW with no dilution (high TS content) and no recirculation, under the above process conditions. The conditions for process stability, and the biogas production parameters as SGP and GPR, that are necessary for the following design and economic evaluation, are the final output results of this experimental activity.

4.2 Material and Methods

4.2.1 Substrate characterisation

To feed the pilot plant, the SS-OFMSW was collected at the Biociclo Composting Plant (Castiglione delle Stiviere, BS, Italy), after mechanical pre-treatment made with the Combined System already discussed in section 3.3.3. According to the analytical monitoring performed by the plant owner, the amount of inert impurities is <5%. For this experimental activity, the OFMSW was collected once every week and maintained at -18°C until use in the experiment. Table 4 summarises the physicochemical characteristics of the fed OFMSW. TS and VS content was measured three times per week; pH, chemical oxygen demand (COD), ammonia nitrogen ($N\text{-}NH_4^+$), and total Kjeldahl nitrogen (TKN) were analysed once per week.

Table 4: Physicochemical characterization of the SS-OFMSW used for the pilot plant feeding

	TS ($g \cdot kg^{-1}$)	VS ($g \cdot kg^{-1}$)	VS (%TS)	pH	Total COD ($gO_2 \cdot kg^{-1}$)	$N\text{-}NH_4^+$ ($g \cdot L\text{-}1$)	TKN ($g \cdot kg^{-1}$ TS)
Mean value	214.5	171.8	80.10%	5.3	203.5	0.63	19.3
Standard deviation	±11.0	±10.6	±3.8	±0.3	±24.9	±0.10	±3.5
Number of samples	23	23	23	10	10	10	10

4.2.2 Pilot Plant setup

The experimental study was performed at the pilot scale using a single-phase PFR. The reactor was designed and built by MicrobEnergy as downscaled replica of the fermenter Euco®, built by Schmack Biogas Slr at the industrial scale. The stainless-steel reactor is of a parallelepiped shape, measuring 0.375 m × 1.2 m × 0.475 m (l1 × l2 × h), with a gross volume of 215 L. The working level was maintained at 0.355 m to obtain a net working volume of 160 L; biogas occupied 55 L of head volume. The digester was equipped with a paddle stirrer that ran its entire length (Figure 15a). The stirrer operated at 8 rpm and was equipped with blades that reached 1.2 cm from the bottom and reached a height of up to 0.360 m to prevent sediment and crust formation.

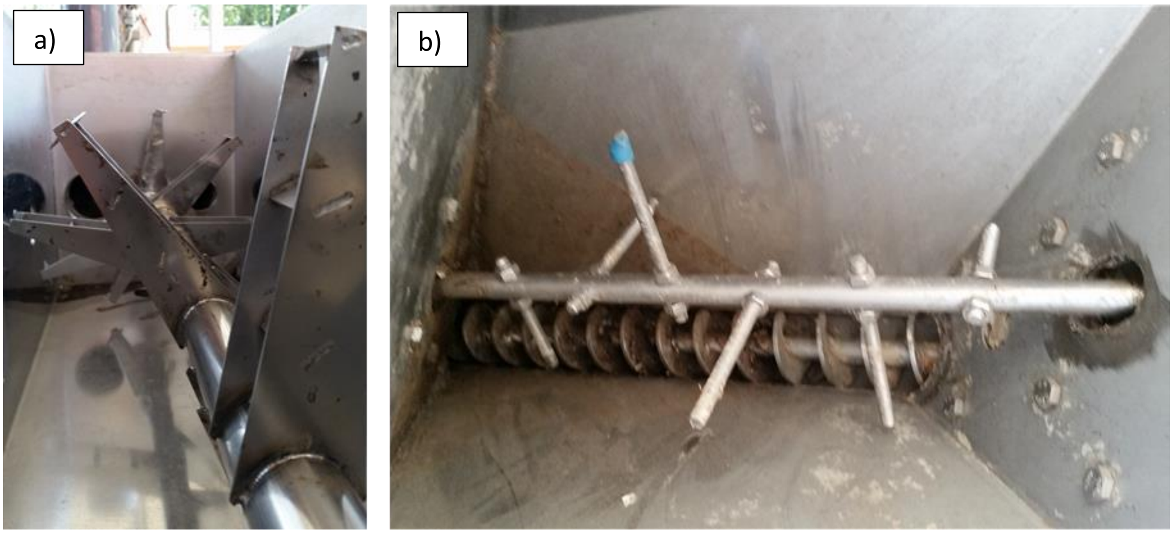


Figure 15: Detail of the pilot reactor agitator (a), and of the automatic loading system operated by a cochlea (b)

The heating system was electric and comprised a heating mat at the bottom and a heating wire around the walls. A 2-cm layer of expanded synthetic polyethylene was used to provide thermal insulation. Temperature was monitored continuously by two temperature probes

(PT100) and was maintained at 38°C. Two 2” ball valves enabled digestate sampling. The feeding system comprised a 30-L tank with a screw for loading OFMSW below the digestate level to prevent biogas from escaping (Figure 15b). The automatic loading works with high accuracy degree, how demonstrated by the calibration line reported in Figure 16 and its R^2 of 0.9738. The calibration line is based on the operating time of the cochlea and an OFMSW flow rate of 0.750 kg·min^{-1}.

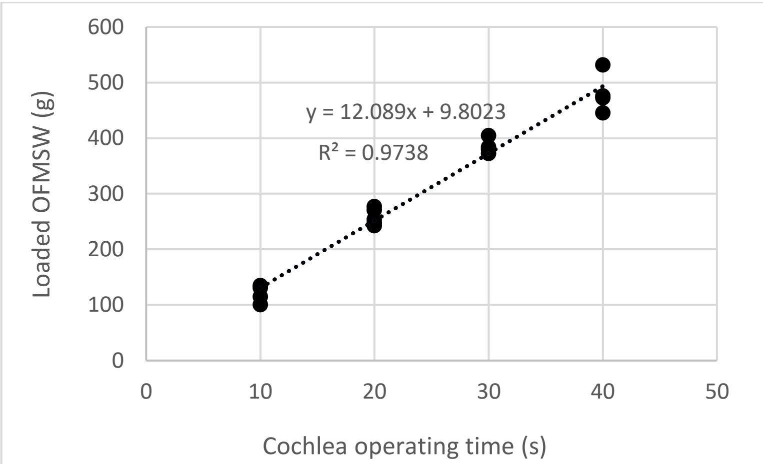


Figure 16: Calibration line for the automatic loading that permitted to manage an accurate feeding of the pilot reactor

Automatic feeding was conducted 10 times a day and 7 days a week. A peristaltic pump and a pneumatic valve operated the automatic digestate discharge before every feed-loading cycle. At the steady state, the digestate discharge was controlled by an Endress+Hauser (Reinach, Switzerland) PROMAG 5 flow meter, and the discharge volume was set to 73% of the feeding volume based on empirical observations (with this value, the digestate level in the fermenter was maintained at 0.355 m). Before discharge, the digestate was collected in a graduated tank to control the daily output volume. Gas was collected at the top of the fermenter at a pressure of 4.5 mbar, and the GPR was measured using a Ritter (Bochum, Germany) gas counter TG1/5 with a pulse generator connected to a programmable logic controller (PLC). Gas composition was monitored automatically and continuously every 6 h with an ETG (Montiglio, AT, Italy) biogas analyser MCA 100 Bio-P. All plant components were connected to the PLC, which permitted fully automatic control of the process and automatic data recording. The pilot plant used a Siemens (Munich, Germany) PLC with the S7 logic. The operator software was designed by Schmack Biogas (Bolzano, BZ, Italy) srl and provided with a remote control. Reactor stability parameters (TS, VS, volatile fatty acid

(VFA), pH, alkalinity, and $N\text{-}NH_4^+$) were analysed two times a week. An overview of the pilot plant is given in Figure 17.

Figure 17: Overview of the PFR pilot plant used for the experimental tests

4.2.3 Analytical Methods

For OFMSW characterisation (mean values are reported in Table 4), TS and VS content was measured twice a week; pH, COD, $N\text{-}NH_4^+$, and TKN were analysed once a week. COD was measured both in the liquid fraction collected after centrifugation at 5,000 rpm as soluble COD (sCOD) and in the dried material. COD of the two fractions was used to calculate total COD per unit of fresh substrate. Similarly, nitrogen was measured in the liquid fraction after centrifugation at 5,000 rpm as $N\text{-}NH_4^+$ and in the dried material as TKN. The two fractions were then used to calculate total nitrogen (TN) per unit of fresh material. For the digestate, stability parameters such as TS, VS, VFA, pH, total and partial alkalinity (TA and PA), and $N\text{-}NH_4^+$ were analysed twice a week. Analyses of all parameters, except VFA, followed the standard methods (APHA/AWWA/WEF, 1998). VFAs were analysed using Gas Chromatography (GC) (Carlo Erba instruments) with H_2 as the gas carrier. The GC was equipped with a fused silica capillary column (Supelco Nukol TM; 15 m, 0.53 mm × 0.5 mm film thickness) and a flame ionisation detector (200°C). The temperature ramp started from 80°C to reach 200°C through two steps at 140°C and 160°C, at a rate of $10°C\cdot min^{-1}$.

Samples were centrifuged and filtered through a 0.22-mm membrane before GC. Butyric, valeric, and hexanoic acids were analysed in both iso- and n-stoichiometric forms and reported as cumulative concentrations.

For the microbial analysis two methods were used. For Escherichia Coli and Coliforms, each sample was firstly diluted homogenizing 1 g of sample with 9 mL of physiologic solution. Several further decimal dilution were carried on. 1 mL of each dilution were then seeded by inclusion in the agar culture medium Brillance E. COLI/COLIFORM SELECTIVE AGAR (Thermo Fisher Diagnostic), a specific culture medium for detecting E. Coli and other Coliforms in food and agricultural samples. The plates as seeded are incubated at 37°C for 24-48 hours. For the presence/absence of Salmonella spp. in 25 g of sample, the ISS A 004A rev. 00 method (Italian National Institute of Health) is applied. 25 g of sample is pre-enriched in 250 mL of Peptonised Water (Thermo Fisher Diagnostic) and incubated at 37°C for 24 hours. A further enrichment is done in selective enrichment broth Rappaport Vassiliadis Broth (Thermo Fisher Diagnostic) and incubated at 42°C for 24 hours. Samples with evidence of microbial contamination were seeded on selective agar medium Hektoen Enteric Agar (Thermo Fisher Diagnostic). Any suspected colonies are eventually specifically checked.

4.2.4 Experimental Design

The reactor was filled with an inoculum from a previous unpublished continuous experiment. The previous experiment was conducted in the same pilot plant for 3 months to test the process response to Organic Loading Rate (OLR) variation and plan the biological start-up of the present work. The same OFMSW was utilised, and the same temperature was applied. Before starting the experiment of the present study, the digestate was sieved through a 1.00-mm membrane and left for mixing at 38°C for 1 month. The inoculum was hence sampled and its physicochemical characterisation was performed (Table 5).

The process start-up was performed at an initial low loading rate, which was increased progressively to allow gradual acclimation of the biomass, as reported previously (Angelidaki et al., 2006). The feeding strategy reported elsewhere (Bolzonella et al., 2003) was applied. Feeding began on day 1 with an OLR of 1.25 $kgVS{\cdot}m^{-3}{\cdot}d^{-1}$, which was then increased by 1.25 $kgVS{\cdot}m^{-3}{\cdot}d^{-1}$ every 7 days to reach 6 $kgVS{\cdot}m^{-3}{\cdot}d^{-1}$; at this point, OLR was stabilised and then increased to the final target of 6.2 $kgVS{\cdot}m^{-3}{\cdot}d^{-1}$ after 16 days. The target OLR of 6.2 $kg\ VS{\cdot}m^{-3}{\cdot}d^{-1}$ was set on the basis of previous unpublished experiences of the author, that showed unbalanced process conditions at an OLR of 6.5–7.0 $kgVS{\cdot}m^{-3}{\cdot}d^{-1}$. Reportedly, for highly biodegradable OFMSW, the OLR should not exceed 6 $kgVS \cdot m^{-3} \cdot d^{-1}$ (Pavan et al., 2000). Moreover, an OLR of 6.2 $kgVS \cdot m^{-3} \cdot d^{-1}$ is considered high, and based on similar experiences, OLR is mostly applied at <4 $kgVS \cdot m^{-3} \cdot d^{-1}$ (Tyagi et al., 2018). Stability parameters were analysed from the beginning to maintain proper microbial conditions during OLR increase. At the steady state, the Hydraulic Retention Time (HRT) as ratio between digester net volume and volume of OFMSW fed, was 26 days. As the process configuration did not imply any form of phase separation or digestate–liquid-phase recirculation, the solid retention time (SRT) was equal to HRT. Once the steady state was reached, the experiment was kept running for a period equal to 3 HRT to obtain full evidence of stability.

Table 5: Inoculum physicochemical characterisation

Parameter	Measure unit	Average value	Standard deviation
TS	($g \cdot kg^{-1}$)	3.0	±0.0
VS	($g \cdot kg^{-1}$)	1.4	±0.0
VS	(%TS)	47.4%	7.9%
pH		8.00	±0.04
Partial alkalinity	(mg $CaCO_3 \cdot L^{-1}$)	7,487	±353
Total alkalinity	(mg $CaCO_3 \cdot L^{-1}$)	9,815	±96
Total VFA	(mg $COD \cdot L^{-1}$)	2,004	±863
Acetic acid	(mg $COD \cdot L^{-1}$)	1180	±754
Propionic acid	(mg $COD \cdot L^{-1}$)	680	±168
Butyric acid	(mg $COD \cdot L^{-1}$)	42	±5
Pentanoic acid	(mg $COD \cdot L^{-1}$)	46	±29
Hexanoic acid	(mg $COD \cdot L^{-1}$)	18	±4
Heptanoic acid	(mg $COD \cdot L^{-1}$)	N.D.	
S-COD	(g $O_2 \cdot L^{-1}$)	5.06	±0.7
COD	(g $O_2 \cdot kg^{-1}$TS)	419.9	±2.3
COD TOT	(g $O_2 \cdot kg^{-1}$)	17.6	±0.7
NH_4^+	($g \cdot L^{-1}$)	2.0	±0.1
TKN	($gN \cdot kg^{-1}$TS)	25.0	±4.3
Total Nitrogen	($gN \cdot kg^{-1}$)	2.7	±0.2

4.3 Results and Discussion

To achieve the steady state and reproducible results, the experimentation involved in four RUNs. Only the RUN_4 succeed to reach the stability, and for this is reason RUN_4 is the only deeply analysed and discussed. The first three RUNs are presented just to report as part of the work done.

4.3.1 RUN_1

During the RUN, maintenance works at the electrical power supply line imposed to turn the power off from the entire experimental area for several days. This blackout occurred in a delicate moment of the fermenter biological start up. To collect reproducible data, the start-up was hence started over from the beginning, losing what done on the previous 30 days.

4.3.2 RUN_2

After a month of RUN_2 in progress, the food waste treatment facility, where the OFMSW was collected, faced an unexpected trouble at the sorting machine. For this reason, they had to temporarily use a wider sorting filter, which resulted in the delivery for few weeks of a OFMSW with different moisture content and particle size. Because of this, the automatic pilot reactor loading system resulted no longer adapt for accurate loading, as the calibration of the system was done with a OFMSW with different physical structure. The lack of accuracy in the feeding for few week no longer permitted to collect valuable data. The RUN was hence stopped after 37 days and the starting of a new experimentation was arranged.

4.3.3 RUN_3

After four weeks of test, some technical problem at the pilot fermenter heating system resulted in a huge foam formation event. The foam was probably consequence of the thermal shocks, that induced the microbial population to produce polysaccharide capsules and other protective extracellular polymeric substances. All those substances, called biosurfactants, are recognize as strong foaming agents in anaerobic digestion (He et al., 2017) (Moeller et al., 2012) (Ganidi et al., 2009). No antifoaming agents (both organic and inorganic), demonstrated to be able to control the problem. The structure of the digestate, after a week, resulted entirely compromised and similar to a pudding cake. The digestate was hence completely disposed after day 39, and a new inoculum was prepared using the outputs digestate from the previous RUNs.

4.3.4 RUN_4

The fourth RUN succeed in reaching the steady state and permitted to collect reproducible data, it is hence deeply analysed and discussed.

Inoculum

Before starting, the digestate from previous RUNs and used as inoculum was sieved through a 1.00-mm membrane and left for mixing at 38°C for 1 month. It was then sampled and its physicochemical characterisation was performed (Table 5).

Start up discussion

As the OLR increased, the daily gas production increased. Figure 18a presents the strong correlation between the OLR and gas production during the start-up period. The target OLR of 6.2 kgVS·m^{-3}·d^{-1} was reached on day 46, and a notable stability in gas production was reached after day 55, with the daily biogas production stabilised at an average of 719 L·day^{-1}. As shown in Figure 18b, CH_4 and CO_2 concentrations at the beginning, specifically during the first 30 days of the experiment when the OLR was increased from 1.25 to 5 kg VS·m^{-3}·d^{-1}, were somewhat variable. After day 30, the gas quality became highly stable, with biogas characterised by 61.4% CH_4 and 38.3% CO_2. The values shown in the graph indicate the daily average of gas analysis performed four times per day (once every 6 h).

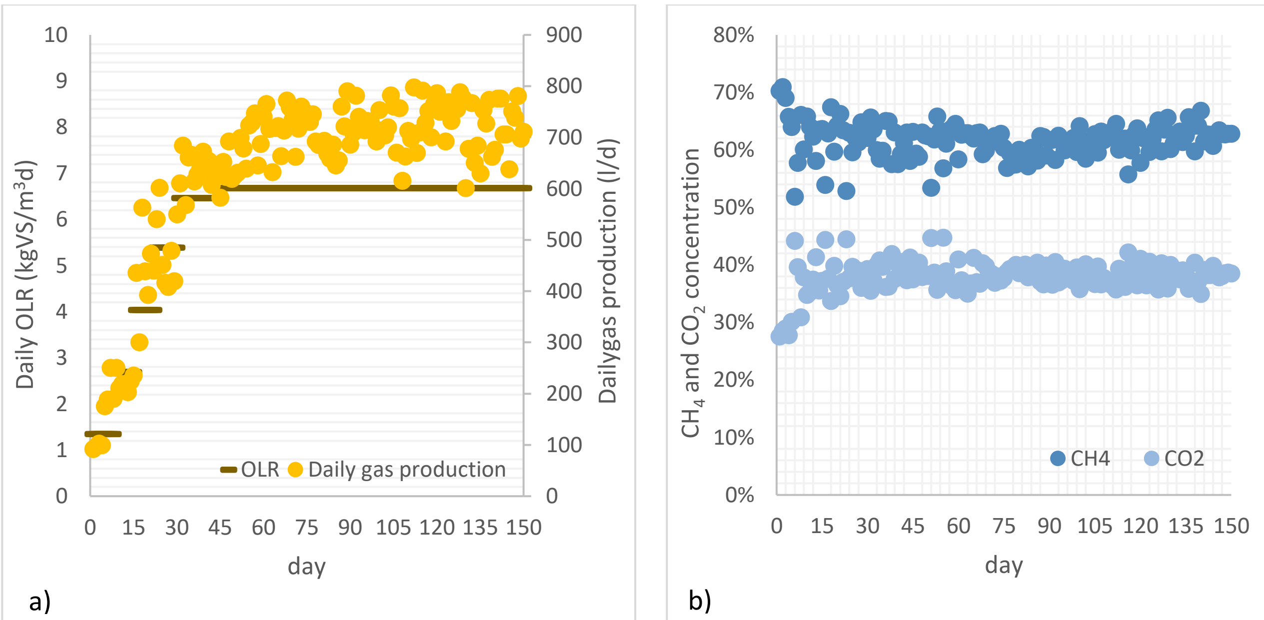


Figure 18: a) Daily gas production and OLR during the start-up and stability; b) CH_4 and CO_2 daily concentration during the start-up and stability.

Figure 19a shows the pH and alkalinity trends and their correlations. The initial pH of the inoculum was 8.05, and this parameter was reasonably stable since the beginning, remaining between 7.5 and 8.0. Conversely, alkalinity required some time to become stable (after day 70). The difference between PA and TA was stable throughout the experiment, with the minimum and maximum values of 1,245 (day 11) and 2,988 (day 123) mg $CaCO_3 \cdot L^{-1}$, respectively. $N\text{-}NH_4^+$ showed a certain variation, with a positive trend for the first 50 days of the experiment, ultimately reaching high stability. The highest $N\text{-}NH_4^+$ concentration was detected at day 15 (2.70 $g \cdot L^{-1}$). Figure 19b shows the variation in $N\text{-}NH_4^+$ concentration during the experiment.

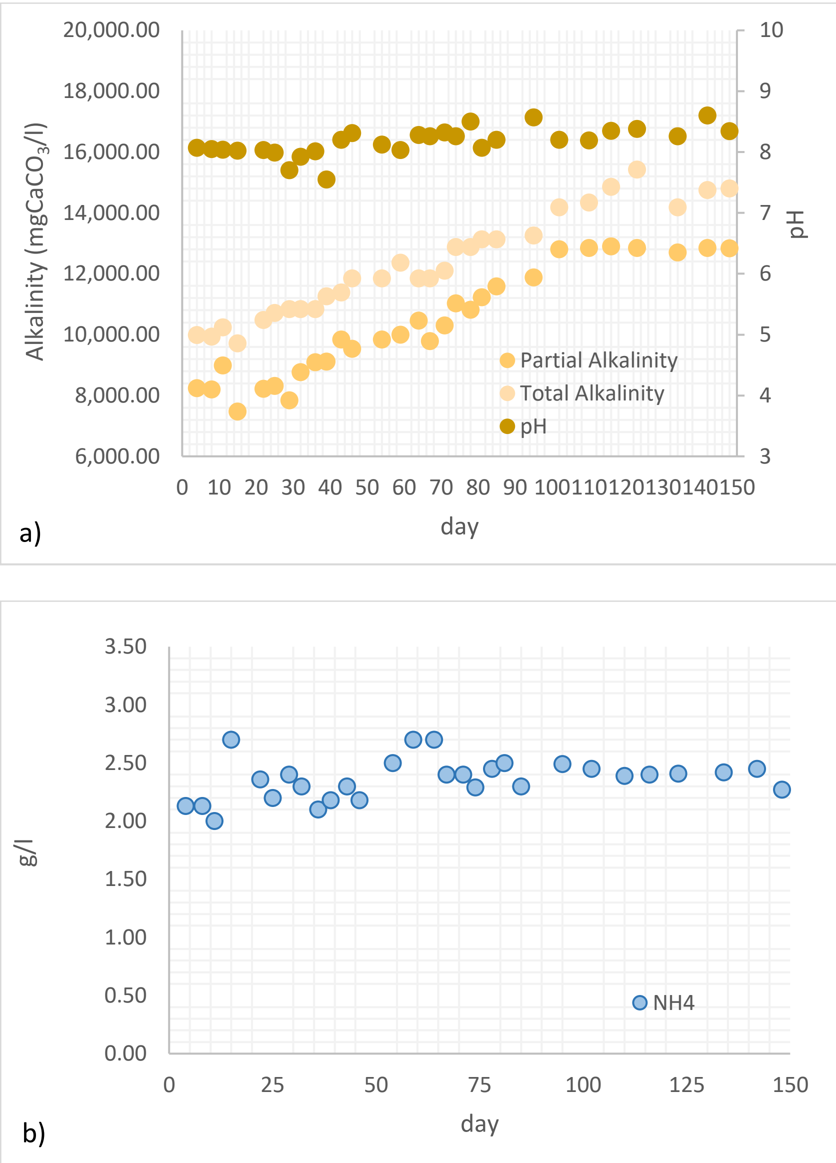


Figure 19: pH and alkalinity (a) and ammonia (b) during start-up and steady state

Regarding VFA, a proper trend could not be identified during the experiment. The results of acetic, propionic and butyric acid monitoring are shown in Figure 20a, 20b and 20c, respectively. Two intermediate peaks were detected both for acetic, propionic and butyric acids, with a trend similarly noted in a previous study (Yirong et al., 2017). The first peak was visible around day 25, when the microorganisms were under stress due to increase in OLR from 3.75 to 5 kgVS$\cdot$m$^{-3}\cdot$d^{-1}. The second peak was observed at around day 70, a few weeks after the stabilisation of the target OLR of 6.2 kgVS$\cdot$m$^{-3}\cdot$d^{-1}. As describes below, a correlation between VFA peaks and sCOD was observed, testifying at day 25 and even more at day 75 a difficulty of organic matter degradation due to OLR. Following this, both acetic and propionic acid concentrations dropped below 1,000 mgCOD$\cdot$L^{-1}, and below 100 mgCOD$\cdot$L^{-1} butyric acid aconcentration.

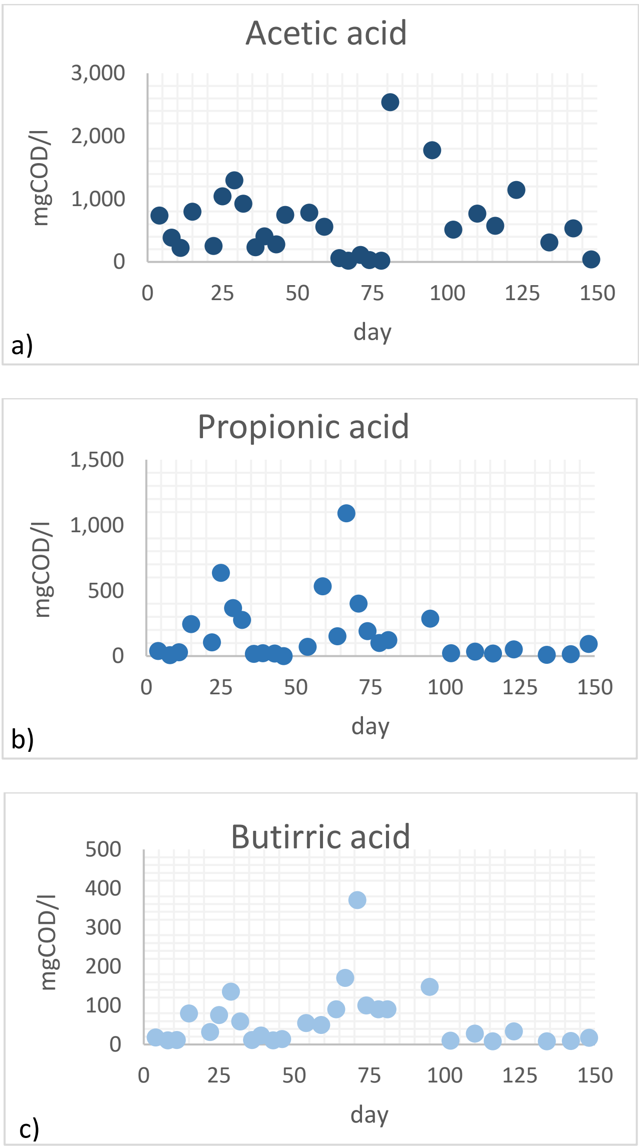


Figure 20: Acetic acid (a) Propionic acid (b) and Butyrric Acid (c) during the start-up and stability

Steady-state and process parameters

As reported in the previous paragraph, different parameters reached stability at different times. Analysis of process and stability parameters showed that a steady state was reached after day 72. As a proof of the correctness of this selection, SGP and GPR were calculated every day on the basis of daily average gas production during the previous 26 days, assuming that 26 days correspond to the HRT at the steady state, as reported in Eqs. 1 and 2. This expansion permitted to better evaluate when gas production stabilised.

Eq. 1 $SGP_d = \frac{\left(\frac{\sum_{i=d-26}^{d} Q_d}{26}\right)}{TVS_d}$

Eq. 2 $GPR_d = \frac{\left(\frac{\sum_{i=d-26}^{d} Q_d}{26}\right)}{V_{REACTOR}}$

where:

$SGP_d = Specific\ gas\ production\ at\ day\ d$

$GPR_d = Gas\ production\ rate\ at\ day\ d$

$Q_d = Daily\ gas\ production\ at\ day\ d$

$TVS_d = Total\ volatile\ solids\ fed\ at\ day\ d$

$V_{REACTOR} = Reactor\ volume$

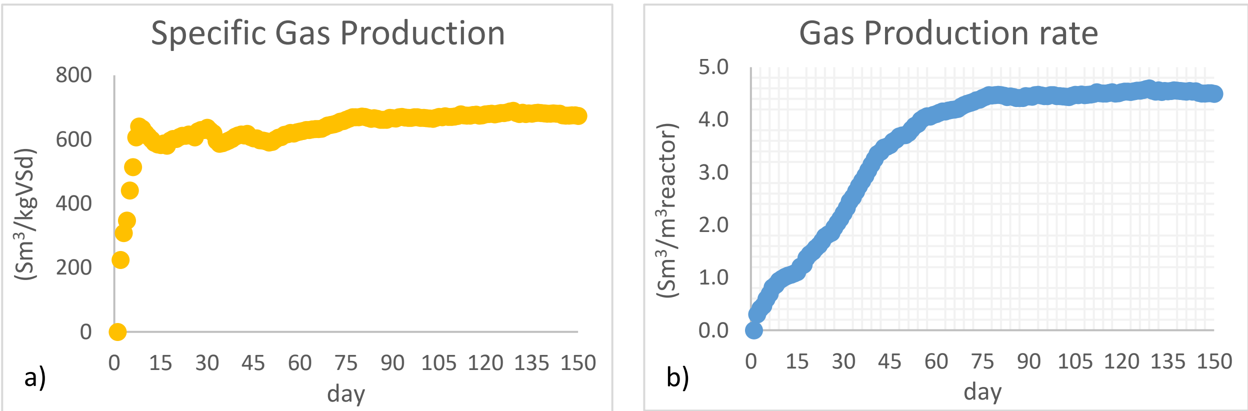


Figure 21: Specific Gas Production (a), and Gas Production Rate (b), calculated on the previous 26 days

The results are shown in Figure 21a and 21b; the trends clearly show that SGP and GPR stabilised after day 72, confirming the results of the preliminary analysis of the process and stability parameters. The experiment was carried out until day 150, after which the steady state was achieved for a period equivalent to 3 HRT.

At the steady state, in the reactor, TS content was 83.6 g·kg^{-1} and VS content was 60.1% of TS. How TS and VS reached stability is reported in Figure 22. TA was 13,840 mg$CaCO_3$·L^{-1}, and PA was 12,046 mg$CaCO_3$·L^{-1}; both parameters were at the steady-state conditions, as reported previously (Martín-González et al., 2013). The difference between TA and PA was 1,794 mg$CaCO_3$·L^{-1}, indicating the stability of the biological process (Palacios-Ruiz et al., 2008). No chemical-mediated pH control was used, to investigate the possibility of sustaining the process without chemical addition. The average measured pH of 7.8 was naturally established as a result of the steady state. This value is much higher than the pH of 5.3, which characterises fresh incoming OFMSW, confirming that the alkalinity achieved by the biochemical system and the balance between VFA-forming and VFA-consuming reactions are sufficient to maintain the required pH for methanogenesis (Lavagnolo et al., 2018).

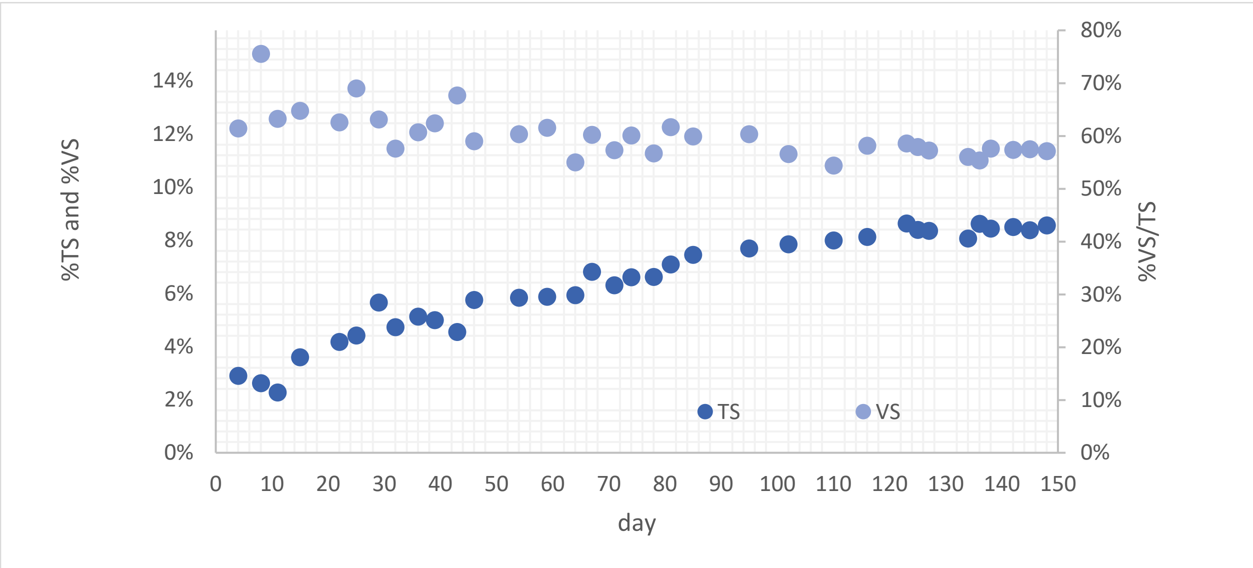


Figure 22: Solid content during steady state

Total VFA content was 1,950 mgCOD·L^{-1}. Results of characterisation are presented in Table 6. Although the overall trends of all process and stability parameters reached a steady state, VFA content at equilibrium was not low, proving the presence of biodegradable carbon in the solution, which must be taken into account to estimate the final fate of the digestate.

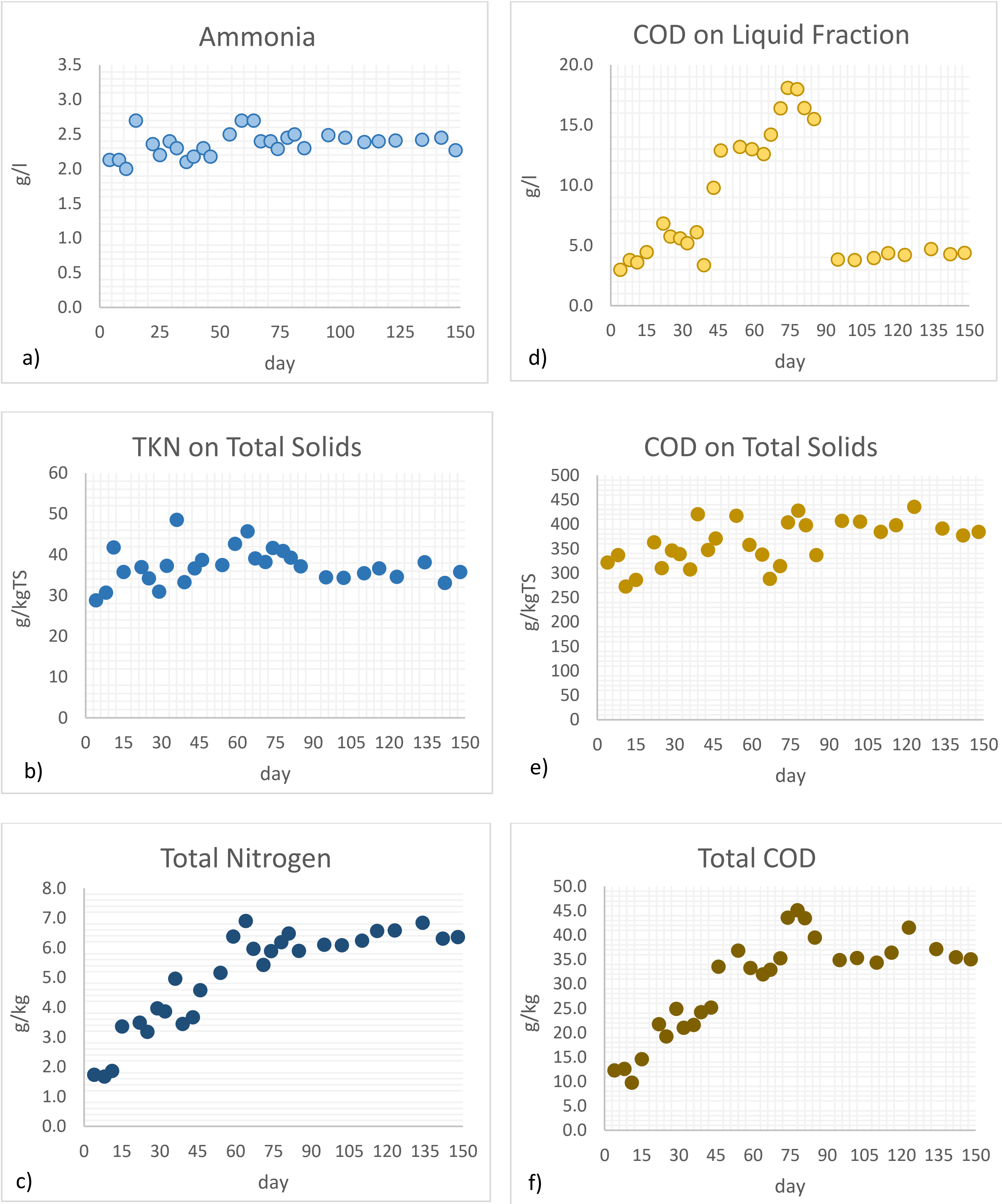


Figure 23: Process parameters during steady state a) Ammonia; b) TKN on dry material; c) Total Nitrogen; d) SCOD on the liquid fraction; e) COD on dry material; f) Total COD

At the steady state, $N\text{-}NH_4^+$ concertation in the digestate liquid fraction was 2.4 $g \cdot L^{-1}$, accounting for 41% of TN in the fed substrate. $N\text{-}NH_4^+$ is one of the main inhibitors of AD, and the typical inhibitory behaviour of $N\text{-}NH_4^+$ is realised when its concentration exceeds 1.5–2.0 $g \cdot L^{-1}$ (Rajagopal et al., 2013) (Salerno et al., 2006). In a previous review (Chen et al., 2008), stability was achieved even at high $N\text{-}NH_4^+$ concentrations. Similarly, in the present study, no signs of inhibition were observed. As reported previously (Poszytek et al., 2017) (Cheng et al., 2020) (Yirong et al., 2017) (Poirier et al., 2017), microbial adaptation to high $N\text{-}NH_4^+$ concentrations is a key factor to avoid instability and inhibition. In the present experiment, the start-up was performed with a slight increase in OLR, and continuous feeding was maintained every 2 h for 7 days a week, thus avoiding localised OLR shock. This approach allowed the microbial community to adapt to an $N\text{-}NH_4^+$ concentration of 2.4 $g \cdot L^{-1}$. Trend of Ammonia is again reported in Figure 23a where a comparison with the other nitrogen forms (TKN and TN) is done.

On the TS, the TKN at the steady state was 35.8 $gN \cdot kgTS^{-1}$. Figure 23b shows that it was quite stable for all the entire duration of the experimentation. This is probably related to the mechanical pre-treatment, that demolished the physical structure of the Organic Matter (OM) at the point to be suddenly accessible to the microbial communities. For this reason, after introduction, the OM loses its hydrolysable nitrogen in a very short time and suddenly reaches the equilibrium concentration. The nitrogen found in the solid component of the digestate at the steady state was probably enclosed in the recalcitrant fraction (to hydrolysis) of the OM, that is lignin mainly (Tambone et al., 2009). By observing Figure 23b it is however very clear that for the first 75-80 days of experimentation, the TKN concentration on solids was quite unstable. After day 78, the TKN reaches a stable concentration with a low %SD of 4.5%. This behaviour is probably related to the TS fate in the first period of the test. It is probable that until the TS haven't reached the stability, some sedimentation occurred. At the bottom of the digester a thin layer of heavy solids (shields, bones, seeds, small residual inerts etc) may have deposited, until reached by the agitator shafts. Until this point, the TS quality on the digestate was not representative and kept changing because of sedimentation in progress. As long as the agitator shafts started to resuspend the sedimented material, a balance between sedimentation and bringing the solids back into suspension was achieved, so a better homogenization of the TS content and quality in the digestate was possible, with evident repercussion on TKN stability. Figure 23c shows how the TN stability was reached. In the first three months, the TN in the digestate shown an increasing trend, to reach stability between day 90 and 100. Explanation of this observation bust be researched in the TS trend, that needed more or less the same period to stabilize. On the digestate, in fact, the 44% of the TN comes from the liquid fraction and the 56% comes from the suspended solids in the digestate. An increase in TS concentration in the digestate, determines a sensible increase in the TN of the digestate. Figure 24 shows how the different contribution of Nitrogen in the liquid fraction and in the Solid fraction, evolved during the 150 days of test.

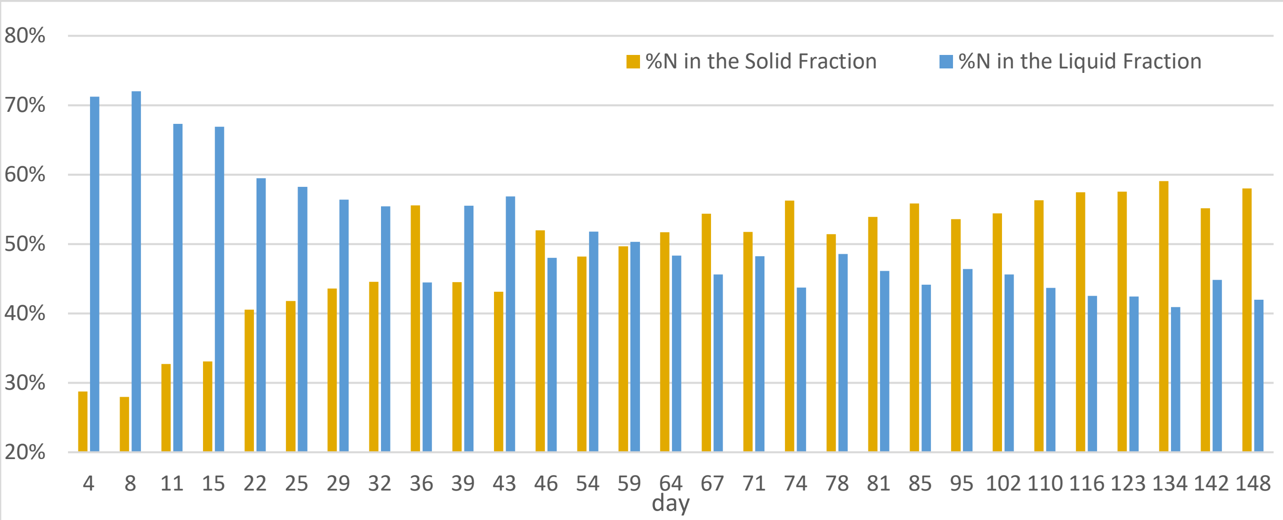


Figure 24: shows how the different contribution of Nitrogen in the liquid fraction and in the Solid fraction, evolved during the 150 days of test.

While Nitrogen in liquid fraction was preponderant due to ammonia, nitrogen on the solid fraction has become more and more prominent as long as the TS increased. TN at steady state was 6.4 $gN \cdot kg^{-1}$. Comparative values in nitrogen and carbon distribution in similar conditions can be found in literature (Schievano et al., 2011).

Regarding the sCOD, the trend is reported in Figure 23d. It possible to observe an intermediate peak on its concentration occurred in proximity of day 75. After this peak, where sCOD reached 18.1 $gO_2 \cdot L^{-1}$, a stability was reached with an average value of 4.2 $gO_2 \cdot L^{-1}$. This behaviour is strictly similar to what observed for VFA, and its relation with previous works is already discussed above. The sCOD trend however (Figure 23e), confirms a momentaneous stress lived by the acetogenic and methanogenic microorganism, as consequence of the OLR increasing. Acclimatation, again, showed to be the key factor to permit the steady state and avoid the process failure. The COD in the solid fraction, instead, shown a trend very similar to the one observed for TKN, with an initial phase of wider instability, and a steady state reached after day 74. At the steady state COD is 396 $gO_2 \cdot kgVS^{-1}$. Explanation of this observation is the same than for TKN and also the way with which the total COD reach stability is strictly similar that for TN, how shown in Figure 23f. Again, the reason comes from the TS, as 89% of the total COD came from the COD in the solid fraction, and only 11% came from the sCOD. The balance between the two aliquots, liquid and solid, is quite regular across the whole 150 days of experimentation. Total COD at steady state was 125.1 $gO_2 \cdot kg^{-1}$.

The mass balance was calculated based on TS, VS, COD and TN and it is schematically reported in Figure 25. At steady state, influent TS and VS were respectively 1.36 and 1.08 $kg \cdot d^{-1}$. The solids converted into biogas, both as TS or VS, were 0.82 $kg \cdot d^{-1}$, calculating using a stochiometric factor of 1.14 that is the one specific according to the biogas composition. The output TS and VS were respectively 0.43 and 0.22 $kg \cdot d^{-1}$. The solids removal efficiency was 61% for TS and 77% for VS.

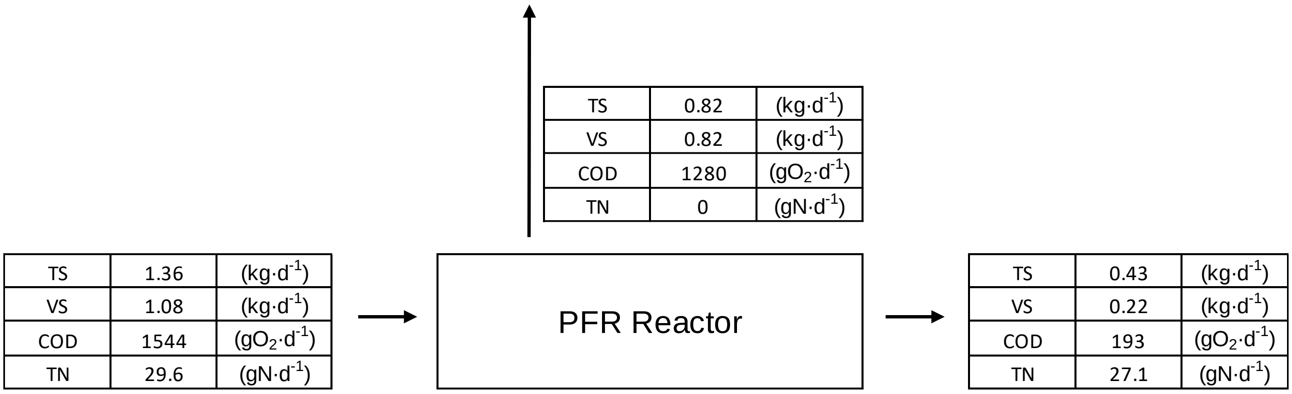


Figure 25: Mass Balance of the basis of TS, VS, COD and Nitrogen

The influent COD at the steady state was 1,544 $gO_2 \cdot day^{-1}$ and the effluent COD during biogas production was 1,280 $gO_2 \cdot day^{-1}$, with a conversion coefficient of 0.35 m^3 $CH_4 \cdot kg^{-1}$ COD, which is equal to the maximum theoretically possible value (stoichiometric). Residual effluent COD of the digestate was 193 g $O_2 \cdot day^{-1}$, and the COD removal efficiency was 83%. Considering the nitrogen, during the steady state, the calculated influent TN was 29.6 $gN \cdot d^{-1}$ and the effluent was 27.1 $gN \cdot d^{-1}$. Mass balance resulted in an error of 7.6% for TS, 2.8% for VS, 4.6% for COD and 8.3% for TN. The system balance, as defined, confirmed the steady state.

Gas quality monitoring showed an average biogas composition of 61.4% CH_4 and 38.2% CO_2. Average H_2S concentration was 358 ppm. Finally, average SGP was 0.674 $Sm^3 \cdot kg^{-1}$ VS in terms of biogas and 0.414 $Sm^3 \cdot kg^{-1}$ VS in terms of methane. As reported in Table 6, variations in parameters were significantly lower than 10%, indicating steady-state conditions. Of note, all observed values were slightly lower than the reported ones, specifically with wet processes (Cecchi et al., 1992) (Chatterjee and Mazumder, 2019) (Micolucci et al., 2018); importantly, however, SS-OFMSW was not artificially reproduced and was collected as available at a full-scale plant. Hence, a certain degree of plastic impurities must be considered, implying a lower gas production when referred to the VS fraction. Average GPR was 4.5 $m^3 \cdot m^{-3}{}_{REACTOR}\ d^{-1}$. For full-scale upgrading, gross biogas production of 116 $Sm^3 \cdot t^{-1}$ is the reference parameter for fresh OFMSW. Average and standard deviation values of all parameters at the steady state are reported in Table 6.

Table 6: Average and standard deviation values for all the parameters at the steady state

Parameter	Measure unit	Average value	Standard deviation	Day for reaching stability
TS	$(g \cdot kg^{-1})$	83.6	±1,7	116
VS	$(g \cdot kg^{-1})$	50.2	±1.9	116
VS	(%TS)	60.1%	±1.0%	116
pH		7.85	±0.14	85
Partial alkalinity	$(mg\ CaCO_3 \cdot L^{-1})$	12,046	±949	85
Total alkalinity	$(mg\ CaCO_3 \cdot L^{-1})$	13,840	±1,000	85
Total VFA	$(mg\ COD \cdot L^{-1})$	1,956	±1,210	78
Acetic acid	$(mg\ COD \cdot L^{-1})$	755	±787	78
Propionic acid	$(mg\ COD \cdot L^{-1})$	113	±129	78
Butyric acid	$(mg\ COD \cdot L^{-1})$	81	±107	78
Pentanoic acid	$(mg\ COD \cdot L^{-1})$	39	±52	78
Hexanoic acid	$(mg\ COD \cdot L^{-1})$	834	±1,012	78
Heptanoic acid	$(mg\ COD \cdot L^{-1})$	97	±96	78
S-COD	$(g\ O_2 \cdot L^{-1})$	4.2	±0.3	95
COD on TS	$(g\ O_2 \cdot kg^{-1} TS)$	396	±25	74
COD TOT	$(g\ O_2 \cdot kg^{-1})$	125.1	±12.3	95
NH_4^+	$(g \cdot L^{-1})$	2.4	±0.1	95
TKN on TS	$(gN \cdot kg^{-1} TS)$	35.8	±1.6	78
Total Nitrogen	$(gN \cdot kg^{-1})$	6.4	±0.3	95
CH_4	(%)	61.4%	±2.2%	90
CO_2	(%)	38.2%	±1.4%	90
H_2S	(ppm)	358	±136	90
SGP	$(m^3 \cdot kg^{-1}\ VS)$	0.674	±0.043	77
GPR	$(m^3 \cdot m^{-3}{}_{REACTOR} d^{-1})$	4.5	±0.3	77

Results of previous studies carried out under similar conditions (mono-digestion of OFMSW with 20% TS in feed) are reported in Table 7. Of note, a better performance in terms of SGP and GPR was obtained with the conditions in the present study. Only one study (Pavan et al., 2000) obtained similar SGP and GPR with pure SS-OFMSW digestion. However, the authors reported unstable process conditions and possible process failure at an OLR as high as 6 kg VS·m^{-3}·d^{-1}. Therefore, they set the OLR of 6.0 kg VS·m^{-3}·d^{-1} as the maximum limit for single-phase processes and recommended two-phase digestion to evaluate whether better stability could be achieved (condition that would have consequently lowered GPR of the process). According to these reports, even a slightly higher OLR applied to stable, single-phase digestion, agitation efficiency, and grade and purity of the fed OFMSW and prolonged HRT are recognised as the key factors for increasing the process performance.

Table 7: Comparison of different OFMSW digestion results (rearranged from Bolzonella et al., 2003) (SS: source selected; MS: mechanically selected)

Reference	SGP (m^3·kg^{-1} VS)	GPR (m^3·m^{-3} d^{-1})	OLR kg VS·m^{-3} d^{-1}	TS in feed (%)	HRT (d)	Type of OFMSW
This study	0.67	4.5	6.2	20.5	26	SS + MS
Bolzonella et al. (2003)	0.23	2.1	9.2	20	13.5	MS
Cecchi et al. (1991)	0.26 - 0.40	2.5-4.1	5.9 - 13.5	16 - 22	8 - 15	MS
Mata-Alvarez et al. (1993)	0.32 - 0.37	3.1-6.1	9.7 - 17.8	18 - 25	8 - 12	MS
Vallini et al. (1993)	0.3	4.1	13.5	22	7.8	MS
Pavan et al. (2000)	0.32	3.1	9.7	25	11.7	MS
Pavan et al. (2000)	0.78	4.9	6	10	11.8	SS-
Scherer et al. (2000)	0.22	5.7	7.6	16	18	MS
Bolzonella et al. (2006)	0.71	3.2	4 - 6	33	40 - 60	SS
Schievano et al. (2012)	0.74	1	1.3	3.9	25	SS
Micolucci et al. (2018)	0.75	2.5	3.5	30	20	SS
Jo et al. (2018)	0.73	1.4	2	10	50	SS
Ganesh et al. (2014)	0.81	1.1	2	12.7	80	SS

Hygienic quality

As pathogenic bacteria are known to affect in general any kind of biowaste, with a potential health risk both people and animals (Sahlström, 2003), a microbiological analysis was conducted to asses hygienic quality and suitability of the digestate as fertilizer. The content of Escherichia Coli, Coliforms and Salmonella were quantified of three samples, for five repetition each, and results are reported in Table 8. Escherichia Coli were found in all the five repetitions of one sample only. The average E. Coli, in the contaminated sample, was

160 ± 134 $UFC \cdot g^{-1}$. This almost means absence of contamination as the EU limit is 1000 $UFC \cdot L^{-1}$ (European Commission, 2014). Coliforms were detected in all the samples in the average measure of 1423 ± 458 $UFC \cdot g^{-1}$. This value is very low as it is already under the limit for quality compost (Teglia et al., 2011). No Salmonella was detected in any of the feed or digestate samples, according to the observation of previous studies that show how Salmonella is not detected after 10 days at 37°C (Sahlström, 2003). Those values are very low and testifies, as reported already elsewhere, a good sanitation ability of the anaerobic process (Micolucci et al., 2016) (Tampio et al., 2015). Moreover, the presence of enteric bacteria with this contamination degree can be easily eliminated by adopting a digestate post-composting treatment (Cekmecelioglu et al., 2005).

Table 8: The content of Escherichia Coli, Coliforms and Salmonella, quantified on three samples during steady state, for five repetition each

Sampling day	Repetition	E. coli UFC/g	Coliformi UFC/g	Salmonella pres-abs/25 g
117	1	n.r.	1600	absent
117	2	n.r.	1800	absent
117	3	n.r.	2000	absent
117	4	n.r.	2000	absent
117	5	n.r.	1500	absent
123	1	n.r.	1200	absent
123	2	n.r.	1400	absent
123	3	n.r.	2000	absent
123	4	n.r.	1700	absent
123	5	n.r.	1300	absent
135	1	400	500	absent
135	2	100	700	absent
135	3	100	1200	absent
135	4	100	1300	absent
135	5	100	1000	absent

4.4 Conclusion

The research demonstrated that SS- OFMSW can be treated in a mesophilic PFR fermenter with an elevate OLR of 6.2 $kgVS \cdot m^{-3} \cdot d^{-1}$ and without any dilution or co-substrates addition. Steady state was observed for all the process parameters, the mass balance of Solids, COD and TN, closed with an error below 10%. Sedmentation must severely be avoided to allow full exploitation of the entire fermentative volume. Mixing system must also be able to avoid formation of floating layers or crusts, in order to assure smooth spill and release of the methane, that would otherwise be toxic for the biological system. TS reached at the steady state was 8.4%. This is related to the high degree of purity of the fed OFMSW and of its degradation potential. The density of the digestate could potentially however cause troubles of mixing efficiency if a normal propelled agitation system is adopted. The process results stable as single stage reactor, no needs of digestate recirculation was detected. The elevate load resulted in a SGP of 0.67 $Sm^{-3} \cdot kgVS^{-1}$ in terms of biogas, and of 0.41 $Sm^{-3} \cdot kgVS^{-1}$ in terms of methane. The low reduction of SGP respect to low solids wet digesters (where SGP of SS-OFMSW is usually > 0.7 $m^3 \cdot kg^{-1}VS$) was justified by a high GPR, that was found to be 4.5 $m^3 \cdot m^{-3} \cdot d^{-1}$ as average on 3 HRT of process stability, so it is considered a good balance between energy extraction and digester size. Hygienic quality of the digested have been assessed with the three main microbial indicators (E. Coli, Coliforms, Salmonella); pathogens contamination is already very close to the safety limits for quality compost, demonstrating that the process is able to assure high degree of sonification. A subsequent step for aerobic stabilization is for sure able to completely remove the residual pathogenic contamination. These results encourage the treatment of sole OFMSW, without necessity of dilution (with water or wastewater) or co-substrates (lignocellulosic materials), and the diffusion of relatively small and easier plants. A proper composting technology to transform the digestate in quality compost must however been foreseen.

Improvement in the tested scenario could be obtained by using an SS-OFMSW with higher TS content. With the same digesting volume and OLR, this would lead to a higher HRT that could be useful for enhancing the SGP. An increased HRT would also probably help to decrease the steady state VFA concentration, detail that would make the subsequent digestate composting easier. Future investigation on rheology could also be useful to understand the mixing attitude of the digestate and to support the design of a proper agitation system.

5. ECONOMIC EVALUATION

5.1 Purpose of the economic evaluation

The ultimate goal of the research is to outline if there are conditions that allow a simplification of AD plants in order to promote their diffusion and a global increase of the amount of OFMSW anaerobically treated. The experimental work showed that, technically, the anaerobic process in a PFR could be stabilized even at single stage, with high OLR and without recirculation. The purpose of this Section is to evaluate the different contribution of CAPEX and OPEX in the economy of scale, and under what conditions a small plant is economically sustainable

In this Section, a brief analysis of the regulatory framework of reference is done, mainly to point out the economic value of the renewable energy produced through the AD of the OFMSW, according to the current regulation in Italy. Proper Business Plans (BP) of realistic projects are then delineated, to study the economic sustainability and profitability of different scenarios, and draw general conclusion on the feasibility of the layout studied in this research. Before, a description of the methodology on how CAPEX and OPEX are estimated and how in general the BP is calculated, is presented.

5.2 Regulatory framework of reference

5.2.1 EU and Italian reference regulations

The Renewable Energy Directive 2009/28/EC and its recasts directive 2018/2001/EU, are still the regulations that establish an overall policy for the production and promotion of energy from renewable sources in the EU. With the RED recasts, EU set the target of achieving with renewable energy at least 32% of its total energy needs and at least 14% of its transport fuels, by 2030. Strengthened criteria for ensuring bioenergy sustainability are also included. Anaerobic Digestion, besides a waste treatment technique, is a whole bioenergy source as it can be exploited for fuel production (biomethane) and for heat and electricity production (co-generation).

In transposition of the European directive, several national regulations have been published to increase the renewable energy production and meet the EU targets. In Italy the Law Decree DL 28/2011 is the standard regulation that provides the governances on how the renewable energy incentive rules must be done. After it, more specifics laws followed, all issued by the Ministry of Economic Development, with technical and operative mechanisms for supporting the diffusion of new renewable energy plants.

5.2.2 Anaerobic Digestion for electricity production

At date, the last law that provided economic incentives for the electricity production through AD, is the DM 23/06/2016 issued by the Ministry of Economic Development. The law foreseen a fixed tariff of 0,233 € per kWh_{el} produced by biogas plants fed with OFMSW, agricultural residuals or energy crops. The law expired on the 31/12/2017, but it has been again reactivated by the 2019 Financial Law (DL 145/2018) with some limitations. In particular it was reproposed for small plants with Combined Heat and Power (CHP) units up to 300 kW_{el}. The OFMSW was however no longer included between the possible feedstocks for producing incentivized electricity. AD plants for electricity production can be built and connected to the grid, as yet regulated by the law DL 387/2003 (art. 12), that gives the rules on the process the renewable energy plants must follow for their authorization. At date, however, they don’t receive any tariff as economical support.

5.2.3 Anaerobic Digestion for Biomethane production

In Italy, at the date, the incentive mechanism for biomethane production by AD is regulated by the law DM 02/03/2016 issued by the Ministry of Economic Development. The law comes from the previous DM 05/12/2013, a law that foreseen an incentive mechanism so complex that the expected incentives was extremely difficult to calculate. Banks didn’t trust to release financing for this kind of plants, and that resulted in only one demonstrative plant built and connected to the grid. The DM 02/03/2016 was released before the ending of the DM 05/12/2013, repeals the previous one and introduces an easier calculation mechanism.

The incentive is based on the concept of *Release Certificates for Consumption*; in Italian they are called CIC (*Certificati di Immissione al Consumo*), firstly introduced by the Ministerial Decree DM 110/2008. They are certificates released in favour of fuels producers from renewable energy sources, and they are exchanged with who produces fuels from non-renewable primary sources, in a virtual CIC market. Every fuel producer is obligate to introduce for consumption a minimum share of biofuels. If not producing, obliged parties may fulfil their obligation, in whole or in part, also through the external purchase of the equivalent share of CIC. Biomethane is hence valorised being sold according to the methane price marked, plus by selling the CIC according to the principle mentioned above. The

DM 02/03/2016 does not fix any deadline for CIC generation: who have the right to receive them, will receive them as long as biomethane is injected into grid.

The biomethane produced by the treatment of the OFMSW in AD plants equipped with biogas upgrading, is all recognize as *Advanced Biomethane*, a technical category defined by the law mentioned above. This status, respect to the biomethane not recognized as *Advanced*, gives two main advantages:

1. Generation of double CIC per unit of energy produced for consumption, that means generation of 1 CIC every 5 Gcal injected into the grid; compared to 1 CIC every 10 Gcal for not-advanced biomethane;
2. Management of the CIC by the Energy Services Manager, in Italian called *Gestore dei Servizi Elettrici* (GSE), for 10 years. This implies that the Advanced Biomethane can be sold to the GSE, who pays a fix tariff according to a calculation done monthly on the basis of the market price. The GSE then sell them back into the market by itself. Even if it means, for the biomethane producer, a lower valorisation of the selling price and CIC value, respect to the price that could be achieved selling them directly into the market, this approach gives a very important advantage. The possibility of a fix and definite withdrawal price by the GSE, make the project much more financially bankable, and that means to make the project practically feasible.

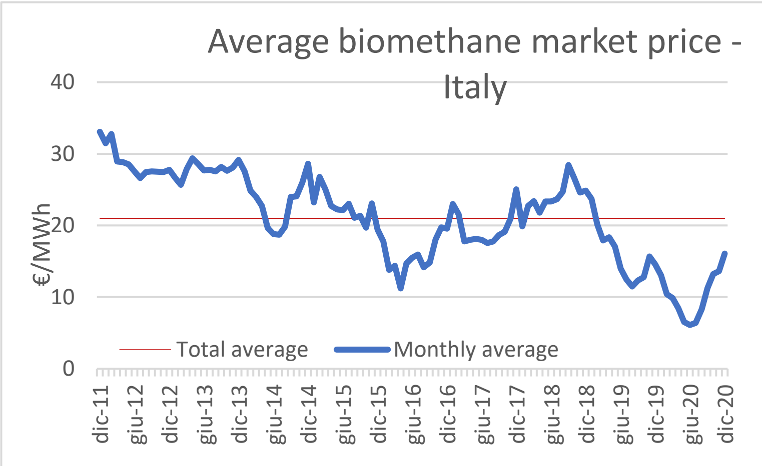
According to the mechanism explained above, from a practical economic point of view, the biomethane produced by the AD of the OFMSW, the minimum biomethane value for a producer can be calculated as following:

1. Receiving 1 CIC every 5 Gcal of biomethane injected into the grid. The CIC is then paid by the GSE at the fix price of 375 € each, this means for a biomethane with 99% of CH_4, a valorisation of 0.585 €·Sm^{-3};
2. Selling the biomethane directly to the GSE at the market price detracted of 5%. The market price is defined in the aftermath, on the basis of the daily price fluctuation and on the basis of the local availability of methane in the area, following a complex calculation. Figure 26 shows the variation of the biomethane price during the last years. The price is not really stable, the average price for 2021 is shown in Figure 26.

On the basis of it, the BP and Economic Simulation presented in the following sections, are elaborated.

In addition to this, the regulations allow a biomethane producer to build an own Compressed Natural Gas (CNG) or Liquified Natural Gas (LNG) pumping station for transport destination.

In this case, besides having higher valorisation of the self-produced biomethane (as it is directly sold to the consumers), a further incentive is also issued for the building of CNG or LNG plant. The incentive covers maximum the 60% of the constructing value of the pumping station, and up to maximum 600,000 € for CNG € and 1,200,000 for LNG. The incentive is paid by releasing of +20% of CIC, util the total amount of the subsidy is reached.



Year	€/MWh
2012	28.54
2013	27.85
2014	23.23
2015	22.48
2016	15.81
2017	19.63
2018	23.94
2019	15.87
2020	10.27

Figure 26: Monthly variation of the biomethane price over the last years, and average calculation of the relative annual average. Adaptation by GME data (https://www.mercatoelettrico.org)

5.3 Methodology

5.3.1 Plant Design

For the economic analysis, different plant size layouts are compared. In all cases, according to the experimental results, the reactor is always a PFR type as built by the company Schmack Biogas under the commercial name of Euco®. This fermenter is the upscaled version from which the pilot system derives. It is equipped with an agitator along the whole length of the digester; the agitator shaft is divided in two sections, each driven by a gearmotor 7.5 kW located outside the fermenter. The agitator is run 24/24 hours. On the layouts analysed, a different number of fermenters, or a fermenter with a different volume, are installed in order to satisfy the necessary OFMSW treatment capacity according to the plant size. For dimensioning the fermentation volume, the experimental OLR and HRT were used, that are 6.2 kg $VS \cdot m^{-3} \cdot d^{-1}$ and 26 d respectively. The OMSFW fed is supposed to have the same physicochemical characterization that at the pilot scale and already reported in Table 4. Regarding biogas production, the experimental SGP of 0.674 $Sm^3 \cdot kg^{-1}$ VS is applied.

Costs considered at the basis of the BP for the economic study of this section, are estimated for all the components necessary to operate an AD plant of organic waste treatment, according to a turn-key supply approach. Everything installed and built inside the perimeter fence of the plant, and all the related costs, are taken in count. It is foreseen to receive SS-OFMSW directly from collection, to mechanically pre-treat it, to anaerobically digest with biomethane or electricity production, and to aerobically stabilize the digestate in order to produce quality compost.

For the mechanical sorting of the incoming SS-OFMSW, an Hammer Mill by Wackerbauer GmbH is considered to be used. The machinery type is the one already analysed and described in section 3.3.1. Only for the smaller size plant (treatment of 3,500 $t \cdot y^{-1}$ of OFMSW), a combined bio-separator by DODA (Buscoldo, MN, Italy), BIO800 Series, is used (DODA, 2021). The reason at the basis of this choice is related to the fact that, in the market, only few machineries are available for treating small quantities of food waste per day, and the one manufactured by DODA is considered the best compromise between costs, efficiency and mechanical reliability for a 20-year lasting project. In both cases, the percentage of the reject material produced by the SS-OFMSW is considered fixed at 5% as precautionary parameter according to previous works (Zhang et al., 2013).

Regarding the post-treatment technology for quality compost production, all the layouts have considered the installation of the CLF Modil® manufactured by Biogest Srl (Cantiano, PU, Italy). It consists on a rectangular reinforced concrete tank where lignocellulosic material is placed (chopped straw, leaves/grass/plant materials, sawdust, wood chips, chopped corn stalks, etc.). A self-propelled carriage runs daily along the length of the yard distributing the exhaust digestate on the absorbent material. The carriage is also provided with a mixing system operated by screws, to allow aeration and evaporation of the lignocellulosic bed. This system is able to produce water adsorption and evaporation, as long as oxidative stabilisation of residual organic matter by aerobic microorganisms. The unique output is hence a quality compost usable as a fertilizer (BIOGEST, 2021), so no liquid fraction is produced by the treatment plant. The treatment costs for the output digestate disposal are hence indirectly quantified in the CAPEX and OPEX as costs for the installation and operation of a technology that permits to avoid the production of a liquid fraction. The installation is modular, so according to the treatment capacity required (according to plant size), one or more tunnels are foreseen. Few details of the CLF Modil® system are shown in Figure 27.

The biogas produced is considered to be utilized for biomethane production or co-generation, according to the case. For biogas upgrading into biomethane, the Carbotech Gas Systems GmbH (Essen, Germany) technology is chosen. For sizes above 300 $Sm^3 \cdot h^{-1}$ of raw biogas, the Pressure Swing Adsorption (PSA) technique is utilized; for smaller sizes the utilization of membranes is foreseen. For cogeneration, a 100 kW_{el} Combined Heat and Power (CHP) unit is foreseen, with electrical efficiency of 38.5% and thermal efficiency of 42.5%. Many manufactures of those types of CHP units are available, almost all with similar costs and characteristics. For this reason, not a specific model is inserted in the BP but an average market price is used for the BP calculation.

Figure 27: Details of the composting system manufactured by BIOGEST srl

5.3.2 Costs Evaluation

CAPEX

All the investment costs for a turn-key plant have been considered for calculating a proper BP. They are estimated by the company Schmack Biogas according to its experience in full scale plants realisation, and based on costs evaluation for recent projects. For allowing an evaluation and a comparison, all the CAPEX have been summarized in 15 expenditure items. Table 9 reports the 15 expenditure items there are cited in the following sections, and what costs they include.

Table 9: Synthesis and schematization of the CAPEX expected for the construction of an AD plant for OFMSW treatment

	CAPEX category	**Cost items included**
1	Anaerobic Digestion plant and biogas utilization unit	Fermenters, sensors, piping, support tanks, pumps and valves, gas storage units, electrical system, safety torch, technical control room with cabinets and all the instruments/devices needed, safety circuits, building finishes and everything not in detail specified but necessary for the operating of the fermenters. BUP or CHP unit according to the biogas utilization.
2	Shed for OFMSW pre-treatment and biofilter	Shed for hosting the OFMSW sorting system, biofilter, ventilation and depressurization system, all the facilities necessary for providing a work environment.
3	System for OFMSW pre-treatment and solid-liquid separation	Machinery for OFMSW pre-treatment and impurity removal, machinery for the solid-liquid separation of the exhaust digestate.
4	Yards for compost and green storage	Covered yards for storing the mature compost or the lignocellulosic material for the biofilter of composting unit.
5	Dynamic composting tunnel	The entire Biogest supply, as described in section 5.3.1.
6	Office and weight	The weight at the entrance of the plant for weighting the incoming or outcoming materials, and it supporting office.
7	Anti-intrusion system	Sensors, cameras, remote access and control system.
8	Fire system	Fire sensors, water tanks and dedicated pump, pipes, hoses for firefighters, lightning rod system.
9	Electrical connection, lighting and electrical systems	Wires, laying of corrugated pipes, electrical panels, switches, and everything needed for the electrical power supply and lighting of the area.
10	Fence and gates	Perimeter wall, fences, entrance gate, service gate for vehicles, perimeter mitigation trees.
11	Technological networks	Internet supply and other communication networks.
12	Soil preparation	Excavation, soil stabilization, debris disposal, viability.
13	Inoculum and biological start-up	Inoculum from an active AD plants, boiler renting, fuel to heat the inoculum, chemicals.
14.a	Remi cabin	Connection to the natural gas grid, compressors, gas analysers, safety systems and everything not specified necessary for the preparation of the technical room. (only for biomethane production).
14.b	Electrical-grid connection	Wires, cable duct, voltage transformer, connection to the electrical grid, electrical safety protection, interface panel. (only for electricity production).
15	Authorization	Preliminary projects, reports, technical tables, meetings with control bodies, technical advice and all the related costs for obtaining the building permission; general preliminary administrative costs.
16	Other costs	General and not specific costs

OPEX

All the OPEX values are made available by Schmack Biogas as used for planning projects under realization. They are all calculated over a plant lifetime of 20 years, indexing the annual cost on the basis of inflation. A detailed account of the main OPEX items is given below when the BP is discussed. They cover completely all the expenses expected for running the plant. An important mention is needed for the reject fraction, that has a disposal price variable between 80 and 130 €·t^{-1} according to the plant size. This responds to what reported by several plant owner, who observed that the bigger is the amount of waste to be landfilled, the higher is the price requested. Another mention must be done for the heating system of the fermenters. In the case of electricity production, as a CHP is installed already in the plant, the heat is not a OPEX item as produced by the cogeneration process itself. For biomethane plants, there are two ways to produce the required thermal energy to heat the digesters: to install an industrial boiler fuelled by methane or biomethane, or to install a CHP fuelled by methane or biomethane to satisfy electrical and heat auto consumption. In order to avoid to make the economic simulation too complex, and add not significative OPEX items, for the biomethane scenarios, the needed thermal energy is considered to be withdrawn from a district heating network at market price. The market price considered for thermal energy is 0.065 €·kWh^{-1} thermal, as reference medium price for North Italy.

Financial Costs

For all the analysed cases, the financial costs are calculated with a fixed approach. The financing is calculated with a fixed equity share of 10% and over a period of 15 years. The nominal interest rate is fixed and set for 3.5%. The calculation methodology follows the Italian method of the capital repayment and amortisation with constant instalments. The financial is supposed to start to be paid since the first year after full plant operation. The investment is calculated over a total duration of 20 years of full plant operation. Inflation, over the 20 years, is calculate at an average annual rate of 1.1%.

5.3.3 Revenues

For an AD plant for the treatment of OFMSW there are three main revenue items:

1. the revenue for receiving the food waste and the green waste for their treatment according to the gate fee;
2. the valorisation of the quality compost produced and sold on the market.

3. the revenue for the utilization of the biogas according the its destination (biomethane or CHP);

The gate fee for the food waste widely depends on where the treatment plant is located, because according to the geographical location, in Italy, there could be a local large treatment capacity (north of Italy, often even saturation limit is already overcome) rather than almost no presence of treatment facilities (south of Italy). This makes, in Italy, the gate fee very different along the country. According to the experience, at date the gate fee in Italy may vary from 60 $€\cdot t^{-1}$ to a peak of 120 $€\cdot t^{-1}$ where the waste treatment is still a dramatic issue. An average value for developing a realistic BP for Italy, under precautionary conditions, is a gate fee of 80 $€\cdot t^{-1}$. Regarding the food waste, the tariff may be more related to the size of the plant, as the bigger is the plant, the bigger is the amount required and the bigger is the distance from where the green waste must be delivered. The average gate tariff for green waste is between 10 and 20 $€\cdot t^{-1}$. For the calculation of the BP in this research, in order to keep a good compromise between the different scenarios analysed and make them comparable, a precautionary gate tariff of 10 $€\cdot t^{-1}$ is considered. Regarding the compost, in Italy a precautionary price to be considered for the estimation of the revenues from the sale, without overestimating, is 15 $€\cdot t^{-1}$. Regarding the revenue from the biogas utilisation, it must be distinguished according to what is done with the biogas. In the BP elaborated in this study, when the biogas is transformed in biomethane, it is considered to take advantage of the dedicated management of CIC and biomethane by the GSE according to the mechanism presented in section 5.2.3. A fixed price of biomethane of 0.20 $€\cdot Sm^{-3}$ is considered. Revenue from the CIC of 375 € every 5 Gcal corresponds to 0.59 $€\cdot Sm^{-3}$. When the biogas is used in CHP units, the revenue depends on the presence or not of a tariff. If there is a tariff, the electricity is injected into the grid and paid with an all-in incentive that used to be 0.236 $€\cdot kW^{-1}\cdot h^{-1}$ (even if at date is no longer active as described in section 5.2.3). If no incentive is foreseen for electrical renewable energy from OFMSW treatment, the electricity can be injected into the grid and paid at the market price that at date is 0.075 $€\cdot kW^{-1}\cdot h^{-1}$.

5.3.4 Assessment of economic profitability

To make an evaluation of the economic profitability of a project according to its calculated BP, several economic indices can be used. In order to avoid a complex economic analysis that would take the research out of its nature, four economical indices are used according to similar literature studies (Arango-Osorio et al., 2019; Carvalho et al., 2021; Chan

Gutiérrez et al., 2018; Jones and Salter, 2013; Li et al., 2020; Mabalane et al., 2020; Pavan et al., 2007):

1. Internal Rate of Return (IRR)
2. Pay Back (PB)
3. Levelized Cost of Energy (LCOE)
4. Levelized Cost of Waste (LCOW)

The IRR is a metric commonly used in financial analysis and mostly ideal to estimate the potential return of a new investment that a company is considering undertaking. It describes the rate of growth that an investment is expected to generate annually. IRR may also be compared against prevailing rates of return in the securities market, and for this reason is often used by who builds waste treatment plants as investments solutions. Normally, at date, with an IRR is lower that 6-7%, the project is considered non profitable as the profit is not paying the risk of the investment. An IRR between 5% and 7% gives enough certainty to save the initial capital but no profit is very likely to be generated. An IRR between 10% and 20% is what normally expected by an investor at date, on the field of renewable energy production and according to the actual regulatory framework and the risk of the activity. More information about the IRR are available in literature (Magni, 2010).

The PB period refers to the amount of time it takes to recover the cost of an investment and the reaching of a breakeven point. Beside the sense of the parameter is that shorter PB means more attractive investments, when a fixed and constant revenue is available it easily leads to wrong decisions. Strictly following the only PB logic, an investor would be tempted to opt for cheap technology in order to make the CAPEX (and the PB) as low as possible. This however would easily imply into increased OPEX, that would probably limit the whole investment profitability. PB is however a very simple and direct method. So, with the due precautions, it is still used as an additional point of reference in a capital budgeting decision framework. Formula on how to calculate and other information on the PB are available in literature (Purser, 2011).

The LCOE and the LCOW are very common parameters used to compare the energy production or the waste treatment costs, by different energy sources or different waste treatment technologies. They represent the unit cost of production or treatment, as explained in literature works (Hadidi and Omer, 2017). For the biomethane production, the LCOE is referred on the biomethane produced so it expressed as €·Sm^{-3} of biomethane.

5.4 Economy of scale in OFMSW treatment for biomethane production

5.4.1 Business Plan calculation

To allow an assessment of the economy of scale in food waste treatment, five different treatment plants have been considered. They all were design according to a similar layout based on PFR type reactors and biomethane production, as reported in section 5.3.1, with the difference of the treatment capacity. The different plant sizes have been distinguished according to the biogas production. The reference unit is the Biomethane Upgrading Potential (BUP) and it is defined as the raw (dry) biogas flow, standard cubic meters per hour, that can be treated into the upgrading unit for biomethane potential. The five scenarios have different BUP in order to make possible an economy of scale evaluations: BUP 50, 150, 300, 600 and 1200. The upgrading technology considered for developing the BP was, as already mentioned in section 5.3.1, manufactured by Carbotech. This company has commercial standard upgrading units, so the plant treatment capacity, in terms of OFMSW tons per year, was calculated in order to satisfy the full operating of the BUP. As mentioned already in section 5.3.1, all the five scenarios were developed with the same type of fermenter, that is the fermenter Euco TS 1000® built by the company Schmack Biogas. According to the plant size, a different number of fermenters have been foreseen: 7, 4, 2 and 1 fermenters respectively for BUP 1200, 600, 300 and 150. For the smallest size, the BUP 50, the same reactor with small volume was considered, commercially known as Euco TS 400®. Necessary support tanks and everything needed for a full plant operation, were always considered even if not specified. In all cases the plant was designed according to the pilot scale experimental values of 26 d for the HRT and 6.2 $kgVS \cdot Sm^{-3} \cdot d^{-3}$ for the OLR. All the details on plant design and the methodology adopted for the BP calculation and evaluation, are already discussed in Section 5.3. The most important parameters and variables at the basis of the BP, are reported in the following tables. Table 10 reports and summarize some costs and revenues parameters used at the basis of the economic evaluation and the plant mass balance calculation. Table 11 summarizes the CAPEX calculations; Table 12 summarizes the OPEX calculations and Table 13 summarize the financial costs as estimated for the realization of the full plant.

Table 10: Costs and revenues parameters used at the basis of the economic evaluation and the plant mass balance calculation

Parameter	Unit	BUP 50	150	300	600	1200
Electricity (purchase price for autoconsumption)	€·kWh^{-1}	0.15	0.15	0.15	0.15	0.15
CIC (Certificate for consuption)	€·5 Gcal^{-1}	375	375	375	375	375
CIC value	€·Sm3^{-1}	0.5855	0.5855	0.5855	0.5855	0.5855
Biomethane Price	€·Sm3^{-1}	0.204	0.204	0.204	0.204	0.204
Thermal energy price	€·kWh-1	0.065	0.065	0.065	0.065	0.065
OFMSW gate fee	€·t^{-1}	80	80	80	80	80
Reject material disposal tariff	€·t^{-1}	80	100	100	130	130
Green waste gate fee (for composting)	€·t^{-1}	10	10	10	10	10
Compost selling price	€·t^{-1}	15	15	15	15	15
OFMSW received	t·y^{-1}	4,158	12,421	24,842	49,684	99,368
Reject material % on OFMSW	%	5.0%	5.0%	5.0%	5.0%	5.0%
Reject material, mass balance	t·y^{-1}	208	621	1242	2484	4968
OFMSW fed, mass balance	t·y^{-1}	3950	11800	23600	47200	94400
Digestate, mass balance	t·y^{-1}	3,358	10,030	20,060	40,120	80,240
Green waste, mass balance	t·y^{-1}	672	2,360	4,012	8,024	16,048
Compost, mass balance	t·y^{-1}	1,242	4,366	7,422	14,844	29,689
Biogas Production	Sm^3·t^{-1}	117	117	117	117	117
Biogas Production	Sm^3·y-^{1}	462,150	1,380,600	2,761,200	5,522,400	11,044,800
Raw biogas (dry)	Sm^3·y-^{1}	437,128	1,305,851	2,611,703	5,223,405	10,446,810
BUP operation's time	h·y^{-1}	8700	8700	8700	8700	8700
Biogas methane content	%	60.0%	60.0%	60.0%	60.0%	60.0%
Methane yield (recovery efficiency from biogas)	%	99.0%	99.0%	99.0%	99.0%	99.0%
Methane content in biomethane	%	95.810%	95.810%	95.810%	95.810%	95.810%
Biomethane production	Sm^3·y-^{1}	271,009	809,598	1,619,196	3,238,391	6,476,782

Table 11: Quantification of the CAPEX items at the basis of the economic evaluation and the plant mass balance calculation

CAPEX items	Unit	BUP 50	150	300	600	1200
Anaerobic Digestion plant and biogas utilization unit	€·y^{-1}	1,750,000	3,200,000	4,700,000	6,800,000	9,500,000
Shed for OFMSW pre-treatment and biofilter	€·y^{-1}	400,000	800,000	800,000	900,000	1,200,000
System for OFMSW pre-treatment and solid-liquid separation	€·y^{-1}	1,200,000	1,600,000	1,600,000	1,800,000	2,200,000
Yards for compost and green storage	€·y^{-1}	50,000	100,000	200,000	30,000	400,000
Dynamic composting tunnel	€·y^{-1}	700,000	700,000	900,000	1,500,000	2,500,000
Office and weight	€·y^{-1}	70,000	80,000	90,000	100,000	110,000
Anti-intrusion system	€·y^{-1}	10,000	15,000	20,000	25,000	30,000
Fire system	€·y^{-1}	60,000	80,000	100,000	120,000	140,000
Electrical connection, lighting and electrical systems	€·y^{-1}	140,000	170,000	200,000	500,000	750,000
Fence and gates	€·y^{-1}	40,000	45,000	50,000	55,000	60,000
Technological networks	€·y^{-1}	16,000	18,000	20,000	24,000	26,000
Soil preparation	€·y^{-1}	350,000	350,000	400,000	600,000	700,000
Inoculum and biological start-up	€·y^{-1}	20,000	30,000	50,000	70,000	90,000
Remi cabin	€·y^{-1}	360,000	360,000	400,000	420,000	440,000
Authorization	€·y^{-1}	150,000	150,000	150,000	150,000	150,000
Other costs	€·y^{-1}	100,000	100,000	150,000	150,000	200,000
Total CAPEX	**€·y^{-1}**	**5,416,000**	**7,798,000**	**9,830,000**	**13,244,000**	**18,496,000**

Table 12: Quantification of the OPEX items at the basis of the economic evaluation and the plant mass balance calculation

OPEX items	Unit	BUP 50	150	300	600	1200
Ordinary biogas plant	€·y^{-1}	15,000	25,000	40,000	70,000	120,000
Pre-treatment system	€·y^{-1}	25,000	40,000	60,000	110,000	200,000
Composting plant	€·y^{-1}	10,000	10,000	10,000	20,000	30,000
Biofilter	€·y^{-1}	5,000	6,000	7,000	8,000	10,000
Extraordinay maintenance	€·y^{-1}	8,750	16,000	23,500	34,000	47,500
Chemicals and materials	€·y^{-1}	2,000	5,000	10,000	20,000	40,000
Energy comsuption	€·y^{-1}	18,059	43,439	78,772	157,427	234,604
Heat comsuption	€·y^{-1}	1,709	13,365	53,388	200,757	828,617
BUP ordinary (maintanence)	€·y^{-1}	16,000	32,000	50,713	80,000	112,000
BUP extraordinary (unexpected)	€·y^{-1}	8,000	11,200	16,000	24,000	32,000
BUP chemicals (activated carbon)	€·y^{-1}	1,600	2,400	4,731	9,600	19,200
BUP energy comsuption	€·y^{-1}	39,026	103,018	103,018	167,404	270,421
Injection system maintenance	€·y^{-1}	30,000	33,000	36,000	40,000	45,000
Reject material disposal	€·y^{-1}	16,632	62,105	124,211	322,947	645,895
Machines rental and fuel	€·y^{-1}	80,000	90,000	100,000	125,000	200,000
Number of employers	n	2	4	6	4	4
Cost for employees	€·y^{-1}	80,000	160,000	240,000	360,000	360,000
Assurance	€·y^{-1}	27,080	38,990	49,150	66,220	92,480
Other fixed not specific costs	€·y^{-1}	20,500	40,500	65,500	115,500	215,500
Electrical consumption for plant operating	kWh·y^{-1}	120,394	289,592	525,145	1,049,515	1,564,026
Electrical consumption for BUP operating	kWh·y^{-1}	260,172	686,784	686,784	1,116,024	1,802,808
Electrical consumption for pre-treatment operating	kWh·y^{-1}	38,610	115,830	302,439	604,878	907,317
Electrical consumption for other plant utilities	kWh·y^{-1}	48,706	122,202	201,042	201,042	360,890
Electrical consumption for gas compression	kWh·y^{-1}	31,696	75,391	134,028	217,796	335,070
Total electrical consumption	kWh·y^{-1}	499,578	1,289,799	1,849,438	3,189,255	4,970,111
Total thermal energy for fermenters heating	kWh·y^{-1}	157,793	411,217	821,351	1,544,285	3,186,988
Total biogas plant maintenance	€·y^{-1}	85,519	158,803	282,660	620,184	1,510,721
Total BUP maintenance	€·y^{-1}	64,626	148,618	174,462	281,004	433,621
Total general costs	€·y^{-1}	254,412	424,845	615,361	1,030,167	1,559,375
Total cost for electricity	€·y^{-1}	74,937	193,470	277,416	478,388	745,517
Total cost for thermal energy	€·y^{-1}	10,257	26,729	53,388	100,379	207,154
Total OPEX	€	9,263,259	16,766,958	30,329,440	44,222,922	80,225,833

Table 13: Financial costs as estimated for the realization of the full plant

Financial items	Unit	BUP 50	150	300	600	1200
Private equity	%	10%	10%	10%	10%	10%
Private equity	€	541,600	779,800	983,000	1,324,400	1,849,600
Financing capital	€	4,874,400	7,018,200	8,847,000	11,919,600	16,646,400
Financing duration	y	15	15	15	15	15
Interest rate	%	3.5%	3.5%	3.5%	3.5%	3.5%
Annual Installment	**€·y^{-1}**	**423,220**	**609,356**	**768,141**	**1,034,920**	**1,445,325**

5.4.2 Business Plan discussion

The final objective of the economic simulation is to understand if, in the food waste treatment, the economy of scale plays an important role on the sustainability of full plants according to their size. In particular, the scope is to assess if the small size plants is a concrete option for favouring the adoption of anaerobic treatment for the OFMSW streams. All the economic calculations above reported were conducted considering in detail all the costs and revenues items responsible for the cash flow of a full plant. They can be summarized with few cumulative parameters: the total CAPEX, total OPEX, total Financial Costs, total Revenues and the Net Cumulative Cash Flow. They have been calculated indexed on the basis of the interest rate and/or inflation and reported in Table 14.

Table 14: Output parameters for the Business Plans calculated for the five different scenarios of OFMSW biomethane plants

Financial items	**Unit**			**BUP**		
		50	**150**	**300**	**600**	**1200**
Technological plant (Biogas + Upgrading)	$€\cdot y^{-1}$	1,750,000	3,200,000	4,700,000	6,800,000	9,500,000
Other costs	$€\cdot y^{-1}$	3,666,000	4,598,000	5,130,000	6,444,000	8,996,000
Total CAPEX	$€\cdot y^{-1}$	**5,416,000**	**7,798,000**	**9,830,000**	**13,244,000**	**18,496,000**
Total OPEX	$€\cdot y^{-1}$	**9,263,259**	**16,766,958**	**30,329,440**	**44,222,922**	**80,225,833**
Financial costs	$€\cdot y^{-1}$	**1,473,902**	**2,122,136**	**2,675,121**	**3,604,201**	**5,033,473**
Total costs CAPEX + OPEX + Financial	$€\cdot y^{-1}$	16,153,161	26,687,093	42,834,561	61,071,123	103,755,306
Revenue from organic waste treatment (Gate Fee)	$€\cdot y^{-1}$	7,141,148	21,589,910	42,664,927	85,329,854	170,659,708
Revenue from Compost sale	$€\cdot y^{-1}$	18,634	65,490	111,333	222,666	445,332
Revenue from Biomethane (methane + CIC)	$€\cdot y^{-1}$	4,278,592	12,781,615	25,563,231	51,126,461	102,252,923
TOTAL REVENUES	$€\cdot y^{-1}$	**11,438,374**	**34,437,015**	**68,339,491**	**136,678,981**	**273,357,963**
Net cumulative Cash Flow (financial costs included)	$€\cdot y^{-1}$	**-4,714,787**	**7,749,922**	**25,504,930**	**75,607,858**	**169,602,657**
PayBack	y	>20	9.2	5.3	3.7	2.8
IRR (before taxes)	%	N.C.	4%	20%	36%	54%

The Pay Back and the IRR for each case is also reported, and are used to the BP evaluation as explained in section 5.3.4. A graphical reproduction of the IRR and the Pay Back is reported in Figure 28a. For the BUP 50, the IRR is lower than 10% and the Pay Back is higher than 20 years, that means the investment is completely out of an economic sustainable possibility. The revenues are not enough to pay the costs for build and operate the plant, and there is no way of making the plant reasonably sustainable. Also the BUP 150, that has a size three times higher than the BUP 50, have a very low operating margin. The estimated net Pay Back is above 9 years and the IRR is 4.5%, indicating that the project is very risky and also a minimum unexpected event would make the project to fail. By increasing the size over the BUP 150, thigs change completely. Investments higher that 42, 61 and 103 million €, respectively for BUP 300, 600 and 1200, permit a Pay Back of just few years, precisely 5.3, 5.7 and 2.8 years respectively. For this project the IRR is very high, up to 54% for the bigger plant. This testifies that, if for small sizes a treatment plant even cannot self-sustain, for medium-high sizes the waste treatment becomes a highly profitable investment. The calculation of the LCOE permitted to estimate a cost production of grid injected biomethane of 2.98, 1.32, 0.92, 0.80 €·Sm^{-3} respectively for the BUP 50, 150, 300, 600 and 1200. Comparing those values with the average market price of the methane (see Figure 26), it is clear that the biomethane itself doesn't generate enough profit to sustain in general the investment of the waste treatment plant. Independently by the treatment capacity. Even at the bigger plant size, the methane is produced at a cost four times higher than the average market price. The LCOE are represented in Figure 28b. It is possible to observe for all the represented parameters, a logarithmic trend. R^2 for IRR is above 0.99 and above 0.9 for PB and LCOW. This suggests that there is a big profit variation by increasing the plant size when the waste treatment capacity is medium-low. For big size plants, a further increasing in the treatment capacity would lead to a lower increase of the profit. This suggests a limit for the economy of scale once reached a certain size, but this evaluation is however out of the present research scope. The LCOW also demonstrated a similar trend. The expected treatment cost for the OFMSW is 194, 107, 86, 61 and 52 €·t^{-1} respectively for the BUP 50, 150, 300, 600 and 1200. As well as showing how influent is the economy of scale in this type of installations, this is also an important observation to evaluate the gate fee value.

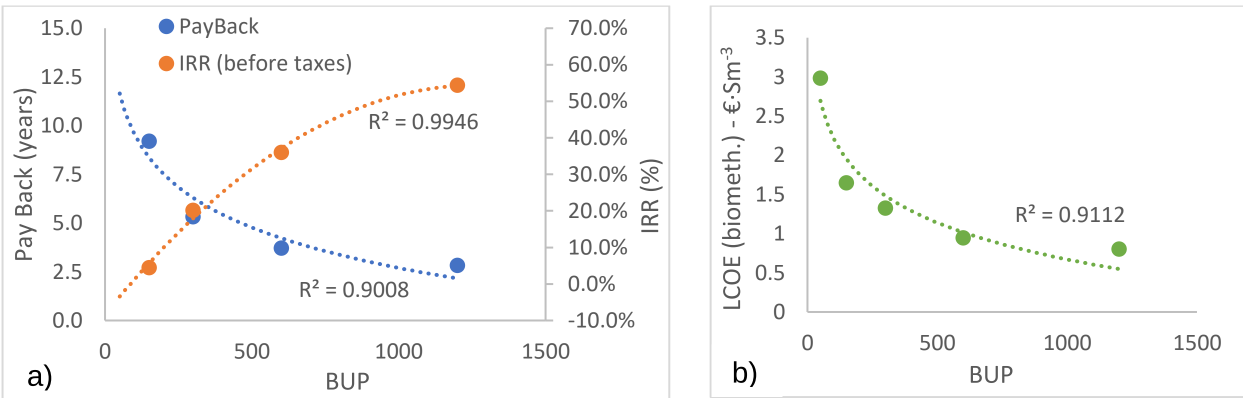


Figure 28: Pay Back and IRR (a), and LCOE calculated on biomethane (B), for estimated Business Plan calculated on the 20 years operation of different size biomethane plants treating OFMSW

To understand the reason of the economic unsustainability of the small plants, an analysis of the revenues and the costs is done in order to understand if the profitable cases can supply important information. Three items define the revenues: sale of compost, sale of biomethane, income by the gate fee of the OFMSW. Independently by the plant size, the total revenue amount is always given for the 62% by the OFMSW tariff, and for the 37% by the biomethane production; the sale of the compost is a marginal income and explains less than 1% of the total revenue. Being a fixed ratio, it is not the key factor to understand the weakness of the small size plant. The total CAPEX, OPEX and Financial Costs are hence plotted in Figure 29. The figure shows the percentage contribution of the three expenditure items on the determination of the total costs for building and operating a treatment plant over a period of 20 years.

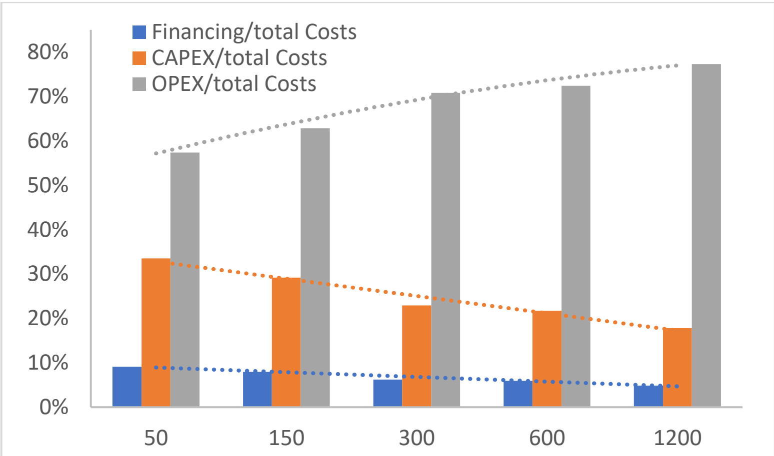


Figure 29: contribution of the three expenditure items on the determination of the total costs for building and operating a treatment plant over a period of 20 years

The Figure show that the OPEX increases with the increasing of the plant size. This means that the bigger is the treatment capacity, the higher is the influence of OPEX on economic balance. The CAPEX also show a lower contribution on the total costs of the plant, as long as the plant size increases. This is a prove of the existence of a heavy economy of scale logic on the waste treatment, strongly determined by the boundary conditions that foreseen fixed revenues linearly depending on the treatment capacity, and not linear expenditures that strongly decrease by increasing the plant size. To better understand which component of the expenditure exerts a greater weight on the economy of scale, the percentage contribution on the total costs of some principal cost items is evaluated, some by itself and some clustered. On total, 44 expenditure items, or cluster of them, have been taken in count. For each variable, the regression line was calculated over the five values given by the five BP. On all the regression lines, the angular coefficients were hence calculated. This mathematical transformation permitted to evaluate the variables that mostly decrease (or increase) by increasing the size of the plant. A negative angular coefficient means that the variable decreases as long as the plant size increases. The bigger is the angular coefficient, the more inclined is the regression line and so the higher is the reduction of the percentage that, that variables, exerts on the total costs. The results are plotted in Figure 30.

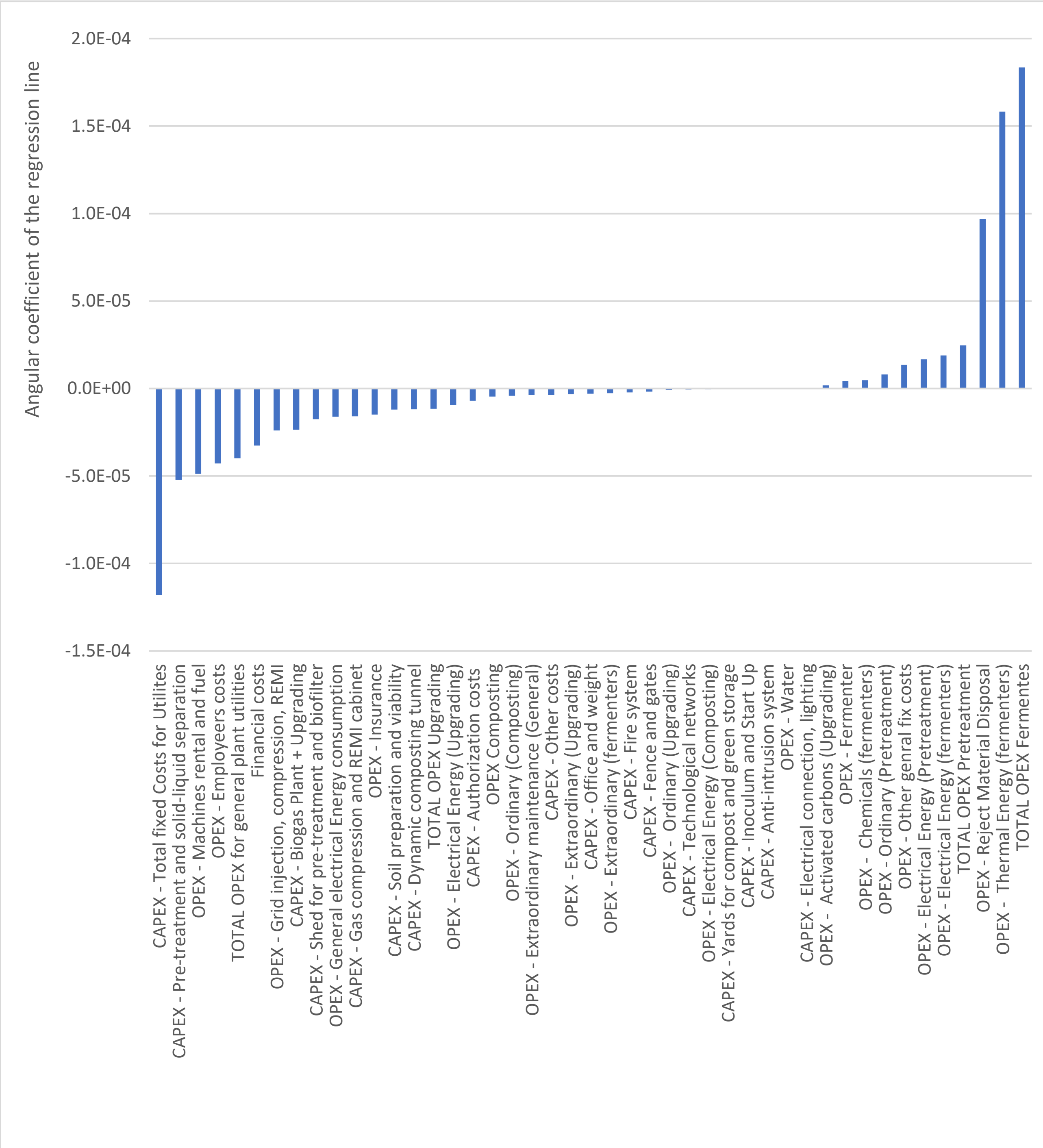


Figure 30: Angular coefficient of the regression line calculated over the variation, at the size increasing, of 44 parameters (CAPEX or OPEX items and cluster of them). The parameters are calculated as percentage of the relative CAPEX/OPEX index on the total costs of the investment

Positive and high angular coefficients were calculated for two OPEX items (the reject material disposal and the thermal energy required for heating the fermenters) and for the total OPEX. This would provide tips on how to increase the profit in big size plants, but is not the scope of the present analysis. The highest negative angular coefficient are, in order, calculated for: the total CAPEX for fixed costs and utilities, CAPEX for pre-treatment and solid liquid separation of the digestate, OPEX for machine rental and fuels, OPEX for employers, total OPEX for general plant utilities, the financial costs. All the six items are considered fixed items, because they are not strongly related to the size of the plant but they are needed independently by the size plant. The CAPEX for fixed costs and utilities, for example, account the costs for buildings, sheds, yards, viability, authorization etc, all costs that are quite similar between the five sizes analysed.

Economy of scale is the very limit of the feasibility of small-scale treatment plants, and there is no way to overcome them. The key factor to support the construction of small-scale plants, is given by the incentive mechanism, that should find a way to assure highly proportional revenues for the small plants compared to what available for the bigger size plant.

5.5 Economic evaluation of small size plant feasibility

5.5.1 Reference plant layout

For the analysis of the feasibility of small size AD plants for OFMSW treatment, as no reafferences are actually available at the market, a special plant typology has been chosen. The reactor type is a PFR that incorporate the characteristics of the fermenter Euco® described above. For small size plants, the company Schmack Biogas developed a special plant layout consisting of a containerized plant, completely built at the factory and delivered to the installation site as a Plug-and-Play supply. An external view and internal details are shown in Figure 31 and 32. Commercially it is called Eucompact® and it is provided with all the facilities necessary to run the plant: fermenters, gas bag, technical room with electrical cabinets, PLC, pumps, piping, valves, sensors, desulfurization unit and CHP. It is excluded only the pre-treatment unit, as it is usually installed inside a depressurised shed where the waste is received. The whole containerized plant has dimensions of 16.5x3.5x3.5 m and consists of two fermenters that could be managed in series (two-phase) or in parallel (one phase), plus the technical room. Total net fermentative volume is of 250 m^3. The plant was designed for processing residuals from the food-industry with highs solids content (as for example olive pomace). For this reason, it is ideally very suitable for allowing decentralization of food waste treatment and support a proliferation of diffused small treatment facilities. For the present research, this type of all-inclusive reactor was integrated in a complete project of turn-key plant, including all the components specified in section 5.3.2, as necessary for running a full-scale plant. An example of a reference layout is given in Figure 33 (the example layout has two Eucompact® units because the figure is used also for different projects). Costs for the entire project realization in reported below, then an economic simulation is conducted comparing different scenarios with different revenues conditions, in order to understand the feasibility of the small-scale approach.

Figure 31: External view of the containerized plant taken as small size plant reference

Figure 32: Details of the containerized plant taken as small size plant reference

Figure 33: Reference layout for a small size anaerobic treatment plant

5.5.2 Costs

For the plant realization, total CAPEX are estimated to be 3,050,000 €, OPEX are estimated to be 171,086 € the first year and 3,804,051 € over the 20 years. They are calculated according to section 5.3.2 and are reported in Table 15 and Table 16 respectively. Total electrical auto consumption is considered to be the 19.5% of the installed capacity of 100 kW, they are detracted by the gross electrical production, so they don't figure as a OPEX item. Considering the premises of section 5.3.2, financial charges are expected to be 830,022 € for the whole period. For the whole 20 year of plant operation, total costs for building and operating an AD plant for treating 3,500 $t \cdot y^{-1}$ are estimated to be 7,684,074 €.

Table 15: Detailed list of the CAPEX estimated for the construction of a turn-key small size plant for the treatment of OFMSW and energy recovery through a CHP with an installed power of 100el

	CAPEX detailed description	
1	Anaerobic Digestion plant and biogas utilization unit	1,350,000 €
2	Shed for OFMSW pre-treatment and biofilter	570,000 €
3	System for OFMSW pre-treatment and solid-liquid separation	250,000 €
4	Yards for compost and green storage	200,000 €
5	Dynamic composting tunnel	300,000 €
6	Office and weight	50,000 €
7	Anti-intrusion system	10,000 €
8	Fire system	70,000 €
9	Electrical connection, lighting and electrical systems	25,000 €
10	Fence and gates	30,000 €
11	Technological networks	5,000 €
12	Soil preparation	70,000 €
13	Inoculum and biological start-up	20,000 €
14	Electrical-grid connection	60,000 €
15	Authorization	40,000 €
	TOTAL CAPEX	**3,050,000 €**

Table 16: Detailed list of the OPEX estimated for the construction of a turn-key small size plant for the treatment of OFMSW and energy recovery through a CHP with an installed power of 100el

	OPEX items	**First year**	**20 years**
1	Ordinary + extraordinary maintenance	65,000 €	1,445,250 €
16	Reject material disposal	14,736 €	327,668 €
17	Employees	60,000 €	1,334,077 €
21	Insurance	21,350 €	474,709 €
24	Other costs (unexpected)	10,000 €	222,346 €
	TOTAL OPEX	**171,086 €**	**3,804,051 €**

5.5.3 Economic evaluation of small size plant feasibility

The revenues of the project above described are calculated according to a sensitivity analysis based on three different scenarios. The first scenario is an elaboration of the revenues by changing the gate fee tariff if no incentive is available for green electricity production. The second scenario shows the expected revenues without any gate fee, in order to evaluate if a hypothetical incentive could support the treatment plant taking out waste disposal tariff for the citizens. The third scenario show the practical case when a gate fee is active and the incentive for electricity is also available for the treatment plant.

Scenario 1 – Absence of incentive, revenue only by Gate Fee

The scenario takes in count the economic sustainability of an AD plant for OFMSW treatment provided with a CHP for renewable electrical energy generation, over an investment period of 20 years, without any economic support by the public community. The produced energy is injected into the grid at the market price of 0.075 €·kW^{-1}.

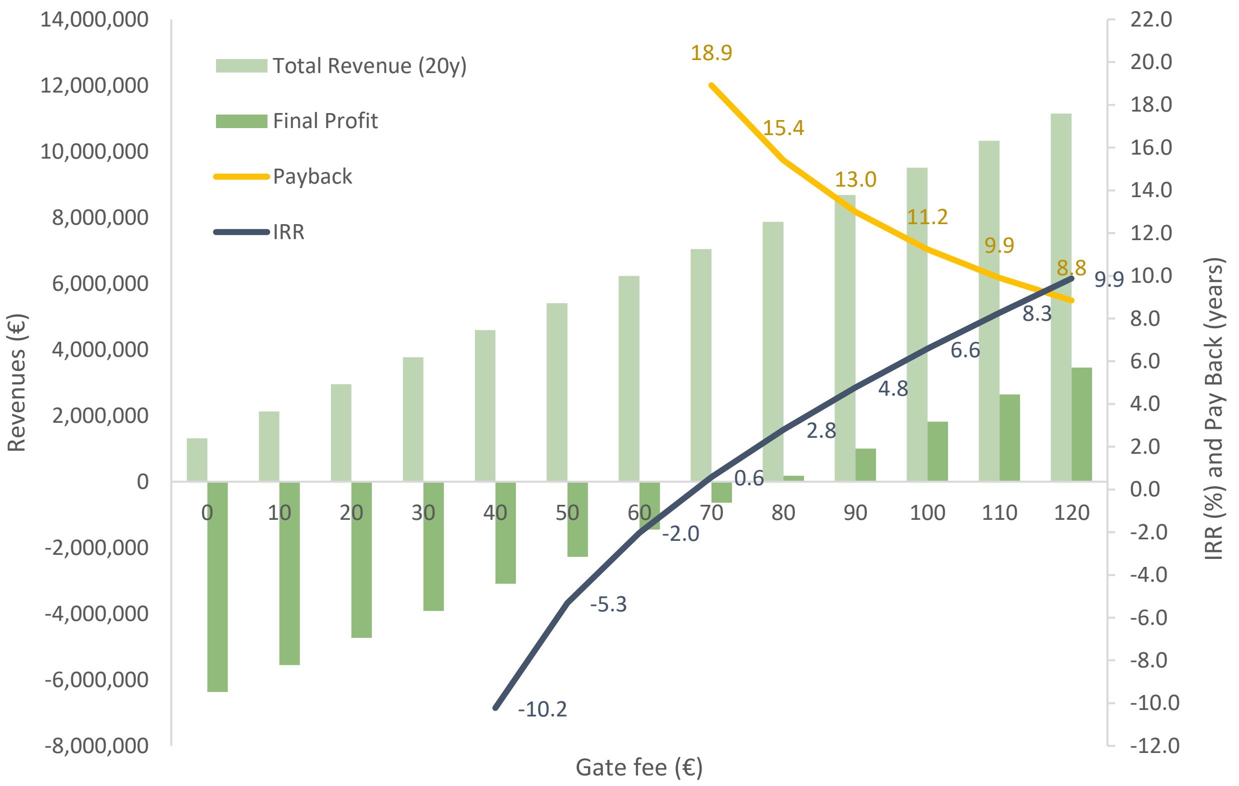


Figure 34: Economic sustainability of a small size AD plant for OFMSW treatment and renewable electrical energy generation, without tariff, as the gate fee changes

This is actually, at date, the state of art, as after the DM 23/06/2016 expired any incentive was prolonged for this type of plant. As shown in Figure 34, the operation of this size plant without incentive and gate fee, has no way to be economical sustainable. The project starts to have a positive breakeven point with a gate fee from 70 and 80 €·t^{-1}. At this gate fee however, the sustainability of the plant is heavily risky because the profit is so small that also an unexpected minimum event may involve in the project failure. A reasonable economic feasibility begins to exist with a gate fee starting from 110 €·t^{-1}, when the IRR is above 6%. This scenario is however an unrealistic option because no one, even not any municipal company or public administration, would never face such a heavy investment for assuring to their citizen a gate fee actually higher than the average market fee.

This scenario testifies that to support small AD size plants, the electrical energy produced by itself, if valorised at the market price, is not enough to give an economical sustainability of the project.

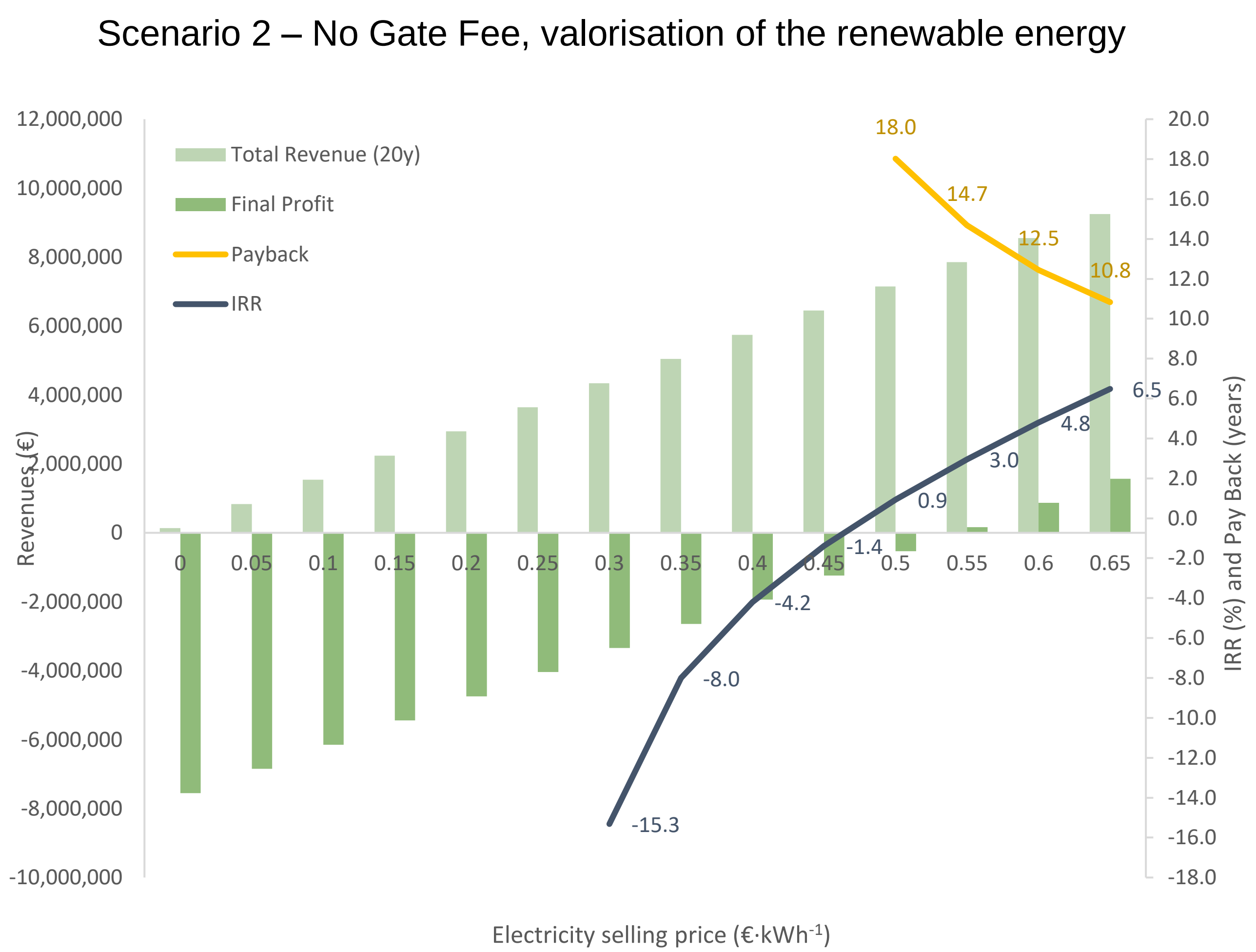


Figure 35: Economic sustainability of a small size AD plant for OFMSW treatment and renewable electrical energy generation, without gate fee, as the electricity price changes

This scenario simulates what would happen if a small size plant would be operated without gate fee at the varying of the electricity selling price. The scenario is meant to calculate the value that the renewable energy would have, through an incentive mechanism, to make the waste treatment at no cost for the citizens. How shown in Figure 35, in 20 years of operating, a breakeven point would start to be positive with a tariff for electricity above 0.55 €·kWh^{-1}. The plant would produce enough profit to result feasible only with the electricity above 0.65 €·kWh^{-1}. The criteria is the evaluation of the IRR, that when above 6% implies a reasonable safety margin to make the investment likely not to fail. Considering, at date, that the production electricity price is around 0.075 €·kWh^{-1}, and that the final purchase price is on average between 0.150 and 0.160 €·kWh^{-1}, also this scenario is demonstrated to be completely senseless.

This elaboration testifies that for the economic sustainability of a small size plan, a gate fee is always necessary because the electricity by itself has not enough value to generate the necessary economic return for counterbalancing the OPEX.

Scenario 3 – Conditions for economic sustainability

For the third scenario, a different approach is used in order to show a practical case of economical sustainability and the positive effect that a small size plant could have to the collectivity. For the scenario, the support of a tariff for the renewable energy production is foreseen to be available. In particular it is considered that the incentive is the one defined by the DM 23/06/2016, that is 0.233 €·kWh^{-1}. The scenario simulates the building of a small treatment plant by a small city of around 35.000 inhabitants. The ideal town chosen, is supposed to be located far from big cities where there are no treatment facilities close by. For this reason, the municipality may have to transport the wastes far away with high costs as it has no choice on where to deliver the wastes. This affects the gate fee that the municipality would be asked to pay, that is a medium-high fee of 100 €·t^{-1}. The scenario simulates that this ideal municipality builds for its own needs a small plant for the treatment of the OFMSW locally produced. The mortgage rate to be paid at the bank lasts 15 years but after 9 years the cash flow starts to be positive. At this point, the municipality starts to reduce its profit margin by the operation of the plant, reducing the gate fee. This in order to grant to the citizens a reduction of the waste disposal tax. The gate tariff is reduced according to the financial analysis and with the objective to arrive at the end of the 20 years with an acceptable IRR. By starting with reducing the gate fee tariff by the 9th year, and reducing it of 10 € per year until reaching 30 €·t^{-1} at the 15th year, the investment reaches an IRR of 5.8% with a Pay Back of 8.7 years. The cash flow of the investment is shown in Figure 36. The municipality has accepted to avoid any profit but did an investment that permitted the final 70% reduction of the waste disposal fee to their citizens. During the 20 years, citizens were able to benefit of an average saving of 26.5%, compared if they would have had to pay the full tariff of 100 € a year.

Figure 36: Cash flow for the operation of a small size for OFMSW treatment and electricity production, supported by a renewable energy incentive of 0.233 €·kWh^{-1}; the Business Plan permits to calculate a reduction of the gate fee keeping an acceptable IRR of 5.8%

5.5.4 Conclusions

The economic analysis showed that, in the biological waste treatment, an economy of scale logic heavily limits the sustainability of small-scale plants. The limit is not given by the costs of the technological units, fermenters primarily, because at the marked modular solutions are available and their CAPEX costs increase linearly according to the plant treatment capacity. The limiting costs that actually make the small-scale approach not feasible, are CAPEX or OPEX related to fixed utilities (boundary components of the waste treatment plant, machineries and labor cost). Financial costs on small plants Business Plans also have a sensible weight. Under realistic condition, a biomethane plant with a PFR type reactor and 250 m^3 of net volume, treating 4,200 $t \cdot y^{-1}$ of SS-OFMSW and producing 50 $m^3 \cdot h^{-1}$ of dry biogas (31.2 $m^3 \cdot h^{-1}$ of biomethane), is not sustainable with the incentive mechanism based on CIC and active at date. The Pay Back is far lower that 20 years and the IRR is heavily negative. A similar plant, where process conditions are linearly upscaled to a dry biogas flow rate of 150 $m^3 \cdot h^{-1}$ of dry biogas (93.1 $m^3 \cdot h^{-1}$ of biomethane), shows an IRR of 4% and a Pay Back period of 9.2 years. At those conditions, the project still results very risky both for a private investor than for a public municipality. Plants with SS-OFMSW treatment capacity higher than 25,000 $t \cdot y^{-1}$ and biomethane production from 190 $m^3 \cdot h^{-1}$, start to be profitable. In particular, regarding the SS-OFMSW, plants with treatment capacity between 13,000 and 25,000 $t \cdot y^{-1}$ are economic sustainable but they don’t generate a profit desirable for private investors. This can be considered the smallest feasible plant size ad date. Plants with treatment capacity above 30,000 $t \cdot y^{-1}$ are highly remunerative and able to generate a profit with an IRR of minimum 20% and up to >50%. The key factor that determines this scenario is the presence of a fixed incentive mechanism that does not counterbalance the economy of scale benefits that the big size plants have.

For small size plants, the economic sustainability is demonstrated to be possible with the presence of a incentive mechanism on the electrical energy production. Biogas plants for the SS-OFMSW tratment provided with a CHP unit, results much simplier and less costly compared to the same treatment size plant for biomethane production, as many fixed costs are avoided. For a sustainable investment, however, both an all-in tariff for electricity and a gate fee for OFMSW is necessary. There is no way to make a small plant feasible only by selling the electricity at the market price of 0.075 $€ \cdot kWh^{-1}$. An all-in tariff of 0.233 $€ \cdot kWh^{-1}$ could however make a hypothetical public municipality able to provide a small city with a facility for satisfying the treatment of their own waste, even reducing the waste disposal tariff to the citizens.

6. CONCLUSIONS

The research investigated the feasibility of small and easier-to-manage anaerobic digestion plants, to promote the decentralization and an increasing of the worldwide total OFMSW amount treated with energy recovery. Technical, process and economic aspect were investigated.

Technical aspects involved the typical mechanical pre-treatment systems to sort the SS-OFMSW and removing the inerts before entering the fermenter. The experimental analysis demonstrated that the Hammer Mill, the Screw Press and the Combined System all can be considered high demolition sorting techniques capable of producing an abundant fraction of supercolloidal organic material with particles below 0.063 mm, where VS in particular distribute. They also show a high homogenization efficiency: no significative seasonal variation has been detected on the organic pulp sent to the digester. The Hammer Mill is the sorting system that produces the more liquid organic pulp, where TS are 8.9% on a mass basis, and the highest inert removal efficiency. The Hammer Mill is also the technique that produces particles with smaller sizes, with a normal distribution around 1 mm. The Extrusion Press is the technique that leaves the highest degree of contaminants, and produces the biggest fraction with particles above 20 mm. The Combined System shows the better separation efficiency as in the reject material the organic matters accounts only for the 50%; for the Hammer Mill and the Screw Press it accounts for the 65% on average.

The pilot experiment was meant to investigate the possibility of reducing as much as possible the fermentative volume in anaerobic digestion, in order to support a cost reduction of full-scale installations. A way to build cheaper and easier small-scale plants was in particular the main target. The experimental tests demonstrated that a reduction fermentative volume can be achieved by feeding SS-OFMSW, with no dilution and 214.5 $gTS \cdot kg^{-1}$ and 80.1% of ratio VS/TS, in a PFR reactor with OLR of 6.2 $kgVS \cdot m^{-3} \cdot d^{-1}$ and HRT of 26 days. No dilution or co-substrates are needed. An SGP of 0.67 $Sm^{-3} \cdot kgVS^{-1}$ in terms of biogas, and of 0.41 $Sm^{-3} \cdot kgVS^{-1}$ in terms of methane, were measured. The GPR, was found to be 4.5 $Sm^{3} \cdot m^{-3} \cdot d^{-1}$. The process is able to assure high degree of sanitation, the digestate is for sure suitable for high quality compost production. The homogeneous mixing system and the stable OLR maintained (avoiding local peaks due to discontinuous feeding) were probably key factors for the steady state sustainability.

The economic analysis was conducted to understand if, with the process configurated how discovered at the pilot scale, a real plant can be sustainable and in case under what conditions. The analysis demonstrated that the small-scale approach cannot be adopted for the biomethane production. Fixed costs related to the biomethane production are too high compared to the revenues for plants with a treating capacity lower than 10,000 $t\cdot y^{-1}$ of SS-OFMSW, they have negative IRR or an IRR to low to make the project reasonably feasible. Plants with treatment capacity between 13,000 and 25,000 $t\cdot y^{-1}$ are economic sustainable but they don't generate a profit. Plants with treatment capacity above 30,000 $t\cdot y^{-1}$ are highly remunerative and able to generate a profit with an IRR of minimum 20% and up to >50%. The presence of a fixed incentive mechanism that do not counterbalance the economy of scale, compromises the feasibility of small-scale plants. The key for the economical sustainability of small size plants is the cogeneration. The CHP involves CAPEX and OPEX much lower than a Biogas Upgrading Unit. The market price of the electrical energy is however not enough for making the investment economically positive. An all-inclusive tariff for the renewable energy production of 0.233 $€\cdot kW^{-1}$ is enough for making feasible a small scale, 100 kW, plant for treating 4,200 $t\cdot y^{-1}$ of SS-OFMSW. The IRR is enough to permit a waste disposal fee reduction for the citizens against a reduced profit margin.

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