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Designing Cost-Effective Digestate Treatment Layouts for Integrated Anaerobic Digestion-Composting Plants

TESI DI LAUREA MAGISTRALE IN
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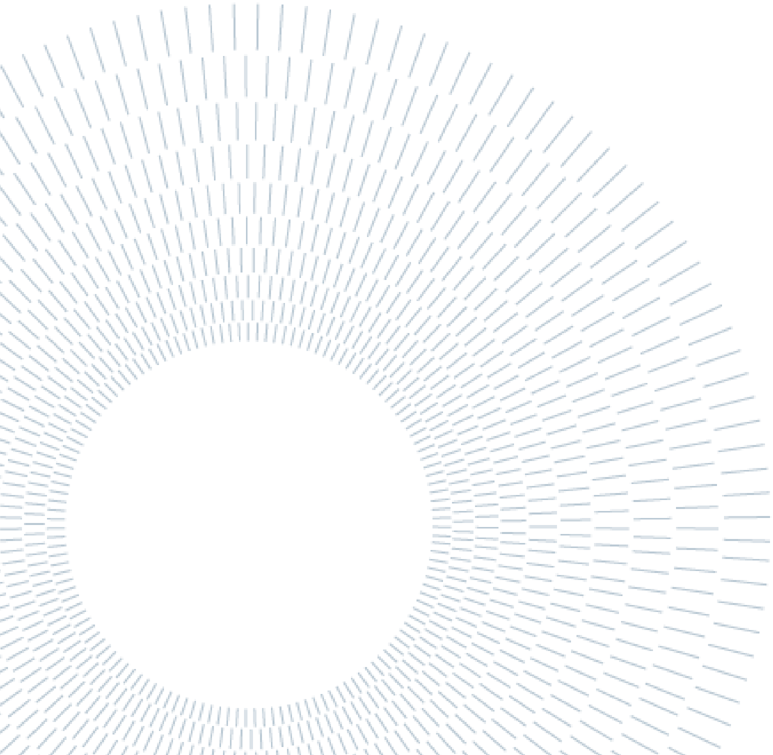
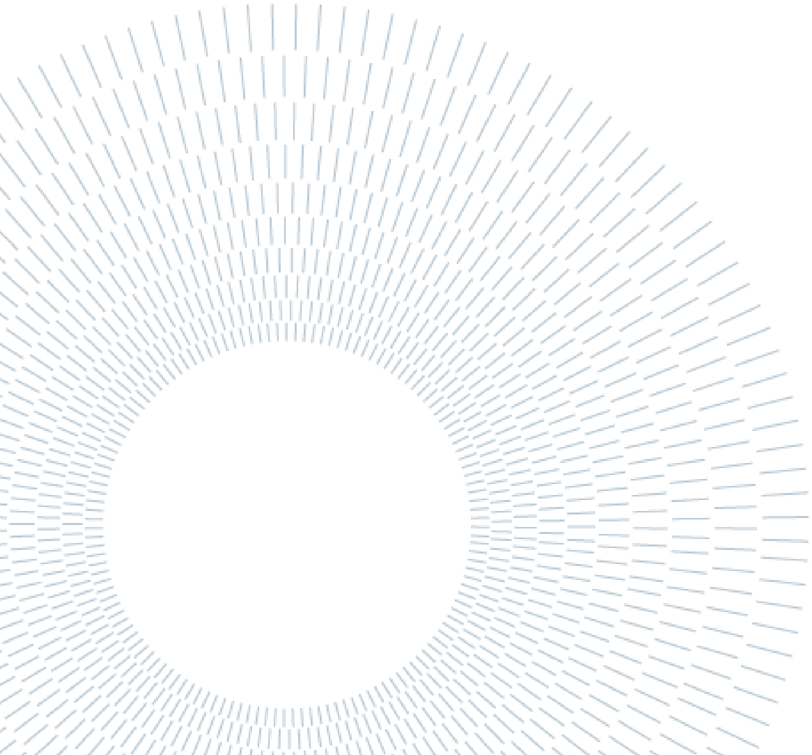


Abstract

Anaerobic digestion (AD) is a promising technique for the energy recovery of the Organic Fraction of Municipal Solid Waste (OFMSW). The organic waste is degraded by means of bacteria obtaining a methane-rich biogas and an inert semi-liquid digestate, which can be upgraded to soil improver through a post-composting process. According to the solid content in the digester, the AD can be conducted in wet (8-15%) or dry (17-25%) conditions, implying technical and operative differences. A combined OFMSW AD-composting plant located in Apuglia, object of the case study, was designed as a dry process but was reported operating under semi-wet conditions (9-15%), with heavy economic impacts on the digestate post-composting costs. The objectives of the work are to identify possible causes of the issue and to suggest alternative cost-effective layouts of the digestate treatment process. The historical data are analysed to investigate the biochemical processes in the digester. Original and additional components are represented in an integrated plant model, developed to characterize interdependent mass balances, to estimate and compare investment and operational costs of each plant configuration. Findings show that the reactor is unable to work in dry regime with the OFMSW input quality, and that a temporary underfeeding favoured excessive liquefaction. Digestate dewatering coupled with pasteurization of the liquid separated stream guarantees the lowest Net Present Cost. Increasing the digester solid content does not improve the economics, because it has a minor effect on the digestate density, that majorly influences the operational costs. To improve the plant profitability, it is vital to maximize material recovery and minimize disposal of reject streams.

Keywords: Organic Fraction of Municipal Solid Waste (OFMSW), dry anaerobic digestion, wet anaerobic digestion, digestate dewatering, digestate post-composting.



Abstract in italiano

La digestione anaerobica (DA) ha un ruolo fondamentale nel recupero energetico della Frazione Organica dei Rifiuti Solidi Urbani (FORSU). Il rifiuto organico è degradato ad opera di comunità batteriche ottenendo un biogas ricco in metano ed un digestato semi liquido, il quale può essere trasformato in ammendante per uso agronomico attraverso un processo di post-compostaggio. A seconda del contenuto di solidi nel digestore, si distingue la DA ad umido (8-15%) e a secco (17-25%), comportando rilevanti differenze impiantistiche ed operative. L'oggetto del caso di studio, un impianto FORSU a DA e compostaggio situato in Puglia e costruito per operare "a secco", ha registrato un comportamento semi umido (9-15%), con pesanti conseguenze economiche legate alla fase di post-compostaggio. Questo lavoro ne ricerca le possibili cause e propone configurazioni alternative del post-compostaggio economicamente convenienti. Lo storico di dati è analizzato per comprendere le dinamiche biochimiche del digestore. Si sviluppa, includendo componenti originali ed aggiuntivi, un modello impiantistico integrato che determini i flussi di massa interdipendenti, con cui vengono stimati i costi impiantistici per ogni configurazione. I risultati mostrano che il digestore non è dimensionato per lavorare a secco con la qualità del materiale organico conferito, e che una temporanea sottoalimentazione ha favorito una eccessiva liquefazione del substrato. La configurazione con disidratazione del digestato e pastorizzazione del suo separato liquido determina l'ottimo economico. Aumentare il tenore di solidi nel digestore non migliora le prestazioni economiche, perché ha poca influenza sulla densità del digestato che maggiormente influenza i costi operativi. Per migliorare la profittabilità dell'impianto è fondamentale implementare il ricircolo di materiale di scarto e minimizzarne lo smaltimento.

Parole chiave: Frazione Organica dei Rifiuti Solidi Urbani (FORSU), digestione anaerobica a secco, digestione anaerobica a umido, digestato anaerobico, separazione liquido-solido, post-compostaggio.

Contents

1 Introduction

1.1. Current role of Waste-to-Energy

There is only one planet Earth, yet by 2050, the world will be consuming as if there were three. [1]

The current global crisis extends far beyond the pure climate change, showing in the first place an unsustainable resource management strategy. Growth of global population and economy, together with the increasing standards of life and sanitation, requires an exponential increase in the utilization and disposal of materials, thus making of fundamental importance the definition of a proper waste management strategy. EU Waste Framework Directive of 2008 [2] defines the hierarchy of activities that must be realized in an efficient integrated waste management system, where energy recovery, or Waste-to Energy, is one of the last but necessary steps.

Figure 1: source EU Waste Framework Directive 2008.

Another current and relevant problem is represented by the energy supply, that should match the increasing demand while ensuring sources diversification and security, improving transmission efficiency and capacity constraints. In this context, Waste-to-Energy (WtE) brings multiple advantages, (1) replacing primary energy demand, (2) reducing import dependence, and (3) substituting fossil sources utilization. Furthermore, being WtE-electricity generated from the waste locally produced, it helps to (4) decentralize the production reducing load and losses on the transmission lines.

It is therefore necessary to invest into the optimization and adoption of WtE technologies, while building social awareness and technical control over the harmful emission of gaseous pollutants, GHG and wastewaters.

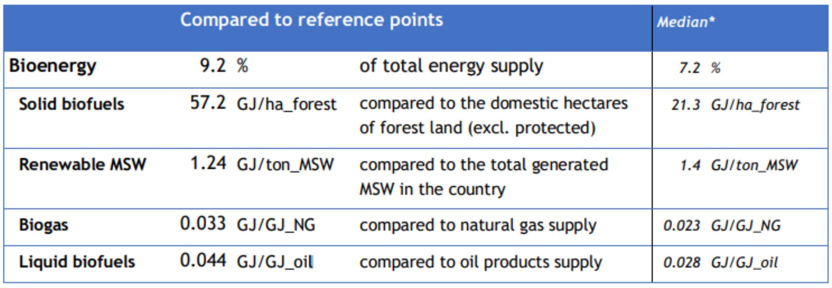
1.2. Introduction to biogas production

The WtE sector includes a wide range of technologies, depending on the source and characteristics of waste. Generally, hazardous, and contaminated industrial and municipal waste is thermally decomposed through thermo-chemical treatments such as incineration, co-combustion, gasification, and pyrolysis. The Organic Fraction of Municipal Solid Waste (OFMSW) and other biodegradable substrates can alternatively be biochemically degraded by means of microbial activity, through aerobic (composting) and Anaerobic Digestion (AD) processes.

Despite being incineration the most economically effective technology, anaerobic digestion is regarded as the best method in terms of environmental performances, being the only one with net negative emission [3, 4, 5], and reporting in life cycle assessments (LCAs) the lowest (i.e. best) score in the highest number of impact categories [6].

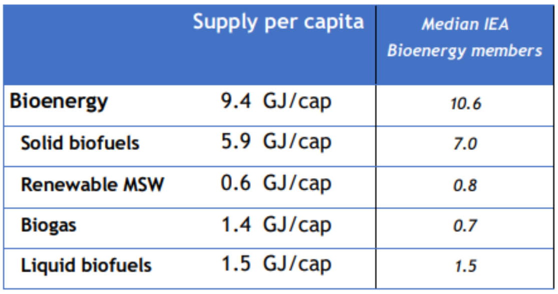
Specifically, Anaerobic Digestion (AD) is the process of biodegrading the organic matter in absence of oxygen and in a controlled environment, producing (1) a biogas rich in methane and carbon dioxide, and (2) an inert, stabilized material. The digestate leaving the digester, poor in organic carbon but rich in nitrogenous and phosphorous compounds, can be (1) directly used as soil conditioner, (2) upgraded to a biologic fertilizer through a composting process, or (3) dewatered and incinerated to produce heat and electricity. Composting is an alternative for OFMSW disposal; it is an aerobic process, cheaper and simpler but without the advantage of energy recovery and including release of odours and greenhouse gasses (GHG).

Biogas from AD is just one of the technologies classified as bioenergy, but represents a relevant fraction of the Italian portfolio, well positioned in Europe, second only to Germany [7], and counting around 1800 active biogas plants in 2021 [8].



	Compared to reference points			Median*
Bioenergy	9.2	%	of total energy supply	*7.2 %*
Solid biofuels	57.2	GJ/ha_forest	compared to the domestic hectares of forest land (excl. protected)	*21.3 GJ/ha_forest*
Renewable MSW	1.24	GJ/ton_MSW	compared to the total generated MSW in the country	*1.4 GJ/ton_MSW*
Biogas	0.033	GJ/GJ_NG	compared to natural gas supply	*0.023 GJ/GJ_NG*
Liquid biofuels	0.044	GJ/GJ_oil	compared to oil products supply	*0.028 GJ/GJ_oil*

Figure 2: Comparison of the supply of different bioenergy carriers in Italy in 2019, to specific reference point. Source: [7]



	Supply per capita	Median IEA Bioenergy members
Bioenergy	9.4 GJ/cap	*10.6*
Solid biofuels	5.9 GJ/cap	*7.0*
Renewable MSW	0.6 GJ/cap	*0.8*
Biogas	1.4 GJ/cap	*0.7*
Liquid biofuels	1.5 GJ/cap	*1.5*

Figure 3: Total energy supply per capita in Italy in 2019 for different bioenergy carriers.

Source: [7]

* Median of the 25 member countries of IEA Bioenergy.

1.3. Work objectives

This work is a case study of a combined anaerobic digestion and composting plant, located in Apuglia, digesting Organic Fraction of Municipal Solid Waste (OFMSW) and producing biomethane and compost. The plant layout mainly consists of a mechanical pre-treatment of the OFMSW, an anaerobic digester of Plug Flow Reactor (PFR) type, a blender to mix the digestate with structuring material and a final composting pit.

An important classification for biogas plants is the wet or dry process, that is adopting a solid content in the digester respectively below and above 15%, and implying differences in the biochemical process and the economics of the facility [9, 10].

The plant under analysis is designed as a dry process facility but was reported operating in wet and semi-wet conditions during the first eight months of operations. The target solid content in the digester is 17%, while on-site measurements showed an average value of 10% to 14%, also reporting low viscosity and issues of stratification and sedimentation.

Before composting, the digestate is mixed with a vegetal matrix to guarantee a proper density and moisture content of the mixture; a lower solid content implies larger volumes of structuring and absorbing material. Consequently, the digestate post-treatment suffered from high purchase cost of green waste to be mixed to the digestate, and from high volumes to be composted, excessive for the installed treating capacity and composting space availability.

Focusing on the specific problem of the semi-wet digester conditions, the objective of this work is to answer the following research questions:

1. what are the causes and the consequences of this issue in terms of technical and economic performances?
2. Which are the plant modifications that could reduce the negative impacts on the plant profitability?

Possible causes might be (1) incoherent sizing of the digester, (2) an improper functioning of the pre-treatment process, or (3) an inconsistency of waste composition conveyed to the plant with respect to the design hypothesis.

Possible modifications to the digestate post-treatment could be (1) the extension of the blender system capacity by addition of a second unit, (2) the installation of a digestate dewatering stage composed by a Filter Screw Press (FSP) separator, or (3) the feeding of dry vegetal material in the digester to increase the solid content upstream. The FSP separated liquid could either be disposed of in wastewater treatment or upgraded to an End of Waste (EOW) soil conditioner though a pasteurization.

To answer the second question, an economic comparison of different plant configurations is carried out, modelling the mass balances of each component, and estimating all the fixed and variable costs related to the digestate post-treatment.

In chapter 2, the basic notions of anaerobic digestion and composting processes are introduced, together with a general description of the components of an AD plant.

In chapter 3, the methodology is presented, describing in detail the plant of the case study, the modelling of its components, the sampling procedures at the base of the on-site measurements, and the economic estimation of the fixed and variable costs.

In chapter 4, the collected data are displayed, organized, and commented, allowing to better understand the biochemical dynamics occurring in the digester.

In chapter 5, the first research question is developed and answered, suggesting the most probable causes at the foundation of the problem.

In chapter 6, all the numerical results of the work are presented and discussed, including the investigation of the inconsistency of on-site data measurements, the feasibility of the feeding of dry vegetal material in the digester, and the economic comparison of configurations adopting additional component non included in the original layout.

In chapter 7, the conclusions are withdrawn.

2 State of the Art

In this chapter, anaerobic digestion and composting are introduced from the technological perspective, giving a theoretical background, and describing the main parameters that are useful to design and monitor the process [11, 12, 13, 14]. Both are organic matter degradation processes performed by bacteria but operated under different conditions. Anaerobic digestion occurs in absence of oxygen, allowing the organic carbon in proteins, lipids, and carbohydrates to be degraded and converted into CH_4 and CO_2, with the double outcome of energy recovery and stabilization of a reactive substrate. Composting instead occurs in aerobic conditions, determining the formation of CO_2 only, losing the energy recovery advantage but performing bio-stabilization and maturation in a more hygienic and accurate way.

2.1. Anaerobic digestion overview

2.1.1. Biochemical reactions

Table 1: anaerobic digestion stages.

Step	Description	Bacteria
Anaerobic hydrolysis (1)	Complex molecules are broken into monomers (sugars, amino acids, LCFAs)	Facultative anaerobes
Primary fermentation (2) - acidogenesis	Monomers are converted to VFAs (propionic, butyric acids...), H_2, alcohols	Acidogens, obligate and facultative anaerobes
Secondary fermentation (3) - acetogenesis	VFAs and alcohols are converted into acetic acid, CO_2 and H_2	Acedogens, obligate and facultative anaerobes
Methanogenesis (4a): acetoclastic m. (70%)	Acetic acid is converted into CH_4 and CO_2	Methanogens, obligate anaerobes
Methanogenesis (4b): hydrogenotrophic (30%)	Reduction of carbon dioxide and oxidation of hydrogen ($CO_2 + H_2 \rightarrow CH_4 + H_2O$)	Methanogens, obligate anaerobes

Under the biochemical perspective anaerobic digestion can be seen as a sequence of four interdependent steps, illustrated in Table 1: anaerobic digestion stages, each one carried out by a different microorganism group, overall converting complex compounds such as carbohydrates, proteins and lipids into methane and carbon dioxide, together with a series of trace molecules present in the biogas (H_2S, NH_3). More details in [12].

$$Complex\ organic\ compounds \rightarrow CH_4 + CO_2 + trace\ gases + Heat$$

Many factors influence the overall process, concerning equilibrium, reaction rates and demographic stability of microbial colonies. Different microbial consortia are interrelated, with the products of the former steps being the reactants of the latter ones. Under these conditions, a higher activity of one step does not assure increased productivity of the overall process since the same modification can simultaneously favour a subprocess and disadvantage another one. The optimal conditions for obligate anaerobes are different from those of facultative anaerobes, and a compromise must be reached and monitored. For lignocellulosic and slowly degradable substrates, hydrolysis is the rate-limiting step, while for easily degradable and reactive feedstocks such as OFMSW, it is the methanogenesis [10, 15].

2.1.2. Biochemical Methane Potential

Being AD a complex set of reactions, a simple and effective design parameter is needed to summarize the productivity of the process and correlate the amount of digested substrate with the obtained energy production. This parameter can either be referred to biogas or biomethane production and is expressed as the volumetric yield in normal cubic meters per ton of substrate (m^3/ton).

The chemical energy of the substrate is measured by the Chemical Oxygen Demand (COD) content, and the theoretical BMP_{th} is calculable by knowing the biochemical composition of the substrate, the stoichiometry of the reactions, and by assuming complete biodegradation to biogas [12]. Alternatively, an experimental potential BMP_{exp} can be determined through a batch laboratory test that measures the gas output produced under controlled conditions from a given feedstock sample [16]. To design and size the plant, the biogas or biomethane *potential* is used, while to evaluate its performances, the *yield* is adopted, representing the gas output obtained under real operative conditions. The yield can be referred to the ton of Volatile Solids (VS), or to the tons of primary fresh substrate.

Actual yields and potentials are dependent on the feedstock type and can vary a lot accounting for seasonality, geographical origin, and environmental conditions during transport and storage. High ambient temperatures lead to uncontrolled degradation before entering the industrial digestion process, reducing the amount of collected output. Furthermore, the same substrate can produce differently depending on the designed plant operation (dry or wet AD, mesophilic or thermophilic), and in general the production is correlated with the degradation efficiency. [9]

2.1.3. FOS/TAC ratio

Among the various indicators of the degradation process conditions [17] stands the accumulation of Volatile Fatty Acids (VFAs), intermediate reaction products such as acetic, propionic, and butyric acid, suggesting whether the chemical equilibrium is leaning towards the right or the left side of the reaction. When VFAs concentration is low, the methanogenesis reaction rate tends to be higher with respect the hydrolysis and fermentation, and vice versa when the level is high.

Among the monitoring techniques broadly employed in AD plant management stands the FOS/TAC[1] value evaluation, easily determined by a titration machine. FOS is an indicator of VFAs accumulation, measured in equivalent acetic acid concentration ($mg_{CH3COOH}/L$), while TAC represents the buffer capacity, or ability to absorb acidic compounds, measured in equivalent calcium carbonate content (mg_{CaCO3}/L) [18].

A high ratio describes a condition of overfeeding and can be seen as an acidification risk warning, even though it does not imply a low pH condition.

Table 2: FOS/TAC ratio interpretation.

FOS/TAC ratio	Organic load	Action
> 0,6	excessive	stop feeding
0,5 - 0,6	very high	reduce feeding
0,4 - 0,5	high	closely monitor FOS/TAC
0,3 - 0,4	ideal	keep conditions
0,2 - 0,3	insufficient	gradually increase feeding
< 0,2	too low	rapidly increase feeding

According to an empirical study [18], the optimal ratio generally stands within 0.3 – 0.4, even though operations are acceptable between 0.2 – 0.6. To manipulate FOS/TAC value towards the optimal one, the substrate feeding can be quantitatively increased or reduced, as well as qualitatively modified in the case of co-digestion of different substrates in agricultural plants. Nonetheless, plants adopting different feedstocks can have a different optimal range, which should be determined through an empirical observation.

It should be remembered that the health of a complex system as an anaerobic digester cannot be extensively described by a single parameter, especially the FOS/TAC value, since the equivalent VFAs content does not account for differences between the acids. In fact, some VFA compounds are inhibitory to methanogenesis if not properly converted into acetic acid by specific bacteria. FOS/TAC is representative of the

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[1] Flüchtige Organische Säure (FOS) and Totales Anorganisches Carbonat (TAC), from the first german manufacturers of the titration machines.

feeding health if the microorganisms' environment is healthy itself, and other parameters are generally required [19].

2.1.4. Influence of the temperature

Temperature and pH are key parameters for the survival and productivity of the microorganisms since their variations can heavily affect the bacterial colonies. Obligate anaerobes are particularly sensitive to temperature fluctuations, the reason why it is vital to maintain the digester temperature as constant as possible. Within the same family, bacteria can be divided into psychrophilic (5–20°C), mesophilic (32-45°C), and thermophilic (50-70°C) strains, each one with its own characteristics. For instance, thermophilic methanogens show higher growth and perform a faster degradation than mesophilic methanogens, even though the latter are more resilient to temperature changes due to their higher biodiversity [10]. Digester operations are generally selected among mesophilic and thermophilic. The mesophilic 38-42°C range has the advantages of faster food waste solubilization and a more stable operation against environmental factors. The thermophilic 50-55°C range assures an increased biogas production, adding a disinfection function but also increasing the heating requirement and the costs associated with it. If any, temperature changes must be as gradual as possible to allow the new bacterial strains to grow, adapt and take over the old ones.

2.1.5. pH influence

Methanogens, obligate anaerobes, maximize methane production in the pH range of 6.8-8.2, while hydrolysis and fermentation bacteria, facultative anaerobes, accomplish optimal performances in the pH range of 5.5-6.5 [20]. Being methanogenesis the biochemical bottleneck of the process, digesters are generally operated in neutral pH conditions (6.8 – 7.2) to favour methanogens, also accounting for the wider tolerance of fermentation bacteria. Organic conversion naturally leads to intermediate acids release, which by accumulation might cause a pH drop. Significant pH changes are prevented by the presence of buffering systems, intended as storage of substances able to absorb free acidic compounds. Two common systems consist of carbon acid/carbonates and ammonia/ammonium equilibrium, which are stable at approximately 6.5 and 10 pH values respectively [10].

2.1.6. Nutrients

Macronutrients (C, N, P, K, S) and micronutrients (trace metal elements) are needed for microorganisms' health and growth, as long as a reasonable balance is respected. The excessive micronutrient concentration in particular causes decompensation by releasing inhibitory compounds, threatening the stability of the biological process. Significant characteristics of the feedstock to be monitored are Total Organic Carbon (TOC), nitrogen differentiated in Total Kjeldahl (TKN) and ammonium nitrogen ($NH4+$ - N), carbon to nitrogen ratio (C/N ratio), Total Phosphorous (TP) and Total

Potassium (TK) [21]. C/N is typically adjusted by mixing carbon-poor substrates as food waste with carbon-rich bulking agents such as sawdust, straw, and wood scraps.

2.2. Composting overview

Composting is the degradation of organic substrates spontaneously occurring in the presence of oxygen, operated by microorganisms different from anaerobic digestion strains.

2.2.1. Biochemical process

The organic matter is converted in humic compound and mineral salts, including the release of water and carbon dioxide. Oxygen is required to mineralize the putrescible components [22]. The reaction is considerably exothermic and high temperature are achieved in the composting material.

$$Org.sub. + O_2 \rightarrow compost + CO_2 + H_2O + \; NO_3^- + SO_4^{2-} + Heat$$

Oxygen availability, temperature, and water content are the three key parameters influencing the process. Oxygen provides the oxidation potential that allows organic carbon degradation. A lack of O_2 slows down the reaction rate, leading to longer composting time, while in presence of high temperatures an O_2 excess might lead to spontaneous self-combustion of the organic matter.

The temperature determines the selectivity of the microorganism type, influencing the processing activity but also implying the death of bacteria living at different temperature ranges. Thermophilic organisms are the most productive strains, and high temperature is a sign of intense activity, but excessive values above 70°C can lead to bacterial death and stop the process. Moisture is required to support microbial activity, and an optimal water content results in enhanced oxygen consumption from the bacteria. Excessive moisture level hinders oxygen diffusion, and a lack of it might lead to biological death [23].

2.2.2. Process monitoring and control

Composting is monitored through some key parameters such as water content, temperature, pH, and composition of the gaseous phase present inside the material including oxygen, carbon dioxide and methane [22]. It is important to notice that a consistent methane content indicates an insufficient oxygen uptake or diffusion, leading to anaerobic digestion reactions and consequent ammonia and hydrogen sulphide formation.

Composting control is mainly operated through aeration and irrigation. The first one guarantees oxygen supply and removal of excess heat through bulk flow heat exchange. Water supply reintegrates evaporated moisture, also contributing to temperature control through phase heat exchange associated with evaporation.

2.2.3. Phases of the process

The process can be divided into the subsequent phases of activation and stabilization.

Active Composting Time (ACT) includes the degradation of most simple and easily degradable compounds, occurring in a short time and resulting in peaking temperatures, oxygen consumption, and carbon dioxide production. A drop in pH is experienced due to the acidification effect of CO_2 release. For such reasons, ACT requires a significant irrigation and aeration supply [22]. This phase includes the sterilization stage, thanks to the material exposition to high temperatures, leading to the deactivation of infectious bacteria such as Escherichia Coli and Salmonella.

The maturation phase consists of the degradation of more complex and less reactive molecules, as well as the final conversion into humic compounds. It involves longer duration, lower temperatures, mesophilic organisms, lower moisture contents, higher oxygen levels and higher pH due to the release of ammonia. Oxygen, aeration, and irrigation demand are significantly lower [22].

Table 3: optimal parameters for composting material in ACT and maturation stage.

Parameter	ACT	Maturation
Temperature [°C]	55-70	35-45
pH	6-7	8-9
Humidity [%]	50-60	35-40
O2 [%]	5-15	1-5
CO2 [%]	>20	5-15
CH4 [%]	0-5	0

At the end of the process, two characteristics are evaluated, stability and maturity. Biological stability occurs when microbial activity is negligible, and it is determined through a respirometry test quantifying microorganisms’ oxygen consumption. Maturity instead is the absence of phytotoxicity, an independent concept from stability, evaluated through a germination test.

2.2.4. Feedstock requirements

Together with the process parameters, the characteristics of the organic feedstock going to composting - nutrients content, humidity, pH, porosity, and density - play a key role in microbial activity and process stability.

The nutrient content is summarized through the C/N ratio, representing the ratio between degradable organic carbon, used by microorganisms to sustain their metabolic activities, and the available organic nitrogen used to synthetize proteins. The amount of carbon determines the duration of the metabolic process, which increases with the available matter for degradation, while the nitrogen content can influence the pH since it determines the potential of nitrogen release in the form of ammonia. At the end of the process, a C/N ratio of 15-20 in the compost is expected.

As mentioned above, since humidity influences the bacterial oxygen consumption processes, it can be adjusted through irrigation but requires an optimal initial value in the range of 55-60% to smoothly start the process. The initial pH should not be too acidic nor alkaline, with a reasonable range between 5.5 and 8. Porosity is defined as the ratio between solid and void volume and is directly linked with the oxygen diffusion phenomenon. Similarly, an adequately low density guarantees the achievement of optimal porosity.

Table 4: ideal initial characteristics of the material to be composted.

	Range	Optimal
C/N [-]	20-40	25-30
Humidity [%]	40-65	50-55
pH	5.5-9.0	6.5-8.5
Porosity [%]	35-50	35
Density [t/m^3]	0.40-0.65	0.55-0.60

2.3. Combined AD and composting plant

Anaerobic digestion consists in capturing the chemical energy of the organic substrate in the form of methane, then collected and upgraded to biofuel. The residual stream, known as digestate, can be converted to high-quality compost through an aerobic process called post-composting. This type of plant is composed of a series of functional steps and associated areas:

1. Reception and storage of the substrate to be digested,
2. Movimentation of the plant streams,
3. Feedstock pre-treatment,
4. Anaerobic digestion of the organic feedstock,
5. Collection and upgrading of the produced biogas,
6. Composting and stocking of final end-of-waste streams.

According to the processed feedstock the facilities are classified as [24]:

- agricultural plants, usually co-digesting mixtures of livestock manure and harvesting residues, adjusting the proportion to guarantee a proper C/N ratio,
- food waste plants, typically digesting food-processing industry waste and OFMSW separated at the source, including kitchen waste, paper and cardboard, garden municipal waste,
- sewage sludge digestion plants, typically embedded in municipal wastewater treatment facilities.

Landfill biogas plants are worth to be mentioned but will not be considered for the purpose of this study. The Organic Fraction of Municipal Solid Waste (OFMSW), focus of this work, is the combined collection of organic household waste, mainly food and kitchen waste, separated at the source and transported in small bioplastic bags.

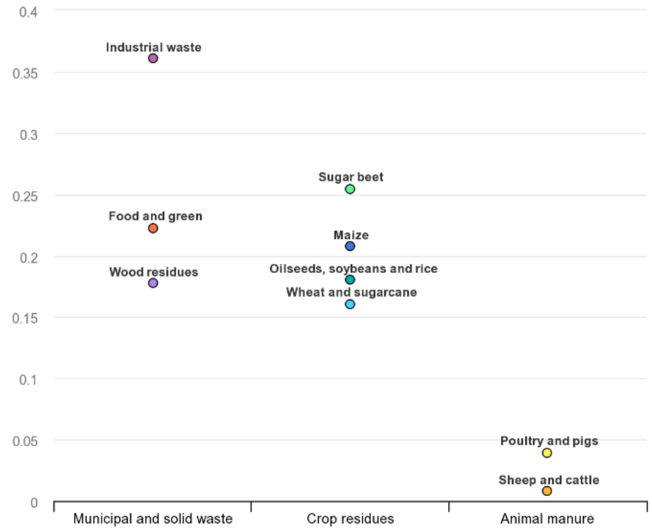


Figure 4: Average biogas production yield by ton of feedstock type [24]

2.3.1. Feedstock delivery and storage

Every feedstock has peculiar properties and is more suitable for specific processes. Highly putrescible and liquid substrates prefer wet digestion in continuously stirred tank reactors (CSTR) or are used in co-digestion, while dry digestion is more indicated for OFMSW and harvest residues and is typically performed in plug flow reactors (PFR). Differently from agricultural residues, waste feedstocks can contain pollutants and pathogens, therefore requiring a thermal sanitation process.

Delivery can be as regular as daily basis for 6 days a week for OFMSW plants. In continuous feeding plants the feedstock is stored in vessels, containers or reception pits depending on the plant size, to ensure the continuity of the operation even with an outage of delivery. For easily degradable and putrescible substrates the production of leachate and biogas directly in the storage area is common, due to spontaneous degradation.

For OFMSW, waste collection is regarded as a disposal service to the society and constitutes a source of income for the plant operator. The gate fee can range from 80 to 120 €/t depending on many factors among which the impurity fraction. Still, quality standards must be respected, out of which the plant has the right to refuse the conferred waste and the conveyer is fined. Agricultural plants are used to recycle farm waste into soil conditioner, reduce air pollution from manure storage, save money on energy and chemical fertilizers consumption, and do not earn any gate fee [25].

The plant startup procedure includes the seeding and stabilization of microbial community through an inoculating substrate, and a feeding ramp up to favour bacteria adaptation to the new feedstock.

- The inoculum is digestate extracted from operating digesters - generally agricultural plants digesting manure, it does not contribute to biogas production, and it is loaded in the empty digester up to half or three quarters of the nominal volume [26].
- The design feedstock, i.e. OFMSW, is then added in small quantities and slowly increased up to the nominal flow rate, with the purpose of gradually adapting the bacteria to the new substrate and building a stable environment.

The whole process duration can vary from few weeks up to 6 months according to the digested feedstock and includes calibration of all the plant machinery [26]. It must be repeated each time the reactor is emptied for cleaning and maintenance, but after the initial tuning is done this will require less time.

2.3.2. Handling

The handling of material flows is a critical feature requiring maximum reliability under a great variety of working conditions. Every piece of the chain should be specifically designed for the type of stream to be handled, ensuring continuity of operations while accounting for fluctuation of density, viscosity, water content, presence of extraneous and bulky elements, and seasonal variability above all. The main adopted equipment are belts for solid and light flows, pipes and ducts for liquid streams, and spiral screw conveyors for semi-solid streams.

Conveyor belts generally move at a low speed and are safe against problems of clogging and occlusion, but are responsible for odour release, contrarily from the other two systems. Screw conveyors are the most suitable for viscous, sticky, stringy, semi-solid streams with high reliability and low maintenance. The shaftless screw type provides further prevention against material build-up on the shaft that reduces the useful passage section. Generally, the rotational speed is low enough to neglect wear phenomena, and failures are mostly due to clogging, weight building-up and cracking of the structure in the middle of axial length. Pipes have the advantage of transporting pressurized streams, regulating the velocity through pumps, and preventing leaking and odour release. Liquid streams might contain acidic and aggressive compounds leading to internal surface corrosion, but also solid, fibrous objects blocking the passage. For viscous fluids as the digestate, hydraulic piston pumps are used for their higher reliability.

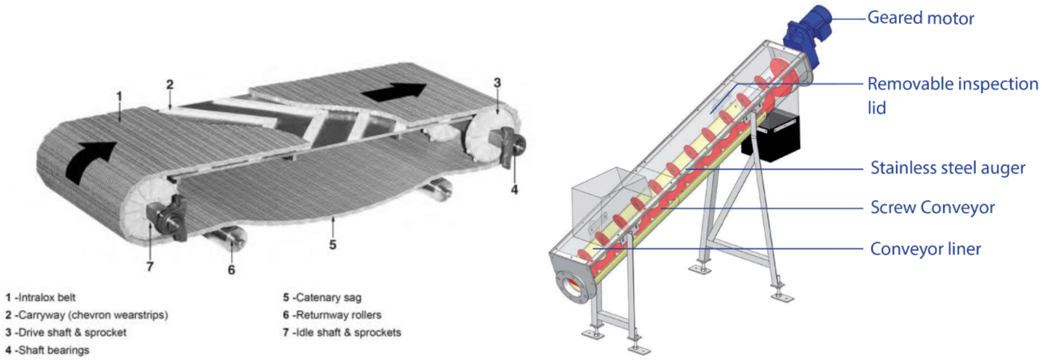


Figure 5: handling equipment, conveyor belt and shaftless screw conveyor.

2.3.3. Substrate pre-treatment

To optimize the anaerobic digestion performances, the feedstock undergoes a refining process located between the storage and the feeding stage. Different types of pre-treatments are available on the market, distinguished in mechanical, thermal, chemical, and biological treatments, with the common goal of increasing the substrate availability to the bacteria and maximize biogas production [27, 28, 29, 15].

Mechanical treatments include [30]:

1. separation of non-organic and ferromagnetic fractions with sorting machines,
2. structural molecules cracking through ultrasonic and high-pressure treatments,
3. comminution, or reduction of particle size, using mills and grinding equipment.

Thermal ones perform pathogens removal (replacing the pasteurization step), and partial degradation of the most complex molecules favouring the solubilization of organic compounds. Similarly, chemical treatments make use of strong acids, alkalis, or oxidants while biological techniques of specific enzymes.

Like for every aspect concerning anaerobic digestion, an improper treatment can have a negative impact on the process, for instance with an excessive size reduction or molecules solubilization leading to accumulation of VFAs [31].

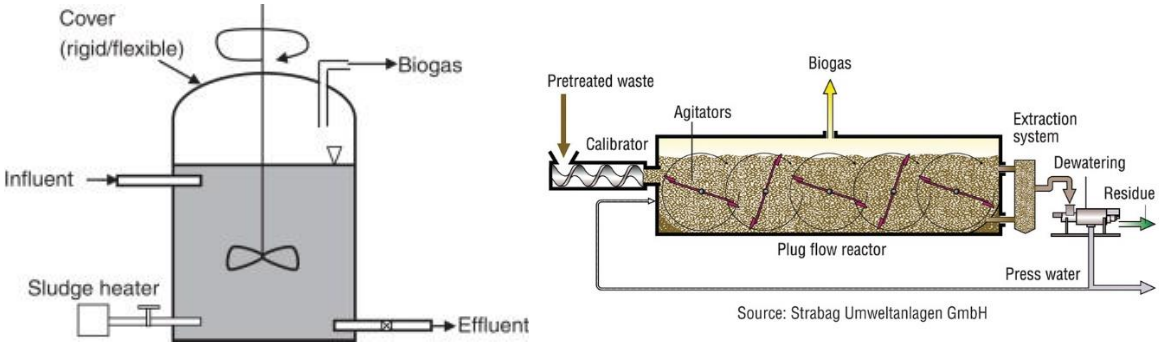
Heterogeneous feedstocks need homogenization to prevent the formation of uneven distribution sections in the digester, which can affect the adaptation and growth of microorganism colonies. Complex organic substrates benefit from a facilitation of the hydrolysis sub-process, being the Rate Determining Step (RDS), by means of a partial thermo-chemical decomposition. Waste streams also need pathogen removal. Generally, chemical treatments are the most suitable for lignocellulosic matrixes, ultrasonic and thermal for sewage sludge. Small scale agricultural plants might not have any treatment in the perspective of minimizing investment costs.

Mechanical treatments are the most suitable for OFMSW plants. State-of-the-art systems include a bag opening and shredding section, a removal of non-organic materials and polluting fractions and a comminution stage. The mechanical reduction of the average particle size improves biogas production by increasing the surface area available to enzymes, it increases degradation rate by homogenizing the retention time of different substrate components [32].

2.3.4. Anaerobic digester

The digester is the place where the set of biochemical reactions occurs, and it should ensure process stability, and safety in terms of gas, liquid leaking, and biogas collection. It is a rigid and sealed structure built of steel and concrete, of different shapes depending on the type:

- Continuous-flow Stirred-Tank Reactors (CSTRs), of cylindrical shape and adopting a central vertical axis mixing system,
- Plug Flow Reactors (PFRs), of tubular shape (regardless of the cross section) with a series of horizontal axis agitator blades.



Source: Strabag Umweltanlagen GmbH

Figure 6: CSTR and PFR type anaerobic digester schemes.

2.3.4.1. Design parameters

The most important design parameters for the digester are the Hydraulic Retention Time (HRT) and the Organic Loading Rate (OLR), measuring the average feedstock's residence time in the reactor, and the amount of degradable organic matter (VS) loaded per day and per volume unit of the digester.

$$HRT\ [d] = \frac{V_{DIG}\ [m^3]}{V_{feed}\ [\frac{m^3}{d}]}$$

$$OLR\,[\frac{kg_{VS}}{m^3\ d}] = \frac{M_{feed_{VS}}\ [\frac{kg_{VS}}{d}]}{V_{DIG}\ [m^3]}$$

A high HRT guarantees a better utilization of the theoretical potential of the substrate, increasing the VS conversion efficiency (η_{VS}), while a more loaded digester can perform a higher specific biogas yield ($yield_{BG}$) per volume unit of the digester.

$$\eta_{VS}\ [-] = \frac{VS_{in} - VS_{out}\ [\frac{t}{d}]}{VS_{in}\ [\frac{t}{d}]}$$

$$yield_{BG}[\frac{t}{m^3\ d}] = \frac{M_{BG}\ [\frac{t}{d}]}{V_{DIG}\ [m^3]}$$

On the other hand, an excessive OLR might lead to overfeeding and acidification, and an excessive HRT might cause a severe drop in solid content in the reactor.

Such process parameters are not independent since, assuming a fixed substrate composition, a higher ORL requires a lower HRT and vice versa. The two parameters are inversely proportional with respect to the VS concentration in the feeding substrate.

$$OLR * HRT = \frac{M_{feed_{VS}}\ \left[\frac{kg_{VS}}{d}\right]}{V_{feed}\ \left[\frac{m^3}{d}\right]} = VS\ [\%]$$

In Table 5, the typical values for high loaded sludge digesters, OFMSW and agricultural reactors:

Table 5: typical values of OLR and HRT for different types of anaerobic reactor.

	Agricultural	OFMSW	Industrial high loaded system
OLR [$kg_{VS}/m^3/d$]	1-3	8-12	50
HRT [d]	60-90	25-35	<1

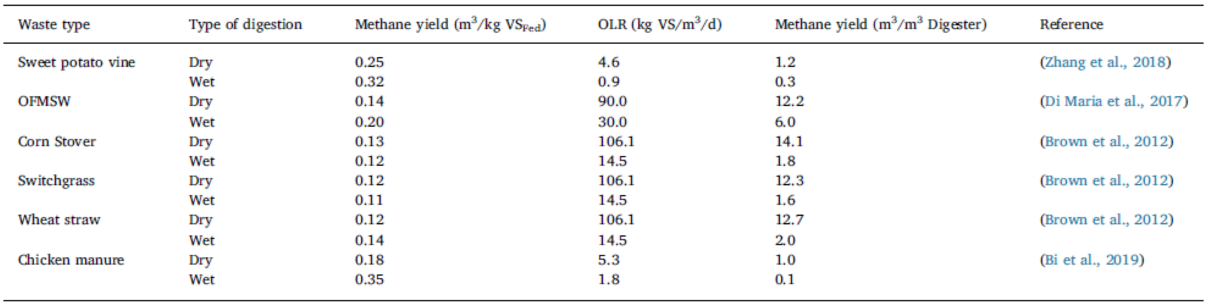
Removal efficiencies of dry OFMSW AD plants can range between 60% and 70% on total VS basis [33, 34].

2.3.4.2. Reactor type classification

Depending on the solid content in the reactor, digesters are classified as dry or wet technologies. Wet systems expect a digester with 8-12% TS, requiring efficient mixing to ensure thermal and density homogenization. Due to low viscosity, an efficient pre-treatment is fundamental to prevent the risk of plastic floating and sand precipitation.

A dry system with 17-25% TS content in the reactor ensures higher OLR and needs a smaller volume to produce the same biogas output. The main purpose of the design is to minimize volume and capital cost while maximizing the volumetric biogas production. The mixing system is simpler and undersized with respect to wet systems since its main role is to push the digestate forward. The higher viscosity helps to keep sand and plastics in suspension, and the drier output digestate requires a lower amount of absorbing material to be blended in the composting mixture.

Overall, at constant volumetric feeding, a wet process with lower solid content implies a reduced OLR, with high conversion efficiencies, but low biogas yield per volume of the reactor.



Waste type	Type of digestion	Methane yield ($m^3/kg\ VS_{Fed}$)	OLR ($kg\ VS/m^3/d$)	Methane yield (m^3/m^3 Digester)	Reference
Sweet potato vine	Dry	0.25	4.6	1.2	(Zhang et al., 2018)
	Wet	0.32	0.9	0.3	
OFMSW	Dry	0.14	90.0	12.2	(Di Maria et al., 2017)
	Wet	0.20	30.0	6.0	
Corn Stover	Dry	0.13	106.1	14.1	(Brown et al., 2012)
	Wet	0.12	14.5	1.8	
Switchgrass	Dry	0.12	106.1	12.3	(Brown et al., 2012)
	Wet	0.11	14.5	1.6	
Wheat straw	Dry	0.12	106.1	12.7	(Brown et al., 2012)
	Wet	0.14	14.5	2.0	
Chicken manure	Dry	0.18	5.3	1.0	(Bi et al., 2019)
	Wet	0.35	1.8	0.1	

Figure 7: Comparison of biogas yields for feedstocks treated by dry and wet digestion [9].

A dry system is more productive, but the higher the TS content in the digester the lower the biomethane yield due to a lack of homogenisation, diffusion, availability of nutrients and dilution of potential inhibitors [34, 9].

CSTRs mimic a perfectly mixed reactor and are especially suitable for wet digestion, also considering the adopted mixing system. PFRs instead are more often adopted with dry digestion due to the higher viscosity of the digestate, which is hard to homogenize from the inlet to the outlet section.

In a single stage reactor, all four biochemical steps are occurring simultaneously, requiring a compromise that must favour the rate determining step. It is possible to decouple the processes with a multiple stage digester, isolating methanogenesis from the other stages, maximizing the productivity of each family of microorganisms and optimizing the collection of different gaseous products. An example is the dark fermentation concept, with a first stage at pH 5.5 favouring hydrolysis and fermentation and collecting biohydrogen, and a second stage at alkaline pH maximizing biomethane production. This solution implies a higher investment cost, space availability, and complexity of the process management, but adds redundancy reducing the risk of plant stop due to failure or digester maintenance. It is only adopted in wet systems since dry digesters are usually oriented towards cost minimization.

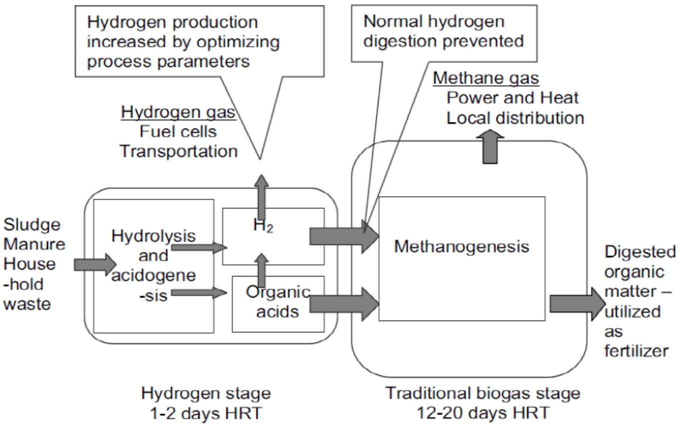


Figure 8: schematic diagram of two-stage process for hydrogen and methane production [35].

2.3.4.3. Operating strategies

The gaseous mixture is heterogeneously synthetized across the active digester volume and stored in the upper volume of the digester. A proper overpressure in the range of 5-45 mbar assures a constant outlet flow to the biomethane upgrading unit, but an excessive one, or an off-specification biogas composition, activates the flare, a safety equipment that burns the gaseous fuel. A minimum flow of biogas is constantly sustaining a pilot flame in the flare so to assure a timely response in case of unexpected digester behaviour.

Digester volume is monitored through the surface height level, visible from portholes, and is controlled by unloading the same volumetric flow rate that is fed. The operational volume is lower than the available one since the upper portion is needed as biogas storage. In agricultural plants, the digester cap is made of an elastic material able to expand and respond to the internal overpressure.

The volume must be kept as constant as possible because changes in the level can affect the biogas overpressure, causing fluctuations and risk of biogas flaring. A maximum level is defined considering a safety margin, accounting for unexpected foaming phenomena.

In the reactor, the relevant environmental conditions are monitored and kept as stable as possible. Temperature is controlled through a heating system, generally constituted by hot water pipes supplied by the heat circuits of the Combined Heat and Power (CHP) unit. The pH can be adjusted through injection of buffering acid/alkaline solutions. A similar method is used in case of foaming phenomena, handled with the addition of vegetal oil. To guarantee homogenization and prevent sedimentation of fine matter on the bottom and floating of light matter on the surface, a mixing system is always present.

2.3.5. Biogas treatment

Apart from methane and carbon dioxide, the biogas also contains water, hydrogen sulphide (H_2S), nitrogen gas, oxygen, ammonia (NH_3), and particles. Their concentration is accurately monitored through a biogas analyser. The raw biogas can be used as-it-is to fuel a CHP unit or upgraded to quality biomethane to either be injected in the gas infrastructure, liquefied, or to be used as a cleaner fuel in a co-generator.

2.3.5.1. Raw biogas cleaning and upgrading

Whether it is directly used as biogas in a CHP unit or upgraded to biomethane, the presence of unwanted compounds can be harmful to the equipment. With pressure and temperatures changes the moisture can condense and cause corrosion in the metallic surfaces, and similarly H_2S can form aggressive and corrosive compounds as sulphuric acid [36]. Gas pipeline applications have very low tolerances regarding the oxygen content due to the risk of explosion. Furthermore, if biogas is upgraded to biomethane, unremoved gaseous pollutants would end up in the separated CO_2-rich stream, preventing its utilization in the food industry.

Desulphurization can be performed with various methods, like precipitation by addition of iron ions, biological treatment, chemical adsorption, oxidation. A consolidated technique is sodium hydroxide washing with reagent recovery. In many cases, H_2S oxidation through oxygen addition is not acceptable because leading to oxygen residual content.

Ammonia is generally removed with water scrubbing, then neutralizing the ammonium sulphate solution with H_2SO_4.

Moisture is removed through compression or cooling cycles and a demister for condensate sequestration, placed right after water scrubbing to deliver a dry gas to the downstream utilization.

2.3.5.2. Biomethane incentives in Italy

Biogas has a different composition than natural gas, implying a lower energy density due to a reduced methane concentration, and a non-optimized behaviour in internal combustion engines. Indeed, CHP generators burning biogas need to be specifically designed for it. Therefore, upgrading is necessary to boost the Lower Heating Value (LHV), to meet the quality requirements of the natural gas pipeline, and the fuel compatibility with standard combustion equipment. Economic advantages are the ability to sell a higher quality product and to benefit from incentives supporting the biomethane industry.

Italy adheres to the European Green Deal and supports the development of the biogas and biomethane industry. Objectives are stated in the RePower-EU plan the New Biomethane Ministerial Decree of September 15th, 2022, pushing the adoption of biomethane in the transport sector, the upgrading of agricultural biogas plants to biomethane production, and the construction of new facilities equipped with liquefaction and distribution technologies.

The strategy includes the emission of biomethane certificate, the CICs, associated with the production and grid injection of 615 Nm^3 of biomethane. Regarding the production of advanced biomethane, a tariff of 375 €/CIC is granted limitedly to 10 years duration, with a tariff supplement and investment costs contribution for specific cases [37]. Furthermore, the European Commissioned recently approved a new development fund for the years to come [38].

2.3.5.3. Biogas upgrading

Biogas upgrading mainly consists in physical separation of methane and carbon dioxide. The four main technologies are Pressure Swing Adsorption (PSA), scrubbing, membrane separation and cryogenic distillation. Since some of them are very sensitive to hydrogen sulphide or water content, additional desulphurization and dehydration stages can be required, for instance with activated carbon filters.

Adsorption and absorption technologies take advantage of the different CO_2 and CH_4 solubility under specific pressures and temperatures and in different solvents. PSA adsorbs and desorbs carbon dioxide, more soluble than methane at high pressures, on a porous carbon matrix, recirculating the CO_2-rich desorbed flow to minimize the CH_4 emissions. Scrubbing technologies use instead temperature cycles, absorbing carbon dioxide through water, amine solution, or organic solvent. Membrane technologies exploit the molecular size of the gas molecules, as carbon dioxide is more likely to pass through semipermeable barrier, allowing to collect methane streams up to 97% purity. Finally, cryogenic distillation uses the difference in boiling point of the two gases [36].

The four technologies have similar investment cost and energy consumption, so that the technical choice must be made on the specific case considering the digested substrate, the raw biogas composition, the final product utilization, the access to consumables (reactants, pH regulation chemicals) and other operational costs [39].

2.3.6. Post-composting

The by-product of anaerobic digestion is an inert effluent, poor in degradable carbon, rich in lignocellulosic fibres and nutrients, but also containing elevated amount of ammonia-nitrogen and metallic salts of zinc and copper.

According to the 2019 EU Fertilizers Regulation [40], the requirements on the digestate production process are the following time-temperature profiles:

- Thermophilic AD at 55°C during at least 24h and an HRT of at least 20 days,
- Thermophilic AD at 55°C with a subsequent pasteurization step (70°C, 1h),
- Thermophilic AD at 55°C, followed by composting*.
- Mesophilic AD at 37 -40°C, with a subsequent pasteurization step (70°C, 1h),
- Mesophilic AD at 37 -40°C, followed by composting*.

* Respecting the EoW time - temperature profiles for composting defined in 0.

According to the Italian legislation (D.M 25/02/2016 and D.Lgs. 152/06), the digestate is differentiated depending on the biomass from which it is originated. Effluents from agricultural AD plants can only be directly used in agronomic application as soil conditioner, but with quantitative limitation due to its high salinity and nitrogen content. The digestate of other wastes is regarded as a special waste due to undesired compounds. In this framework, composting of the digestate is an interesting alternative in terms of circular economy and economic viability, considering the high cost of WWTP treatment. The resulting compost is a good soil conditioner and, within specific quality standards, can be considered an end-of-waste stream with market value.

To guarantee adequate characteristics of the matrix to be composted, the digestate is combined with vegetal absorbing and structuring material. The ingredients are mixed in a blender with the important function of homogenizing the material. The blended matrix is then stored in piles and sent to ACT phase. A maturation stage will complete the aerobic degradation process, ensuring proper features of the soil improver. The piles are periodically turned to guarantee sufficient aeration. Differences in porosity and humidity across the pile volume can interfere with the monitoring process, leading to simultaneous presence of different issues (self-combustion, bacterial death). Similarly, non-uniform C/N ratio might lead to a different composting duration in different sections of the piles.

After ACT and maturation phases are completed, the compost is sieved to collect and sell the powder-fine material, while large over sieve fibres are retained and recirculated in the process as structuring material.

2.3.6.1. Process layout

Composting material is disposed in piles of triangular or trapezoidal shape and variable length. The pile's height must not be excessive, to provide a homogeneous oxygen diffusion to the metabolic process. The external layer can be made of finished compost to provide thermal insulation and acting as a biofilter to the released air.

According to the state-of-the-art technology, composting is divided into ACT and maturation phases, providing different spaces with different characteristics. ACT area should be confined, with movable or permanent structures, to limit odours and pollutants release during the stages with high metabolic activity. The floor should be impermeable, to avoid soil pollution, and equipped with draining ducts that collects contaminated liquid to recirculate it in the process or to dispose it in WWTPs. If present, aeration equipment consists of a ventilation system insufflating air from a series of holes on the floor, equally distributed along the surface.

Maturation stage has less technological requirements, the confinement is not necessary, but needs a larger surface due to the longer process duration. It can be covered or uncovered, with the difference of pile temperature stability and the unpredictable influence of atmospheric agents on the humidity level. Ideally, a covered area would be preferrable.

Before release in the atmosphere, the exhaust insufflation air requires a filtration from undesired volatile compounds as Volatile Organic Carbon (VOC), hydrogen sulphide and ammonia, operated through a biofilter consisting in a bed of lignocellulosic material.

2.3.6.2. Normative requirements

In the current legislation concerning fertilizers, compost is classified as a soil improver, due to its capability to maintain or improve physical, chemical properties and biological activity of the soil. According to D.Lgs 75/2010, if obtained from food or animal waste, it is defined as composted miscellaneous soil improver, or Ammendante Compostato Misto (ACM).

According to the decree 5/2/98, the composting process must be carried out ensuring:

- control of ingredients mixing ratios to guarantee adequate chemical and physical of the initial organic matrix,
- Process temperature control,
- Adequate oxygen supply.

For disinfection time-temperature curves, the EU Fertilizers Regulation [40] states:

- 70 °C or more for at least 3 days,
- 65 °C or more for at least 5 days,
- 60 °C or more for at least 7 days,
- 55 °C or more for at least 14 days.

In the annex Q of Legislative Decree 152/2006 are stated the minimum time requirements, being 60 days of composting duration with at least 72 hours at a temperature 55°C or above.

Furthermore, the annex recognizes the specific case of digestate composting, setting a minimum duration of the integrated anaerobic and aerobic digestion is 60 days in total, with at least 15 days of AD and 30 of composting. Nonetheless, the process duration should always ensure adequate properties of the finished product.

To be sold on the market, ACM must meet specific requirements in terms of physical and chemical properties, indicated in the Legislative Decree 75/2010:

- Maximum humidity of 50%
- pH between 6 and 8.5
- maximum C/N ratio 25
- minimum organic C on dry basis 20%
- minimum humic C on dry basis 7%
- minimum organic N on dry basis 80%

The values are controlled by authorized laboratories.

3 Materials and methods

To answer the thesis questions, it is necessary to introduce features and behaviour of the plant under study, to model the plant components and their interactions in terms of mass balances, to define the laboratory procedures used to sample the plant streams and measure their characteristics, and to estimate fixed and variable costs associated with the operation of each operative stage. All of this is described in this chapter.

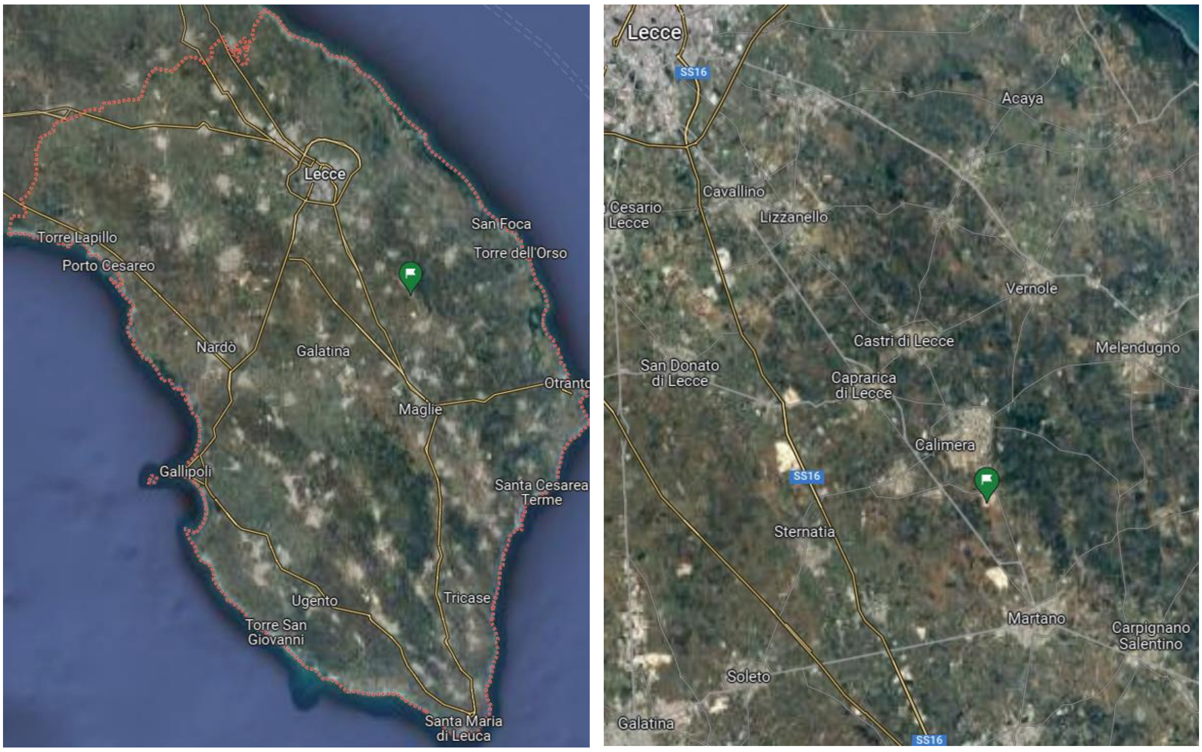


Figure 9: localization of the case-study plant

3.1. Plant description

The focus of the study is an OFMSW AD plant located in southern Italy, Apuglia, in a rural area characterized by the presence of small towns of few thousand inhabitants, vivid agricultural activity, and market for trade of green waste and compost.

The food waste undergoes a mechanical pre-treatment consisting in a bag opener and a hammer mill separator, and is then fed into a single substrate, single stage, plug flow digester, designed to operate under dry and mesophilic conditions. The produced biogas is treated and upgraded to biomethane, while the digestate is blended with absorbing and structuring vegetal material, to dry and build porosity in the mixture, and then sent to a post-composting process, out of which quality compost is obtained.

The biogas facility is authorized to process 24.000 tons of food waste per year, separated at the source, collected from about 20 surrounding cities. According to the design, on an average day 66 tons of OFMSW are conveyed to the plant, 54 tons of treated substrate are fed into the digester after pre-treatments, 12 tons of biogas are produced, 7 tons of upgraded biomethane are injected into the grid, and 13 tons of quality compost are recovered.

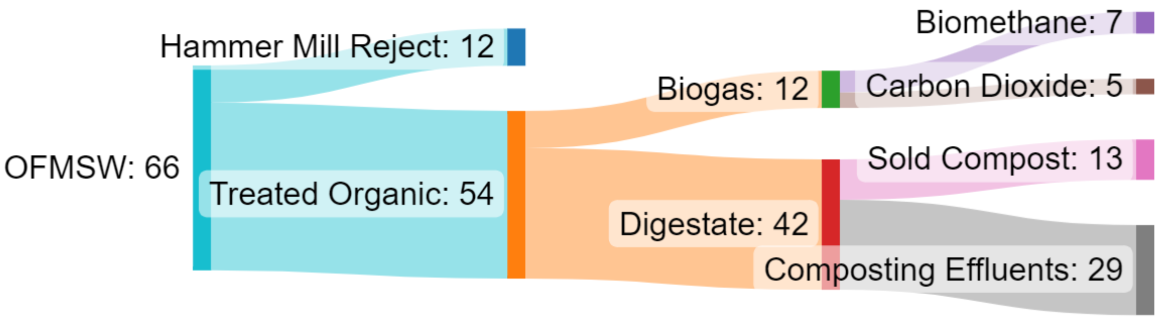


Figure 10: Simplified Sankey diagram of the plant input and output streams

The main input and output streams are represented in Figure 10. The digestate post-composting is extremely simplified and will be described in detail in the next chapters.

3.1.1. OFMSW delivery and storage

The whole plant sizing is based on the maximum yearly amount of conferrable waste, authorized by the municipal institution responsible for waste management, set to 24.000 tons per year. It must not be exceeded unless upon request approved by the authority. The OFMSW is conveyed to the plant six days a week, for an average conferral of 77 tons per day, and includes households, restaurants, fisheries, and food industry organic waste, which is sometimes inadequate to be digested. Quality standards must be respected in terms of European List of Waste (ELW) codes authorised for conferral, out of which the plant has the right to refuse the load and the conveyer is fined.

3.1.1.1. Handling equipment

During the entrance and exit of OFMSW trucks, a load-cell bridge records the truck's weight to keep track of the conferred waste. Upon ensuring that the transported load can be accepted by the plant, the OFMSW is unloaded and stored in a reception pit, where it is mixed and loaded in the pre-treatment process by an automatic overhead crane. The crane's polyp bucket has a capacity of approximately 2 m^3 and is designed to handle 10 to 15 tons per hour, compatible with the daily load to be processed.

Figure 11: Polyp bucket crane.

An essential parameter is the reception pit height level, used to monitor the accumulation of waste, which must not exceed safety limits. To decrease the level in case of need, the handling capacity must be slightly oversized.

A tire washing yard is present to remove the leachate on truck wheels and avoid odours release on the nearby roads. The wastewater is collected in an underground basin and can be conveyed to the digester, together with other leachate streams, or sent to disposal in a WWTP.

3.1.2. Mechanical pre-treatment

A bag opener and a hammer mill are included in the pre-digestion treatment layout, which is sized accounting for a working time of 12 hours a day for 7 days a week. A separator can be added downstream the hammer mill to isolate and recover vegetal fibres in the reject stream.

3.1.2.1. Bag opener

The bag opener is equipped with rotating blades to shred plastic bags, films, and packaging to let as much organic matter as possible out. The operation is quite stable and robust, but might be affected by a high liquid presence since all the light and bulky matter would float and get stuck in the machine.

Figure 12: bag opener in operation.

3.1.2.2. Hammer mill

The hammer mill works as a grinding machine that comminutes and homogenizes the feedstocks and separates the clean organic fraction of the OFMSW. It consists of a steel drum equipped with a rotating shaft on which several hammers are mounted, left free to swing. The machine has a maximum capacity of 22 t/h, with an electrical power of about 90 kW.

Figure 13: hammermill unit (left) with internal view of hammers and metallic screen (right).

The rotor is spun at high speed so that hammers inertially crush the substrate, repeatedly shredding it by dynamic impact and shear stress, to guarantee a sufficient fragmentation of the organic fraction. As the hammers squeeze the waste through the screen, the drum retains bi-dimensional materials (plastics, fibres), letting only the fine organic fraction out, which is then conveyed to the live bottom bin. Coarse materials are axially discharged, where the reject is collected.

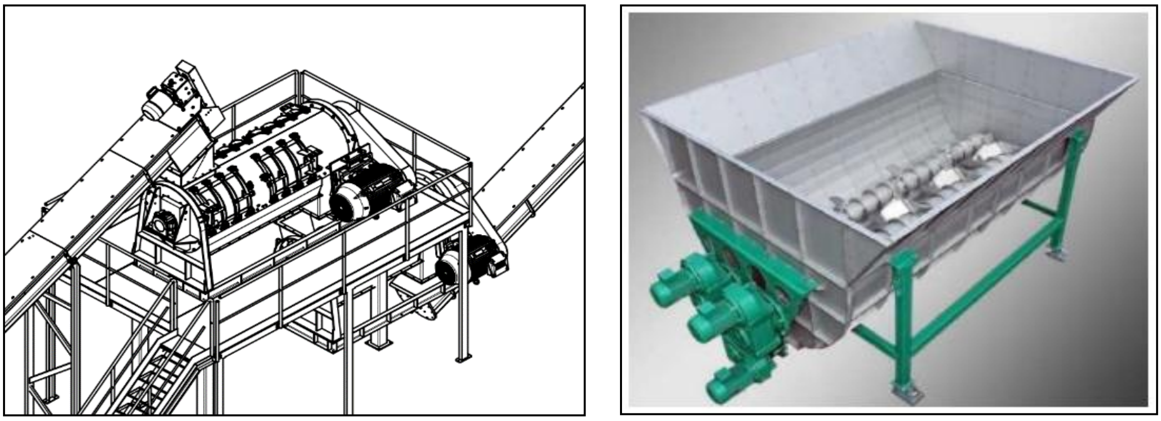


Figure 14: hammer mill (left) and live bottom bin (right) modelling draft.

The rotational speed contributes to wear and tear of the components by friction and centrifugal stress. A dilution can be applied by injecting water or recirculated leachate, to drag fine material or dirt throughout the screen and clean the outlet streams, and to reduce mechanical wear on the machine surfaces. The injection can be calibrated closer to the inlet section to maximize organic collection, or towards the outlet one to obtain a cleaner plastic reject stream.

According to plant records, the organic matter separation rate ranges between 70% and 85%, while the remaining 30% to 15% of treated OFMSW is discarded as reject. In this flow are collected the bulkier and bidimensional materials such as fibres, fruit scraps, fragments of the OFMSW bags, which by law should be composed of bioplastic only but, in reality, are often made of normal plastic [41]. The distinction is not in the scope of this work and, from here after, the mixture of biologic and traditional plastic will be referred as "plastics".

The metal screen retains most of available vegetal lignocellulosic fibres, together with a significant amount of fine organic fraction dragged by the plastics. In the reject stream, on average, organic fibres account for 73% on dry mass basis of the whole flow. Screen diameter can be calibrated to optimize separation, and differentiated for inlet, mid and outlet section.

3.1.2.3. Separator

The device, not yet adopted in the plant, would separate the plastics of the hammer mill reject, obtaining a remaining stream of organic fibres that can be recirculated in the composting process as vegetal blending material. Furthermore, reject is considered as ELW 19.12.04 (contaminated plastic waste), and it is composed of organic material by about 73% on a dry basis. Such strategy would doubly reduce the operative costs:

- By decreasing the amount of absorbent material to be purchased, and
- By cutting a major fraction of reject disposal cost.

3.1.3. PFR digester

The plug flow type digester is a horizontal container-shaped structure, built of steel and concrete, where the digestate is slowly pushed from the inlet to outlet section with the aid of rotating blades. It is suitable for dry digestion, with reduced space requirements, and higher tolerance of impurities with respect to wet systems, concerning build-up and floating of plastics, paper, metals, sand, wood.

Figure 15: PFR digester external view.

The reactor is sized on the organic flow rate to be digested, approximately 54 tons per day equally distributed on 8760 hours per year. Reasonable values for HRT and OLR guarantee a good balance between biogas yield (BGP) and organic matter removal. The design values in Table 6 are reached after the stabilization of both feeding conditions and the biological process.

Table 6: design and reference values of OLR and HRT for the case-study plant.

	HRT [d]	OLR [$kg_{VS}/m^3/d$]
OFMSW plant range	25-35	8-12
Case study design	32	7.3

The total internal volume is 2061 m^3, with 1800 m^3 of active volume available to the digestate, corresponding to a maximum height of 7.5 m with a surface of 240 m^2. Since unexpected foaming phenomena caused by fermentation of the fed substrate can create up to 1 meter of level increase, the operative height ranges between 6.25 and 6.75 m, equivalent to a digestate volume of 1500 to 1600 m^3. Grit deposition on the bottom decreases the useful active volume available to the bacterial conversion.

Expected biogas production has an average value of 405 m^3/h, with a maximum capacity of 470 m^3/h.

The PFR is compact and scalable and consists of a gas-tight sealed vessel featuring:

1. A heating system,
2. A mixing system,
3. A piping circuit.

3.1.3.1. Heating system and CHP

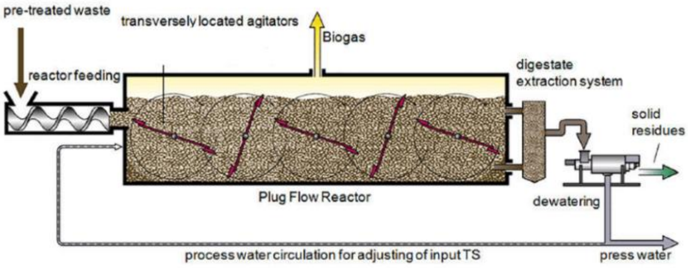


Figure 16: PFR digester schematic layout.

The reactor operates in mesophilic conditions, ranging between 38 and 42°C. The temperature is maintained by a heating system consisting of iron pipes mounted on the internal digester walls, supplied by hot water produced in the CHP, and operating by indirect heat exchange. The co-generator is fuelled with grid methane and has nominal electric and thermal capacities of 350 kW_{el} and 200 kW_{th}. The average digester thermal request is 87 and 45 kW_{th} in cold and warm season, respectively. In the warmest weeks of the year, the anaerobic digestion reactions are exothermic enough to keep a constant mesophilic temperature without the aid of the heating system.

Figure 17: internal view of the PFR digester with the heating system pipes (left) and the mixing system agitator's shaft and blades (right).

3.1.3.2. Mixing system

The mixing system consists of five agitators, sets of long and thin blades mounted on horizontal shafts, slowly rotating to push the digestate towards the outlet of the digester and to keep the floating and precipitate fractions in suspension. The last shaft rotates backwards to improve the homogeneity of the outlet digestate. Each mixer works for a few hours per day, which should be sufficient for a dry process digestate.

3.1.3.3. Piping system

Digester feeding is automatized by controlling the screw conveyors linked to the live bottom bin where the treated organic substrate is stored. Feeding estimation is either weight-based, measuring the live bottom bin weight difference after each cycle, or time-based, running the screws for a given amount of time and assuming a loading rate of approximately 2 tons every 10 minutes. Two feeding ports are located on top of the inlet wall, while the outlet port is located at the bottom of the outlet wall.

The digestate discharge can either be spontaneous for a digester level increase or remotely controlled, and it is performed by piston pumps with a capacity of 200 L/min. Two different piston pumps are installed, one to operate the normal digestate unloading and a second unit to supply digestate recirculation. Three sampling points, equipped with a double safety valve, located at the bottom of one lateral wall, allow to extract digestate samples from the initial, middle, or ending part of the process.

3.1.4. Biogas cleaning and membrane upgrading

The system must be able to treat the maximum allowed biogas rate, set to 470 m^3/h. A constant monitoring of the biogas quality is carried out in terms of methane, oxygen, carbon dioxide, and hydrogen sulphide composition. Main pollutants (H_2S, NH_3 together with moisture) are then removed before the upgrading to biomethane. The treatment system is composed by a desulphurization tower with reagent recovery, and an ammonia water scrubber.

3.1.4.1. Desulphurization tower

The desulphurization equipment washes out the hydrogen sulphide by means of a low-speed, counter-current shower of sodium hydroxide (NaOH) solution. The sulphur-rich liquid is then sent, through communicating vessels, to the recovery tank where, thanks to air insufflation, the reagent is regenerated to reduce its consumption. The elemental sulphur and the sulphates settle in the sedimentation tank where they can be easily removed. Finally, the clean liquid is sent back from the tank through the recirculating pump to the tower to be used again. A demister stage before biogas discharge prevents carry-over of the cleaning solution.

3.1.4.2. Ammonia scrubber

As desulphurisation, the biogas passes through the scrubber packing material wetted with sprayed water, and ammonia is removed by gas-liquid mass transfer and consequent precipitation as ammonium sulphate salts. The gaseous flow is cross or counter-current to the liquid one, which is falling by gravity, to maximize contact and enhance mass transfer. The contaminated liquid solution is then partly discharged, and partly regenerated and recirculated to reduce water consumption. Regeneration occurs with the passage through a sulphuric acid dosing station placed prior to the reinjection in the system.

3.1.4.3. Upgrading preparation

Before upgrading, the clean biogas must be compressed and prepared for the process. A refrigerated dryer dehumidifies the gaseous stream by indirect glycol cooling down to 7°C, followed by a demister. The following compression stage, incorporating a screw compressor equipped with cooling and demister system, delivers the stream to the filtrating system at 8 bar pressure compatible with the injection in the gas grid. Here, oil filtration and activated carbon filter remove the remaining traces of particles, hydrogen sulphide and VOC, which would irreversibly damage the upgrading equipment installed downstream.

3.1.4.4. Membrane separation

The upgrading system exploits the different molecular size of methane and carbon dioxide, collecting an average and maximum (235 and 272 m^3/h) flow of biomethane above 97% purity. Eventual residual moisture and pollutants end up in the discarded CO_2 stream. The system consists of three separation stages, the first two treating the biogas and delivering a biomethane flow, and the third one permeating the discarded CO_2 flows to recover eventual unseparated biomethane.

Pure separated CO_2 (170 to 185 m^3/h) is currently released in the atmosphere, but with the future possibility of collection and reutilization in a bioethanol plant.

A flare is present for safety purposes, burning the biogas or the biomethane in case of off-specification production, or in case of a malfunction of the biogas treatment chain. The maximum flare burning capacity is set by the tolerable thermal stress and depends on the Lower Heating Value (LHV) of the burned gas, corresponding to a maximum 470 m^3/h for raw biogas and maximum 280 m^3/h for biomethane.

3.1.5. Digestate post-treatment

The plant produces between 40 and 45 tons per day of digestate, for a total of approximately 15.000 tons per year. For its high nutrients and humic content, digestate is used to produce between 15 and 25 tons per day of a quality soil improver, obtained through a post-composting process that ensures biostability and maturity of the final product.

Table 7: TS, C/N and density characteristics of the blender ingredients.

	TS [%]	**C/N ratio**	**Density [t/m^3]**
Digestate	10-18	3-9	0.95-1.05
Fine Green Waste	45	60	0.4
Fibrous material	75	100	0.5
Straw	80	70	0.2
Compost/Over Sieve - recirculation	65	30	0.6
Expected blended mixture	45	30	0.55

Vegetal material and recirculated composted material is added to the digestate, to guarantee specific requirements of the mixture to be composted. Fine green waste, fibrous material, and straw are mixed into a so called prepared green waste mixture. Fibrous residues from sieving process as well as finished compost are included in the recirculation. Expected features of the ingredients available to the plant are summarized in Table 7, together with the ideal final mixture characteristics.

The blending recipe main objectives are increasing the C/N ratio and decreasing the humidity content and density to proper values. Porosity is another important factor, and it is controlled through average size of the blended structuring material, ensuring a range of 25 to 75 mm. Finished compost recirculation is included for inoculating purposes. Overall, the mass volumetric flow rate of the mixture is considerably higher than the digestate one.

Mixing ratios must ensure proper quality of the final blend and can heavily impact the economic performance of the plant. Indeed, a higher digestate water content requires a higher amount of vegetal additives, which partly need to be purchased at a high specific cost, together with the increasing volume to be treated with the same available space and processing capacity. For such reasons, different layouts elements are taken into consideration, depending on the TS content of the digestate.

The digestate treatment process can be composed of:

- Mixture blending stage,
- Dewatering stage,
- Pasteurization stage.

3.1.5.1. Blender

Playing the fundamental role of mixing the recipe ingredients, the blender is the essential stage for the composting process, ensuring homogenization of the material in terms of composition (C/N ratio, humidity) and size (density, porosity). An incorrect blending process can result in serious downstream problems concerning composting.

Figure 18: blender external view (left) with manual loading operations (right).

The digestate is directly conveyed to the blender hopper through the digester outlet pipes, dosing the quantity through cycle duration by knowing the pump capacity of 200 L/min. The green material is instead manually moved with a wheeler loader and gradually added in the hopper by plant operators, dosing the recipe by knowing the bucket volume. Similarly, the blended material is manually transported from the blend pit to the bio-cells to start the composting process.

The machine is composed of a 21 m^3 vessel equipped with load cells and rotating screw mixers powered by a 90-kW electric motor. The treating capacity is defined by the maximum weight bearable by the screws, corresponding to 6 tons, together with the recipe mass mixing ratios. A green waste pre-mixture is prepared and stored, to guarantee a faster loading procedure.

In Table 8 the recipe of the preliminary dry-process design.

Table 8: preliminary blending recipe on a yearly basis.

	ton/year	mix ratio
digestate	14600	43.2%
green waste mixture	10000	29.6%
Over sieve >40 mm	4200	12.4%
Over sieve >10 mm	2000	5.9%
recirculated compost	3000	8.9%

3.1.5.2. Dewatering stage

Dewatering is applied when the digestate water content is excessive, and the recipe would otherwise require a too high quantity of vegetal additives. The two outputs are a cake flow, semisolid material, and a filtrate flow, liquid stream that can either be treated or directly disposed.

There is no dewatering stage in the original project, but a testing unit was installed to verify the compatibility and functioning of the machine with the existing layout. The device must be compatible with the TS content of the digestate to be treated, and two solutions were identified: (1) a simple and cheap model, which can withstand a solid content up to 14%, and (2) a more complex and expensive multistage device able to handle up to 25% TS. Nonetheless, the simpler machine was able to work off-specification and treat digestate up to 16% TS without any major technical issues.

The technology adopted on-site is the Filter Screw Press (FSP) type, similar to a screw compressor, paired with a screen with adjustable diameter, from 50 to 100 mm. Increasing diameter and reducing the input solid content allows a higher treating capacity in tons per hour. The device is sized on the digestate stream, considering the hourly capacity of the FSP at the rated TS and screen size.

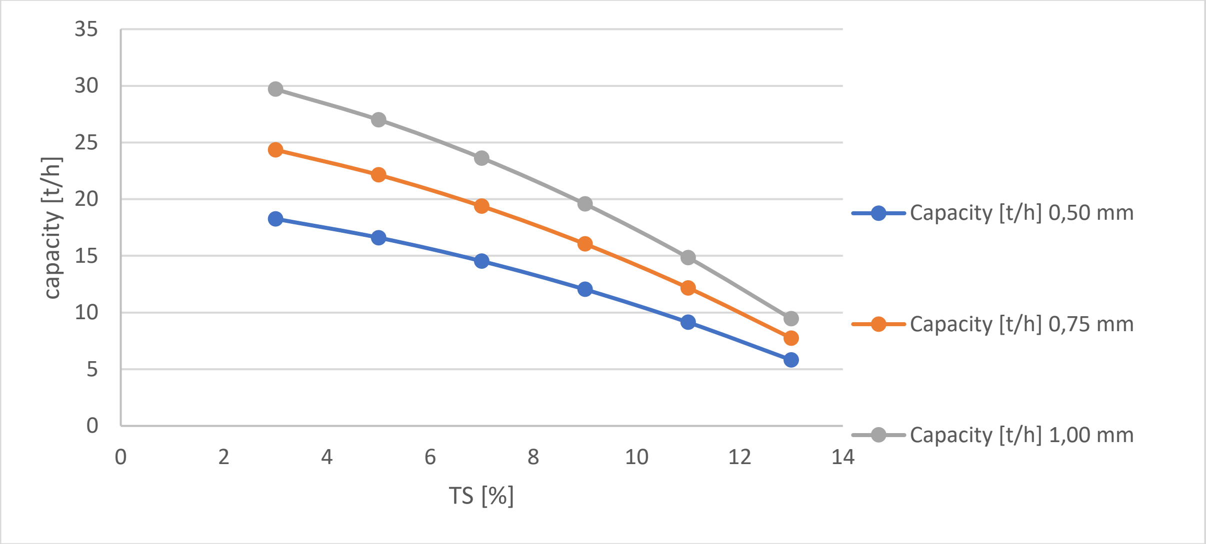


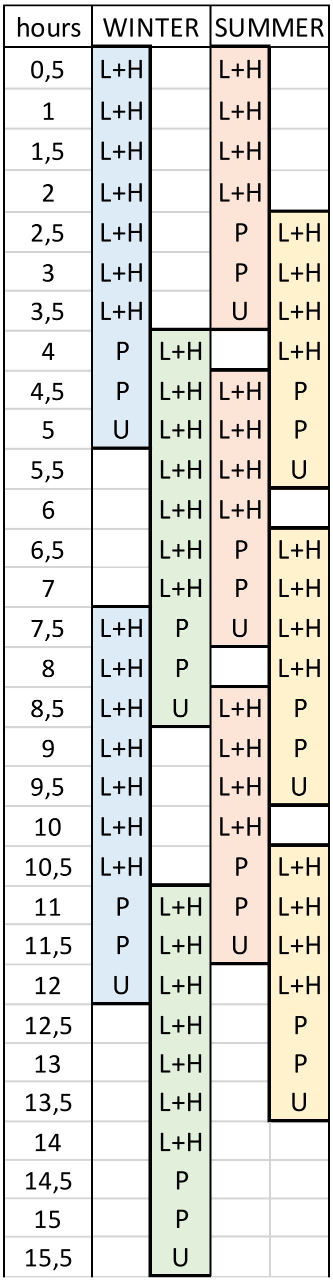
Figure 19: FSP dewatering unit - capacity – TS dependency curve

3.1.5.3. Pasteurization

FSP filtrate is considered as a special waste, and its disposal represents a major expense which can be avoided through the installation of a pasteurizer, providing a sanitation treatment to ensure pathogen removal and release a harmless liquid, eligible as an EOW. It would also allow to cut the irrigation water consumption by recirculating pasteurized liquid in the composting process.

The device consists of a series of indirect heat exchangers conveying thermal power from the heating circuits of the CHP unit to the pasteurizer tanks, where the filtrate is stored. The process is made of a (1) loading stage, a (2) heating stage - where the batch is brought from ambient to pasteurization temperature, a (3) pasteurization stage – where the batch is kept for at least one hour at 73°C, and a final (4) unloading stage. The plant under study would adopt a batch two-tanks system, each one with a useful capacity of 7.5 m^3 per batch. The system is sized on a filtrate flow rate of 30 to 40 tons per day.

During summer, the average thermal request for heating the digester is lower than during winter, and complementarily the higher power available to the pasteurizer allows to reduce the duration of the heating phase. Consequently, warmer months allow to run a higher number of batches, overall increasing the daily treating capacity.



hours	WINTER		SUMMER	
0,5	L+H		L+H	
1	L+H		L+H	
1,5	L+H		L+H	
2	L+H		L+H	
2,5	L+H		P	L+H
3	L+H		P	L+H
3,5	L+H		U	L+H
4	P	L+H		L+H
4,5	P	L+H	L+H	P
5	U	L+H	L+H	P
5,5		L+H	L+H	U
6		L+H	L+H	
6,5		L+H	P	L+H
7		L+H	P	L+H
7,5	L+H	P	U	L+H
8	L+H	P		L+H
8,5	L+H	U	L+H	P
9	L+H		L+H	P
9,5	L+H		L+H	U
10	L+H		L+H	
10,5	L+H		P	L+H
11	P	L+H	P	L+H
11,5	P	L+H	U	L+H
12	U	L+H		L+H
12,5		L+H		P
13		L+H		P
13,5		L+H		U
14		L+H		
14,5		P		
15		P		
15,5		U		

Figure 20: pasteurisation cycles: as soon as the heating (L+H) stage of tank 1 is concluded, the thermal power is conveyed to the tank 2 to start the loading and heating stage, and vice versa. Such strategy optimizes utilization of the available heat.

3.1.6. Composting areas

After blending, the material starts the composting process, divided in ACT, maturation, and sieving stage.

- From the blending area, the mixture is manually moved with wheel loaders and stored in the bio cells, confined spaces made of concrete, equipped with aeration and irrigation systems, where the first stage is carried out.

- After the ACT stage, the material is moved to the maturation aisles, located in a covered space protected from atmospheric agents, where it is kept for the required duration, and periodically turned over with wheel loaders.
- Finally, the matured material is transported in the sieving area, where the fine final compost is separated from the coarse fraction, which is then mostly recirculated in the blending process.

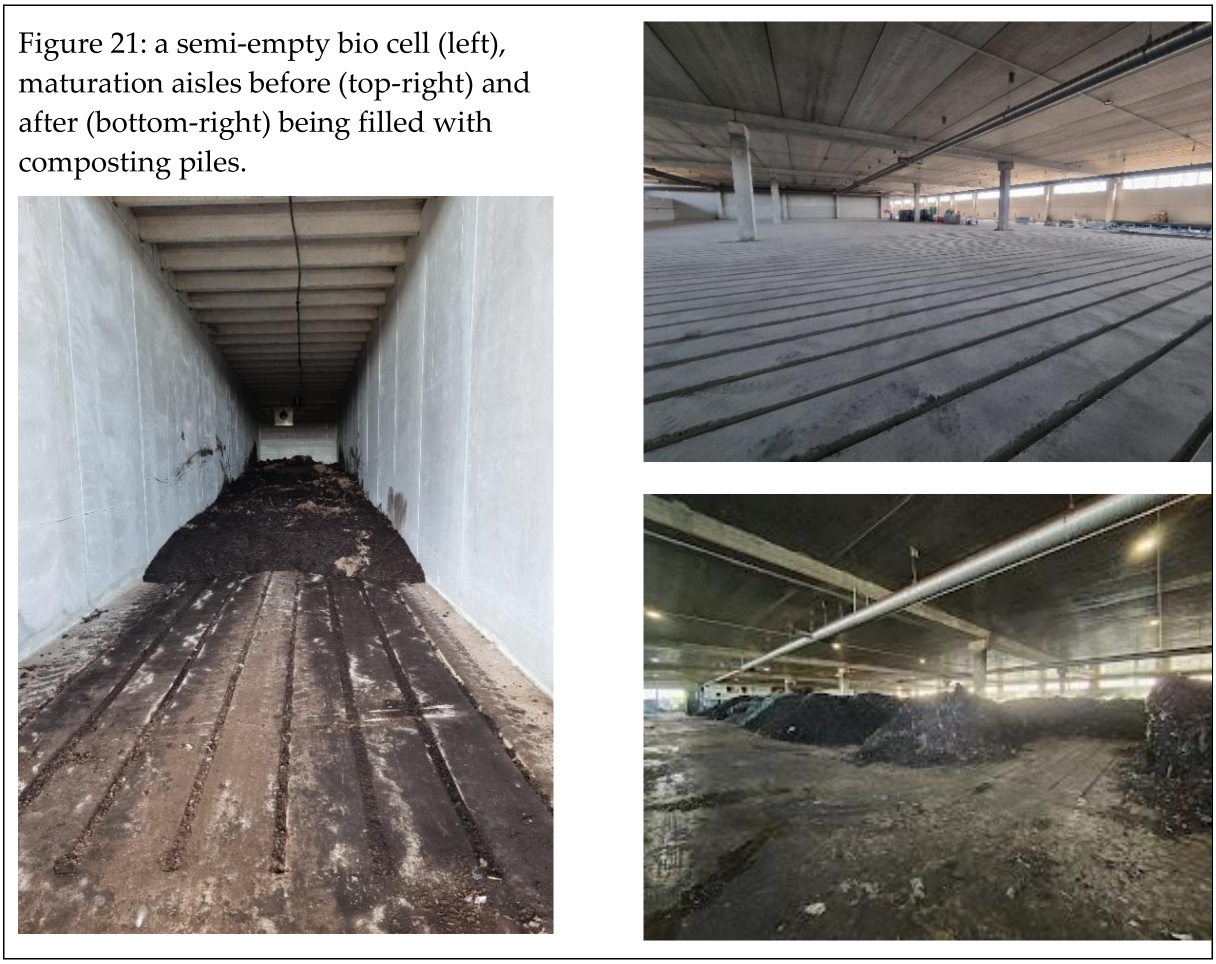


Figure 21: a semi-empty bio cell (left), maturation aisles before (top-right) and after (bottom-right) being filled with composting piles.

In the bio cells and maturation aisles, the material is stored in trapezoidal piles. With 7 units, the total volume of the ACT stage is about 1600 m^3, which corresponds to a maximum blended mixture flow rate of 107 m^3/d, if the duration of 15 days is respected. Maturation aisles account for a larger volume, with 12 units of 420 m^3 each, for a total of about 5000 m^3, with an allowable incoming volumetric flow rate of 84 m^3. The evaporation occurring in ACT phase shrinks the actual volume, so that the bottleneck is represented by the bio cells available space.

Composting areas characteristics are reported in The aeration system is based on blowers, underground ducts, and a special floor equipped with numerous small nozzles for air insufflation, uniformly distributed on the pile base surface. Each bio cell has a dedicated blower, while in the maturation building each one of the six blowers supply two of the twelve aisles. Nozzles require maintenance, since sedimented material could fall and build up in the air ducts, obstructing the insufflation.

Table 9.

The aeration system is based on blowers, underground ducts, and a special floor equipped with numerous small nozzles for air insufflation, uniformly distributed on the pile base surface. Each bio cell has a dedicated blower, while in the maturation building each one of the six blowers supply two of the twelve aisles. Nozzles require maintenance, since sedimented material could fall and build up in the air ducts, obstructing the insufflation.

Table 9: sizing of bio cells and maturation aisles.

	ACT	maturation
Length [m]	25,6	40
Width [m]	3,2	3,5
Height [m]	2,8	3
Unit volume [m3]	229	420
Units [u]	7	12
Total volume [m3]	1606	5040
Stage duration [d]	15	60
Allowed flow rate [m3/d]	107	84

The original project includes a multiple sieving stage passing through a 40 mm and a 10 mm stellar screen. The sieving mass balance indicated in the PFD reports:

Table 10: design mass balance of the compost sieving process.

	[t/d]	fraction
Total matured material	42,5	100%
40 mm over sieve	13,5	32%
10 mm over sieve	6,4	15%
final compost	22,6	53%
recirculated compost	9,6	23%
final compost out	13	**31%**
total to blender	29,5	**69%**

In actual operation, only one screen size of 10 mm is adopted. A smaller fraction of the final compost is recirculated for inoculation purposes, since it can boost the growing and adaptation process of aerobic microbial communities.

3.1.6.1. Air treatment

OFMSW reception and pre-treatment building, as well as the composting area, contribute to the contamination of a large volume of air that cannot be vented into the atmosphere as it is. Together with the other plant air consumptions, the air treatment system must ensure a capacity of 85000 m^3/h that are routed to a two-stage wet scrubber and finally through a biofilter for pollutants removal.

The ammonia removal section is composed by two stages of scrubbing, the first one with acid scrub agent, the last one operating neutralization to deliver air directly to the biofilter. The latter consists in a media bed made of a selected woody mixture, characterized by high porosity and humidity retention. Passing through the 2 m thick bed, odorous and compounds are converted to CO_2 and water by bacteria.

3.2. Plant modelling

The main plant components are modelled in terms of mass and volumetric flow rates of fresh substrate (as-is), total solids and volatile solids:

- To investigate and understand the occurring biochemical processes,
- To check on the consistency of collected data,
- To represent the system and predict future behaviour,
- To model an integrated plant mass balance.

3.2.1. Pre-treatment components

Bag opener, hammer mill and reject separator are included in the pre-treatment line, but only the two separators are analysed. The bag shredder does not affect the properties of the waste, and is therefore not modelled, while the other two act on the distribution of fresh, solid, and liquid matter in the output streams.

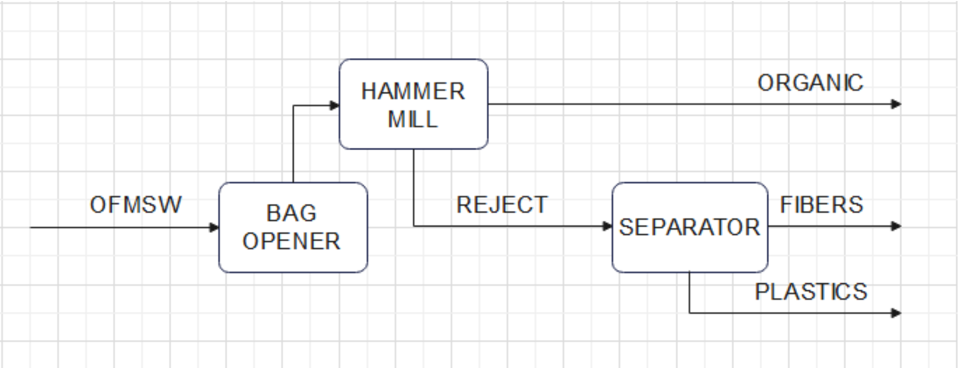


Figure 22: pre-treatment section schematic layout.

3.2.1.1. Hammer mill

The behaviour of the hammer mill can be represented through the distribution and the characteristics of the output streams.

Figure 23: OFMSW (left), treated organic waste (center) and hammermill reject (right).

During the OFMSW handling and treatment process a considerable amount of leachate is produced from the waste, being generated from the spontaneous hydrolyzation of the more putrescible matter, also associated with biogas release. This liquid flow is drained from different steps of the chain (crane lifting, bag shredding, hammer mill separation), making it hard to quantify the exact mass loss. Therefore, analytical mass balance on the component would not be accurate enough due to the leachate draining.

3.2.1.2. Reject separator

For the fibres-plastics separator that processes the reject flow, instead, no leachate loss is present, and the analytical mass balance is applied considering the machine specifications provided by the manufacturer:

Table 11: separator parameters declared by the manufacturer.

Plastic removal efficiency	>90%
Organic in plastic stream	<10%
TS of plastic stream	>75%

An open system mass balance is performed, with the accumulation term being null due to the steady state assumption:

$$\dot{\mathrm{m}}_{in} - \dot{\mathrm{m}}_{out} = \frac{d}{dt} m_{system} = 0$$

Considering the eventuality of multiple streams, and replacing for convenience $\dot{m}$ with M to indicate mass flow rates:

$$\sum\nolimits_{k} M_{k,in} = \sum\nolimits_{k} M_{k,out}$$

The separator mass balance considers reject stream as inlet, and plastics and fibres streams as outlet flow. Since $M_{reject}\left[\frac{t}{y}\right]$ is known, the model can be represented as a set of 2 equations in 5 unknowns, requiring 3 auxiliary equations.

$$\begin{cases} M_{reject} = M_{plastics} + M_{fibres} \\ M_{reject_{TS}} = M_{plastics_{TS}} + M_{fibres_{TS}} \end{cases}$$

The known parameters are (1) TS_{reject} [%], (2) $TS_{plastics}$[%], (3) plastic removal efficiency and (4) dry basis fraction of plastics and (5) fibres in the reject flow, adopted in the following auxiliary equations:

$$\begin{cases} M_{reject_{TS}} = M_{reject} * TS_{reject} \\ M_{plastics_{TS}} = M_{plastics} * TS_{plastics} \\ M_{plastics_{TS}} = M_{reject_{TS}} * (\%dm_{plastic} * \eta_{rem_{plastic}} + \%dm_{fibres} * (1 - \eta_{rem_{plastic}}) \end{cases}$$

3.2.2. Plug Flow Reactor

The digester is the key component to investigate biochemical processes and to predict the transients of biogas production and solid concentration associated with feeding conditions. A steady state and a dynamic mass balance models are introduced.

3.2.2.1. Steady state mass balance

The mass balance is based on the biochemical conversion of the organic degradable dry matter, here referred as VS, into biogas. The organic substrate is progressively converted into biogas throughout the HRT, and the associated biogas production is distributed along this time. However, by feeding a constant daily flow rate of substrate, a steady daily flow rate of biogas is ideally produced. Therefore, steady state operations are represented by using daily flow rates, assuming that the potential biogas is produced in a concentrated way.

Either the biogas potential (BGP) or the VS removal efficiency is required to characterize the model. Biogas density, TS and VS content of the inlet feedstock are always required. *The produced biogas mass is subtracted to the inlet VS, TS, and total feeding flow rate, to obtain the outlet flows.* As described above, an open system steady state mass balance is adopted in the form:

$$\sum_k M_{k,in} = \sum_k M_{k,out}$$

The inlet flow is the sum of the feeding streams, namely organic waste and eventually leachate or finely grinded green waste. Assuming a perfect mixing and homogenization, the inlet feedstock characteristics are the weighted average of the separated streams. The outlet flow is composed by the produced biogas and the discharged digestate. Three mass conservation equations are considered, for fresh mass flow, TS flow, and VS flow, in addition to the biogas specific weight relation. Since M_{feed}, ρ_{bg} are known, the model consists in 4 equations and 7 unknows, requiring 3 auxiliary equations.

$$\begin{cases} M_{feed} = M_{bg} + M_{dig} \\ M_{feed_{TS}} = M_{bg} + M_{dig_{TS}} \\ M_{feed_{VS}} = M_{bg} + M_{dig_{VS}} \\ M_{bg} = V_{bg} * \rho_{bg} \end{cases}$$

There are two possible ways of solving the system, consisting in adopting a different auxiliary equation to represent the biological conversion of the volatile solids:

1. Using *BGP* to directly compute the biogas output knowing the feedstock input,
2. Imposing the VS removal efficiency ($\eta_{rem_{VS}}$) requiring a non-linear solution.

The other two auxiliary equations remain unchanged, implementing the boundary conditions of TS_{feed}, VS_{feed},.

$$\begin{cases} M_{feed_{TS}} = M_{feed} * TS_{feed} \\ M_{feed_{VS}} = M_{feed} * VS_{feed} \\ V_{bg} = BGP * M_{feed_{VS}} \ \ (OR) \ \ \eta_{rem_{VS}} = \dfrac{VS_{feed} - VS_{dig}}{VS_{feed}} \end{cases}$$

3.2.2.2. Dynamic mass balance

The steady state model does not describe transient phenomena associated with the plant startup. Furthermore, the biogas production occurs gradually along the substrate residence time, leading to a non-linear accumulation of the solid content along the transient. With these considerations, a more complex model is developed to describe the reactor behaviour and solid concentration evolution.

The dynamic model is a time-dependent mass balance, discretized in daily timesteps, consisting of the iteration of the daily steady state mass balance, updating the digester content and solid concentration according to the daily input and output streams.

Spatially, instead, the reactor is still represented as a lumped model, as the solid concentration is considered as a unique value and not differentiated for the inlet, middle, and outlet section. This representation fits a CSTR better than a PFR digester.

M stands for mass flow rate (ton per day), *m* for mass (ton), the time step Δt is unitary, corresponding to one day. Since M_{feed}^{i} is known, the time-step iteration model consists in 3 equations and 12 unknowns, requiring 9 auxiliary equations:

$$\begin{cases} m_{PFR}^{i} = m_{PFR}^{i-1} + (M_{feed}^{i} - M_{bg}^{i} - M_{dig}^{i}) * \ \Delta t \\ m_{PFR_{TS}}^{i} = m_{PFR_{TS}}^{i-1} + (M_{feed_{TS}}^{i} - M_{bg}^{i} - M_{dig_{TS}}^{i}) * 1 \\ m_{PFR_{VS}}^{i} = m_{PFR_{VS}}^{i-1} + M_{feed_{VS}}^{i} - M_{bg}^{i} - M_{dig_{VS}}^{i} \end{cases}$$

Three of them are the initial conditions, corresponding to the inoculum characteristics, allowing to calculate $m_{PFR}^{i-1}, TS_{PFR,}^{i-1}VS_{PFR}^{i-1}$ at each time step:

$$\begin{cases} m_{PFR}^{0} = 1600 \ tons \\ TS_{PFR}^{0} = 10\% \\ VS_{PFR}^{0} = 60\% \end{cases}$$

The remaining six equations are defined with the $TS_{feed}^{i}, VS_{feed}^{i}, BGP^{i}$ conditions:

$$\begin{cases} M_{dig}^{i} = M_{feed}^{i} - M_{bg}^{i} \\ M_{dig_{TS}}^{i} = M_{dig}^{i} * TS_{PFR}^{i-1} \\ M_{dig_{VS}}^{i} = M_{dig}^{i} * VS_{PFR}^{i-1} \\ M_{feed_{TS}}^{i} = M_{feed}^{i} * TS_{feed}^{i} \\ M_{feed_{VS}}^{i} = M_{feed}^{i} * VS_{feed}^{i} \\ M_{bg}^{i} = \boldsymbol{BGP^{i}} * \boldsymbol{M_{feed}^{i}} \end{cases}$$

To account for time-distributed biogas production, the daily biogas yield is modelled as the scalar product of two vectors of 29 elements, corresponding to the days of residence time. The feeding vector in composed by the daily loading rate for the antecedent 29 days, while BGP vector by contains the fraction of potential yield released in each day of the HRT, measured in cubic meters per ton of fresh matter.

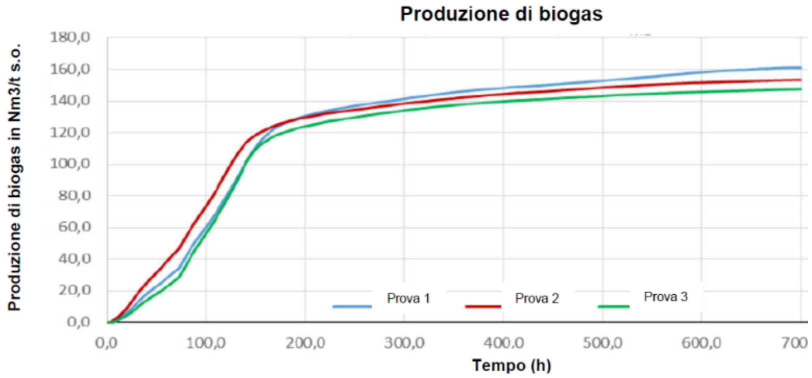


Figure 24: BMP test biogas production curve.

Parameter	Result	unit
Biogas production	154	[L/kg$_{ORG}$]
Test duration	29	[d]
Test temperature	38	[°C]
TS	35	[%w/w]
VS	88	[%w/w]
Methane	58	[%vol]
Carbon dioxide	42	[%vol]

Table 12: BMP test results.

A BMP batch test was commissioned to an external laboratory, to determine the biogas production curve of organic waste samples taken from the plant in July. Between 75% and 80% of the potential production occurs in the first 150 hours of degradation, corresponding to about 7 days of the total 29 days of test duration.

The curve is normalized to a unitary BGP value, and simplified in two linear parts of which the slope is calculated (0.110 for 7 days and 0.011 for 22 days). The slope represents the daily production fraction, which is then multiplied by the average BGP extracted from real plant operations.

With a fixed BGP, the model is not able to account for evolving microbial degradation capacity during the plant start-up, because both the biogas productivity and the HRT are changing:

- Such limit can be partially solved, by starting the feeding transient with a low BGP value and gradually increasing it until reaching the nominal design potential at the end of the adaptation process.
- The HRT, being the length of the $\boldsymbol{BGP^i}$ and $\boldsymbol{M^i_{feed}}$ vectors, cannot be changed, but the biogas yield can be adjusted to an equivalent factor. To state an example, to implement a start-up biogas yield of 120 m^3/t produced in 50 days, an

equivalent BGP of 207 m³/t would produce the same effect in the 29 days of modelled HRT.

3.2.3. Digestate treatment components

3.2.3.1. Blender

The blender model equations consist of the conservation of mass flows and of the partial volume reduction of the volumetric flow. The volume reduction factor is taken from the PFD balances. The mix density, fundamental parameter, comes as follows:

$$\begin{cases} M_{dig} + M_{vegetal} + M_{compost,rec} = M_{blend} \\ \left(V_{dig} + V_{vegetal} + V_{compost,rec}\right) * VolRed = V_{blend} \\ \rho_{blend} = M_{blend} \div V_{blend} \end{cases}$$

3.2.3.2. Filter Screw Press (FSP)

The main parameters to model the behaviour of the machine are:

- the mass flow rate separation in terms of tons per hour of output streams
- the capture rate of TS, which is the fraction of solids ending up in cake flow.

The TS content of the cake flow can range between 25 and 40%, while the liquid one around 9-12%. The component is modelled by assuming reasonable values for the introduced parameters and by applying mass conservation equations for both solid and liquid phases, as in the reject separator.

$$\begin{cases} M_{dig} = M_{cake} + M_{filtrate} = M_{dig} * SepRate_{cake} + M_{dig} * (1 - SepRate_{cake}) \\ M_{dig_{TS}} = M_{cake_{TS}} + M_{filtrate_{TS}} = M_{dig_{TS}} * CapRate_{cake} + M_{dig_{TS}} * (1 - CapRate_{cake}) \end{cases}$$

3.2.4. Composting process

In the International Compost Seminar held by Compost System [42], a simplified holistic approach is presented to represent the complex biological process and perform preliminary sizing of composting plants. This method has been adopted to size the digestate post-composting stage of the case study plant.

Mesophilic and thermophilic bacteria perform the aerobic degradation by converting organic matter into gaseous compounds, with release of energy in the form of heat. The main outputs are CO_2, gaseous water, heat, estimated through empirical coefficients that link their production to the mass of degraded organic matter.

3.2.4.1. Simplified mass balance

The mass balance is based on incorporating the involved plant streams into four flows: two inputs, irrigation water and organic substrate to be composted, and two outputs, being the final compost and the reaction products released in gaseous state (Figure 25).

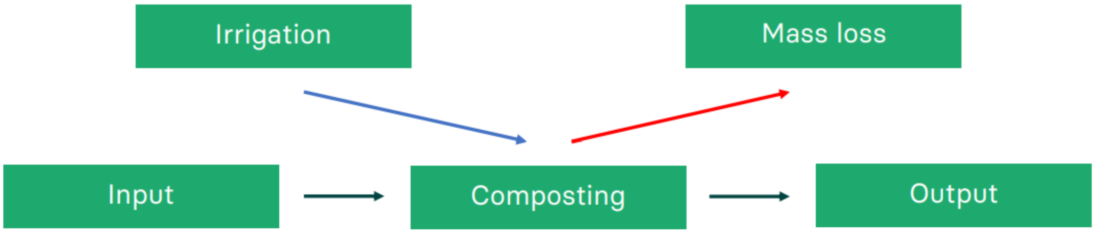


Figure 25: schematic composting mass balance.

Other streams and species take part in the reaction, but do not explicitly appear in the balance. Nonetheless, this holistic approach accounts for all solid, liquid, and gaseous flows, incorporating a rough mass and energy balance.

Irrigation Water

The irrigation water makes up for the evaporated vapour and ensures a proper moisture level of the final compost.

Organic substrate

The initial substrate, in this case the blended mixture, is characterized by its water and solid content, as well as by coefficients used to quantify the organic degradation.

Out of the total dry matter (TS) of the composting material, only a fraction is organic and theoretically degradable (VS), out of which only a fraction is actually degraded (DVS), as graphically summarized in Figure 26. According to the reference [42], VS/TS usually ranges within 50-70%, and DVS/VS between 40 and 60%.

Mass loss

The gaseous reaction products are gathered in two main streams: gaseous water and CO_2. The oxygen supplied by forced aeration is not considered in the inputs and consequently, in the gaseous outputs, the mass balance only accounts for the carbon contained in the carbon dioxide (C-CO_2), balancing for the missing oxygen.

Vapour and C-CO_2 are computed starting from the degraded organic matter, by multiplication of an empirical coefficient. For each degraded ton:

1. 1 ton of C-CO_2 is produced by oxidation of organic carbon,
2. 6 tons of water are evaporated as heat dissipation phenomenon.

Considering the whole framework, the mass is conserved, because the release of 7 tons of gaseous compounds is supplied by the 1 ton of degraded matter, by the irrigation water and by the moisture content of the input substrate.

Compost

The final compost is the remaining stream after the mass loss and is characterized by a target humidity of 35% [22], met by supplying the right amount of irrigation water.

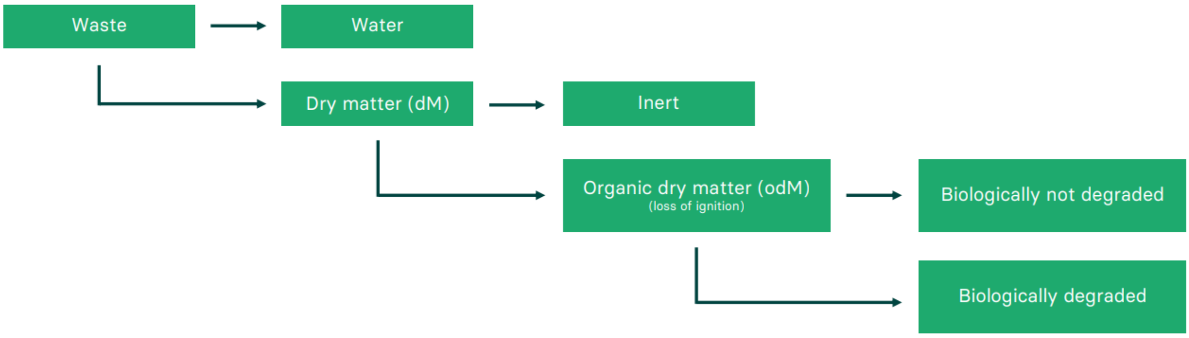


Figure 26: schematic composting degradation pathway.

Equations

In this work, TS and VS of the blended mixture are computed from the upstream mass balances applied on the blender, while for DVS/VS a 50% is taken, being the average value of the suggested range. Providing TS, VS, DVS content of the organic substrate, the degraded matter is computed, and it is possible to estimate the reaction products through the empirical parameters presented above. The irrigation water will complete the simplified mass balance, reintegrating the evaporated moisture and ensuring a proper final compost humidity.

The mass balance consists in applying mass conservation equations to the total mass and the liquid phase. The input mass flow rate M_{blend} is known, and the model consists in 2 equations, 6 unknows, requiring 4 auxiliary equations.

$$\begin{cases} M_{blend} + M_{irr_{water}} = M_{CO_2,deg} + M_{evap_{water}} + M_{compost} \\ M_{blend_{water}} + M_{irr_{water}} = M_{evap_{water}} + M_{compost_{water}} \end{cases}$$

The boundary condition parameters are $TS_{blend}, \frac{VS}{TS}, \frac{DVS}{VS}$, and the target compost humidity $HUM_{compost}$, used to define the four equations:

$$\begin{cases} M_{blend_{water}} = M_{blend} * (1 - TS_{blend}) \\ M_{CO_2,deg} = M_{blend} * TS_{blend} * \frac{ODM}{DM} * \frac{DDM}{ODM} \\ M_{evap_{water}} = 6 * M_{CO_2,deg} \\ M_{compost_{water}} = HUM_{compost} * M_{compost} \end{cases}$$

Numerical example

Characterize organic substrate:

- Input substrate 1000 tons,
- Water content 65%, corresponding to 650 tons,
- Solid content TS = 35%, corresponding to 350 tons,
- Degradable organic matter VS/TS = 60%, corresponding to 210 tons,
- Degraded organic matter DVS/VS = 50%, corresponding to 105 tons,
- Residual solid matter: 350 – 105 = 245 tons.

Characterize mass loss:

- Carbon dioxide conversion: 1*105 = 105 tons,
- Vapour release: 6*105 = 630 tons.

Solve water balance:

- Target compost humidity 35%, on the residual solid matter of 245 tons,
- Compost output 377 tons with 132 tons of water,
- Irrigation needed = 132 + 630 – 650 = 112 tons.

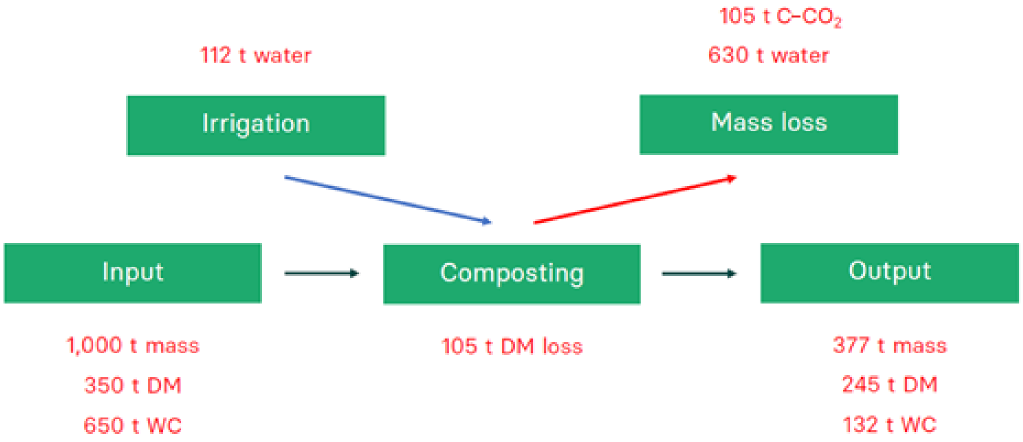


Figure 27: numerical example of composting simplified mass balance

3.2.5. Integrated mass balance

To determine the quantitative and qualitative variations of digestate, green waste, and compost streams at the change of feeding conditions and plant layout, an integrated mass balance is developed by aggregating the modelling of the single components and by linking mass and volumetric flows rates in an interdependent way.

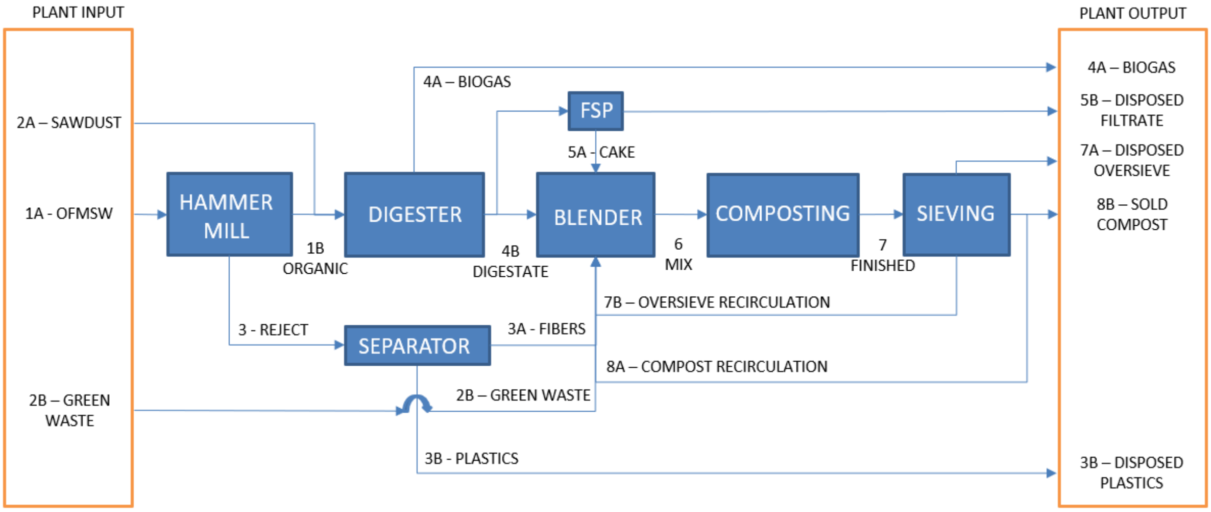


Figure 28: integrated modelling layout of the case-study plant.

The layout includes all the possible plant components, either included in the original configuration or not. The extra components, of which the techno-economic performance is investigated, can be either included or bypassed to draw different possible configurations. The pasteurizer is not modelled in terms of mass flow rates.

The feeding conditions are imposed in terms of treated organic features (mass flow rate (MFR), TS, VS, C/N), since the OFMSW characteristics are hardly measurable. An additional flow can be fed, for example leachate of finely grinded green waste.

The hammer mill allows to compute quantity and quality of the reject flow starting from the organic stream. The reject separator parameters split the flow in plastics and fibres streams. If not bypassed, the reject fibres are added in the blender mass balance, allowing to reduce the green waste input.

Table 13: modelling parameters of the pre-treatment section

HAMMER MILL	%
Reject/FORSU	27%
TS Reject	38%
%plastics/dm (TS)	27%
%fibres/dm (TS)	73%

REJECT SEPARATOR	
plastics TS	75%
plastic removal efficiency	90%
organic in plastic stream	10%

For the purposes of the integrated mass balance, the digester steady state model is enough to determine the biogas and digestate production. The biogas potential varies according to the considered season, and a green waste BGP is included to account for partial volatilization of the grinded green waste that is eventually fed, together with a 75% C/N reduction factor to adjust the digestate ratio according to literature [43].

Table 14: modelling parameters of the digester.

DIGESTER	
BGP [Nm3/t_{feed}]	221-212
BGP of green waste	20
$C/N_{digestate}$ / C/N_{feed}	0.25

If not bypassed, the FSP splits the digestate in cake and filtrate according to the tuned parameters. A major part of the digestate will be discarded with the filtrate stream, reducing by 80% the mass flow rate to the blender. The capture rate is 35% with semi-wet digestate and 25% with dry digestate, to respect the maximum cake TS of 25%.

Table 15: modelling parameters of the dewatering stage.

FSP	
% cake (fresh)	20%
% filtrate (fresh)	80%
Capture Rate (cake TS %)	35% - 25%
filtrate TS %	65% - 75%

Green waste is the weighted average of grinded vegetal waste, structuring material, straw, with known TS, C/N, density. The mixing ratio can be adjusted in the model. Straw is not included due to a very high cost.

Table 16: definition of the green waste pre-mixture to the blender.

GREEN WASTE	TS [%]	C/N	Density [t/m3]	Mass FR [%]
fine green waste	45%	60	0.30	60%
structuring mat.	75%	100	0.40	40%
straw	80.0%	70	0.20	0%

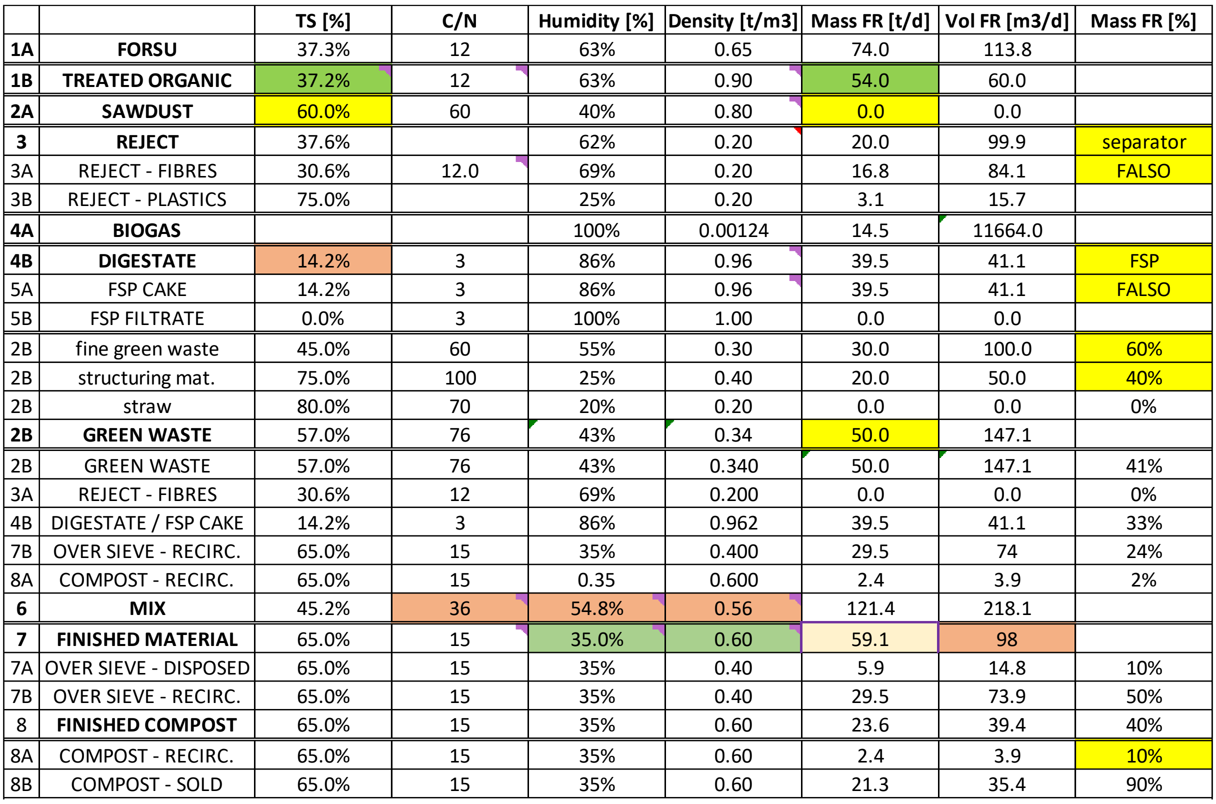
The blender input includes digestate or FSP cake, green waste, reject fibres, recirculation of compost and over sieve material. The blended composition is affected by the compost and sieving material flows, which are on turn determined starting from the mixture. Blending, composting, and sieving stages depend on each other, and the balance is iteratively solved.

Table 17: modelling parameters of the digestate post-treatment section.

BLENDER	
Blending volume reduction	0.82

COMPOSTING	%
ODM (VS/TS)	60%
DDM	50%
target compost humidity	35%

SIEVING	
Over sieve - disposed	10%
Over sieve - recirculated	50%
finished compost	40%
compost - sold	10%
compost - recirculated	90%



		TS [%]	C/N	Humidity [%]	Density [t/m3]	Mass FR [t/d]	Vol FR [m3/d]	Mass FR [%]
1A	**FORSU**	37.3%	12	63%	0.65	74.0	113.8	
1B	**TREATED ORGANIC**	37.2%	12	63%	0.90	54.0	60.0	
2A	**SAWDUST**	60.0%	60	40%	0.80	0.0	0.0	
3	**REJECT**	37.6%		62%	0.20	20.0	99.9	separator
3A	REJECT - FIBRES	30.6%	12.0	69%	0.20	16.8	84.1	FALSO
3B	REJECT - PLASTICS	75.0%		25%	0.20	3.1	15.7	
4A	**BIOGAS**			100%	0.00124	14.5	11664.0	
4B	**DIGESTATE**	14.2%	3	86%	0.96	39.5	41.1	FSP
5A	FSP CAKE	14.2%	3	86%	0.96	39.5	41.1	FALSO
5B	FSP FILTRATE	0.0%	3	100%	1.00	0.0	0.0	
2B	fine green waste	45.0%	60	55%	0.30	30.0	100.0	60%
2B	structuring mat.	75.0%	100	25%	0.40	20.0	50.0	40%
2B	straw	80.0%	70	20%	0.20	0.0	0.0	0%
2B	**GREEN WASTE**	57.0%	76	43%	0.34	50.0	147.1	
2B	GREEN WASTE	57.0%	76	43%	0.340	50.0	147.1	41%
3A	REJECT - FIBRES	30.6%	12	69%	0.200	0.0	0.0	0%
4B	DIGESTATE / FSP CAKE	14.2%	3	86%	0.962	39.5	41.1	33%
7B	OVER SIEVE - RECIRC.	65.0%	15	35%	0.400	29.5	74	24%
8A	COMPOST - RECIRC.	65.0%	15	0.35	0.600	2.4	3.9	2%
6	**MIX**	45.2%	36	54.8%	0.56	121.4	218.1	
7	**FINISHED MATERIAL**	65.0%	15	35.0%	0.60	59.1	98	
7A	OVER SIEVE - DISPOSED	65.0%	15	35%	0.40	5.9	14.8	10%
7B	OVER SIEVE - RECIRC.	65.0%	15	35%	0.40	29.5	73.9	50%
8	**FINISHED COMPOST**	65.0%	15	35%	0.60	23.6	39.4	40%
8A	COMPOST - RECIRC.	65.0%	15	35%	0.60	2.4	3.9	10%
8B	COMPOST - SOLD	65.0%	15	35%	0.60	21.3	35.4	90%

Figure 29: screen capture of the integrated mass balance model, with winter operations with the original layout.

The green cells are the fixed boundary conditions, including:

- The seasonal TS content, BGP, and mass flow rate of the feeding organic waste
- The target humidity and density of the finished compost

The orange cells are the output values of interest:

- The TS content of the digestate
- The C/N, humidity, and density characteristics of blended mixture
- The Volumetric flow rate to the composting process

The yellow cells are the variable parameters that are adjusted to obtain desirable values of the output cells, namely:

- The TS and MFR of the grinded green waste to be injected into the digester,
- The Activation/bypass button of the reject separator and FSP,
- The MFR of green waste to be added in the blender,
- The Mixing ratio of the green waste mix to the blender,
- The Recirculation fraction of finished compost.

3.3. Sampling procedure

A series of tests was carried out in the plant laboratory to characterize and monitor the plant streams. The collected information is used as parameters to model the system and to forecast its future behaviour.

3.3.1. Density

A container of known weight and volume, generally a bucket, is filled with the fluid or material in scope and the gross weight is recorded with a bathroom scale.

$$density\left[\frac{kg}{L}\right]=\frac{Gross-Tare}{Volume}$$

For dense streams as digestate, a 10 L bucket is used, while for lighter materials as straw, green waste, and compost a bigger bin of 43 L is employed.

The digestate density is periodically sampled to feed data in a TS-density correlation. Digestate, structuring material and green waste density is important to tune the blender recipe so to obtain a composting mixture within specifications. PuV (weight per unit of volume) is also one of the main requirements for finished compost.

3.3.2. pH, FOS, TAC

pH, FOS and TAC are measured by a potentiometric titration machine that operates through an electrode and a titrant solution. The electrode is periodically calibrated on two points via two samples of buffer solutions, corresponding to the pH values of 4.00 and 7.00, correlating the measured potentials to the reference pHs and building a pH-potential curve.

The pH can be determined by directly submerging the electrode in the sample. FOS and TAC measurement instead requires 5.0 ml of sample filtrate diluted in demineralized water until reaching 25 ml of solution. The sample solution is then homogenized and titrated through progressive injection of 0.1N sulfuric acid (titrant solution), gradually decreasing the pH. After a first titration down to pH 5.0, the TAC is calculated, and similarly FOS value is determined with a second titration down to pH 4.4, respectively expressed in mg_{CaCO3}/L and $mg_{CH3COOH}/L$.

Titration is generally applied to digestate, which is slightly alkaline, in the range of pH 8-9. The FOS/TAC ratio gives an indication of the VFAs accumulation in the digester and should ideally fall in the range 0.3 – 0.4 [18]. It is generally lower for older digestate than for younger one, since a greater fraction of acid has already been converted into CO_2, H_2 and biogas.

3.3.3. TS, VS

The solid content is a key parameter to monitor the fluid dynamics of digestate in the reactor, as well as to adjust the blending recipe for the composting mixture. The volatile solids fraction gives an indication of the organic carbon available to the bacteria and therefore on the efficiency of the biochemical degradation process.

For the analysis an electronic scale, a desiccator oven and a muffle furnace are required, together with aluminium trays. Such containers are resistant to high temperatures, but it should be kept in mind that after a few cycles in the muffle at 550°C the material could degrade, volatizing part of the mass.

The tray is weighted before and after the addition of the sample, determining tare, gross and net weight in humid conditions. A first nine-hours-long desiccation cycle is carried out in the oven at 105°C, during which all the extrinsic and intrinsic moisture evaporates. Gross weight of the dry sample is used to determine the TS as:

$$TS\ [\%] = \frac{Gross_{105°C} - Tare}{Gross_{fresh} - Tare}$$

A second heating cycle of three hours at 550 °C is conducted in the muffle, during which all organic matter is oxidized and after which only inert ashes remains.

$$VS\ [\%] = \frac{Gross_{105°C} - Gross_{550°C}}{Gross_{fresh} - Tare}$$

A relevant issue of this methodology is the evaporation of volatile organic compounds during the first desiccation cycle, that can lead to the underestimation of the VS content [44].

3.3.4. Fibres – plastic separation

To assess the pre-treatment separation efficiency, a test was developed to establish the dry weight partition of materials in the sample. Three containers are needed, two aluminium trays for desiccation of plastic and fibres and a third for plastic washing.

In addition to the normal TS assessment, there is a separation phase and a washing phase. Fresh sample is placed and weighted in the first tray. Then, plastics are separated and moved to the second tray. Here, plastics are cleaned by immersion in the water bowl to collect the organic matter trapped in, placed again in the second tray and weighted. Finally, dirty water containing fibres is added in the first tray. Such operation will not influence the results since the desiccation cycle will evaporate all the added water.

3.3.5. Soil quality

The soil analysis consists in determining different characteristics and chemical properties as pH, and content of sulphides and nitrogen, partitioned between nitrites, nitrates, and ammonium. The analysis is typically performed on finished compost, since the measured parameters must fall within a given specification range for the end product to be commercialized in the EU market [40]. However, it can also be conducted on conventional soil or on composting material to monitor the ongoing process.

The measuring procedure is defined in the context of the Controlled Microbial Composting (CMC) method developed by Compost System [45], and performed with a laboratory kit [46]. The procedure starts with the dilution of two samples of soil in two solvents, demineralized water and KCl. The dilution ratio depends on the age of the soil, being 1:5 for material still in maturation stage and 1:3 for finished compost. For both solutions pH is measured in the titration machine as seen before. The filtrate of the KCl diluted sample is used for NO^{-}_{2} and NO^{-}_{3} estimation via a colour test strip, and for NH^{+}_{4} assessment through colour reading of the solution after adding specific reactants. The nitrogen content is a fundamental indicator, since it is the limiting criteria to define the maximum quantity of compost that can be used on a soil for agronomic purposes.

3.3.6. Soil activity

The biological activity can be monitored through the temperature and the composition of the gas trapped into the piles. Tubular steel probes are inserted at three-quarters of the pile height with an angle of 45° to reach the centre of the volume. A biogas analyser collects the gaseous sample through holes at the probe tip, while for temperature a thermocouple is connected to the probe.

From internal measurements, an aerobically active pile shows CO_2 content in the range between 5%-15%, with O_2 consequently dropping below 10%.

A study performed on composting of agri-food industry waste measured the evolution of oxygen and carbon dioxide concentrations along the process, negatively correlated as reported in Figure 30 and Figure 31 [47]. The concentrations vary significantly with the sampling depth, as showed in Figure 32, obtained from a study performed of AD digestate composting windrows kept in open-air [48].

A significant presence of CH_4 indicates an incorrect aeration, with absence of oxygen and the start of anaerobic digestion, and it is usually associated with a too high moisture content and very young material. Methane concentration can reach values of 30 to 50%m according to internal measurements and literature [48].

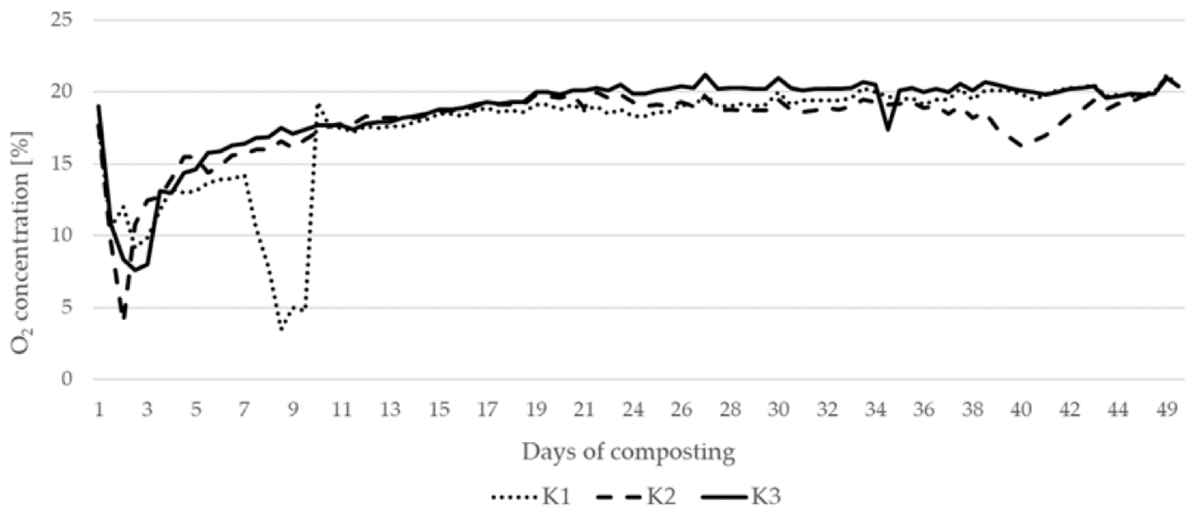


Figure 30: O_2 concentration in the composting of three mixtures of agri-food waste.

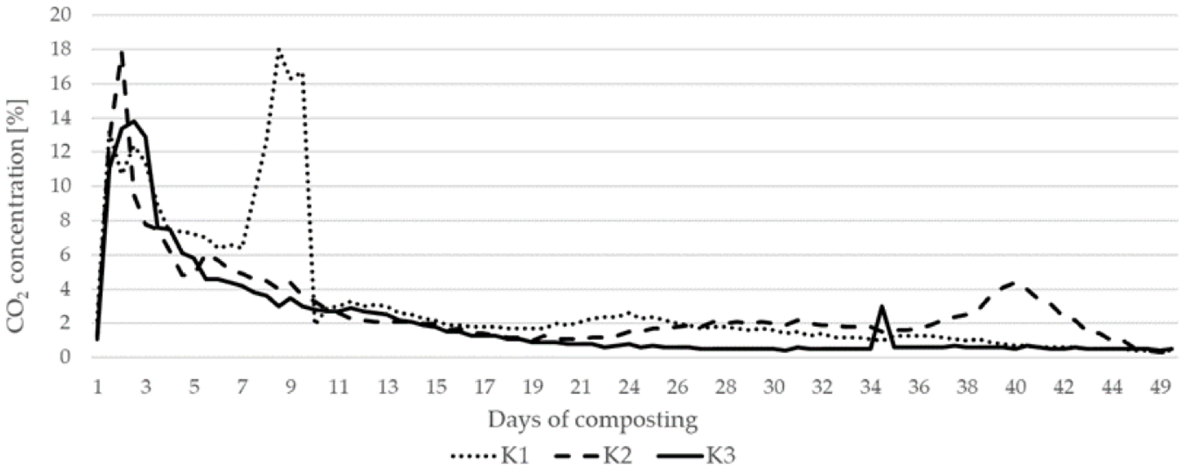


Figure 31: CO_2 concentration in the composting of three mixtures of agri-food waste.

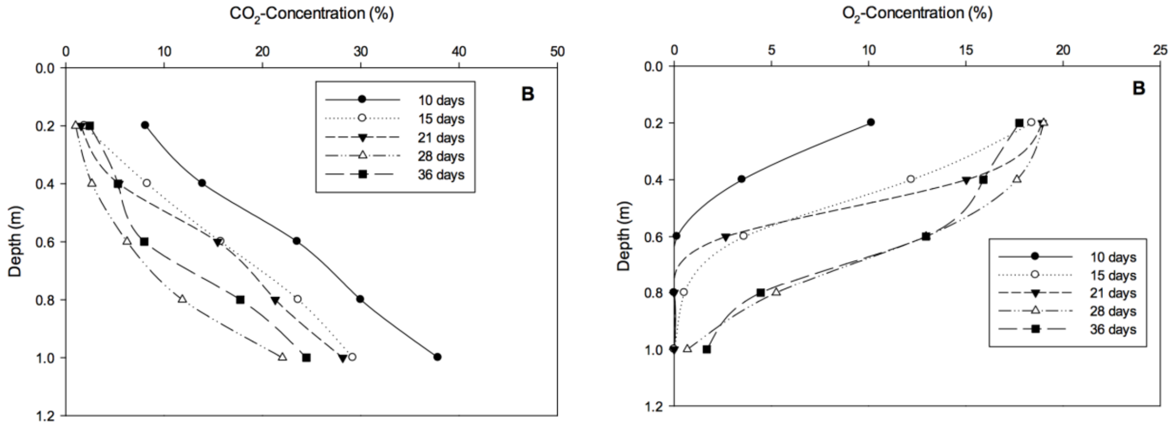


Figure 32: CO_2 and O_2 concentration at varying depth and maturation of AD digestate composting

3.4. Economic evaluation

To evaluate the economic performances of the plant, the Net Present Value (NPV) indicator is used, representing the net balance of the lifetime cashflow actualized to their respective value in the initial year. For its calculation, the plant lifetime and the discount rate are needed, representing the horizon of expected operation and the opportunity cost associated with the immobilization of money. A sustainable project should have a positive NPV.

If considering the expenditures only, it is called Net Present Cost (NPC), and NPC of different configurations will be compared, identifying the lowest one. NPC is defined as follows, where n represents the lifetime in number of years and d the discount rate:

$$NPC = \sum_{i=1}^{n} \frac{cashflow_i}{(1+d)^i}$$

Assuming constant annual expenditures along the lifetime, the NPC calculation can be simplified through the Capital Recovery Factor (CRF), a mathematical relation function of lifetime and discount rate that returns the present value of a recurrent annuity.

$$CRF = \frac{d\,(1+d)^n}{(1+d)^n - 1}$$

NPC can be calculated as follows, being C_{inv} the total investment incurred in the first year, and $Annuity$ the constant annual expense that includes all the fixed and variable operating costs:

$$NPC = C_{inv} + \frac{Annuity}{CRF}$$

Biomass projects life assumption is around 20 years on a global basis, and in 2018 the suggested discount rate for the biomass sector in the European countries ranged between 8% and 11% [49, 50]. Therefore, the assumptions adopted in the evaluation are of 20 years of lifetime and 10% discount rate, with a resulting CRF of 0.117.

An example: a yearly expenditure of 1000 € along 20 years with 10% discount rate results in an NPC of € 8513.6, regardless of using the standard or the CRF formula:

$$NPC_{standard} = 1000 * \sum_{i=1}^{20} \frac{1}{(1+0.1)^i} = 8513.6$$

$$NPC_{CRF} = \frac{1000}{0.117} = 8513.6$$

The Net Present Cost is much lower than the sum of twenty annuities, because the further in time the expenditures incur, the lower is their value in the present moment. Therefore, the economic impact of the investment is greater than the one of annuities.

3.4.1. Investment costs

The capital disbursements are defined separately for each plant component and are associated with the purchase and the installation of each machinery unit. In the NPC calculation they are considered as a unique disbursement occurring in the initial year.

The plant owner provided the financial datasheet from which each component's investment cost has been calculated as the sum of machinery purchase cost and of the component's fraction of the development and installation costs (technological labour, construction, piping and metalworks) shared between different components.

$$C_{inv,k} = purchase_k + \sum_i sharedCost_i * fraction_{i,k}$$

3.4.2. Fixed costs

All the cashflows that do not depend on the volume of processed substrate are categorized under the category of fixed costs. This specific case study only focuses on the digestate post-treatment process costs, and the main entry is the maintenance cost, defined for each plant component.

Each machine has an associated fixed O&M cost, corresponding to the yearly ordinary maintenance contract provided by the manufacturer, calculated as a percentage of the investment cost. The risk of component failure, and consequently the maintenance percentage, can vary according to the processed stream. For instance, the closer to the chain inlet (OFMSW, unsorted green waste), the higher the probability of impurities (metals, bulky objects, kitchen appliances, rocks) that can harm the machine. Treated streams as organic waste, digestate, maturing compost have a lower intrinsic risk with a lower maintenance cost.

$$C_{OM,k} = C_{inv,k} * percentage_{OM,k}$$

The maintenance cost allocation is based on internal data. Knowing the real maintenance yearly cost, comprehensive of all the components included in the operating configuration, the percentages are estimated weighting the risk factor. In this way, the overall maintenance cost of configurations with different components can be estimated.

3.4.3. Variable costs

Variable costs comprise all the cashflows depending on the volume of the streams processed in each component.

The average summer and winter variable costs are differentiated, as the OFMSW seasonal variations affects the quantity and quality of the downstream flows, heavily impacting the digestate post-processing.

Starting from the average summer and winter waste characteristics, the integrated mass balance model will estimate the quantity and quality of each material flow, and the economic model will evaluate the NPC of the system as a whole.

The considered variable cost categories are:

- Electric consumption
- Fuel consumption
- Thermal consumption
- Manpower salary
- Material purchase
- Material disposal
- Material selling

Each category includes costs of different machines and functional areas, and is depending on several numerical assumptions, illustrated in the following paragraphs.

3.4.3.1. Electric consumption

It is calculated from the cost of electricity, assumed at 0.2 *€/kWh*, and the yearly electricity consumption in *kWh/year* of the specific component.

$$c_{el,k} = elCons_k \left[\frac{kWh}{y}\right] * 0.2\ [\frac{€}{kWh}]$$

The consumption can depend on

- the amount of substrate to be processed by the component, in terms of average flow rate in *tons/hour, tons/day* or *tons/year*,
- the machine processing or working rate in *tons/hour*,
- the average machine power in *kWe*,
- the equivalent working hours in *hours/day* or *hours/year.*

Each considered component has a different level of aggregation of the parameters:

1. Feeding belts, which consumption is computed through the yearly feeding load in *tons/year*, the average feeding rate in *tons/hour* and the average power in *kWe.*

$$elCons_k = feedingLoad \left[\frac{t}{y}\right] * 10.8 \left[\frac{t}{h}\right] * 12\ [kW_e]$$

2. Digester hydraulic appliances, which consumption is computed through the working hours in *hours/day*, the average power in *kWe*, and the coefficient of power boost for high viscosity included in case of green waste feeding.

$$elCons_k = K_{viscosity} * 6 \left[\frac{h}{d}\right] * 365 \left[\frac{d}{y}\right] * 13.5\ [kW_e](* 150\%)$$

3. Blender, which consumption is computed through the blending cycles per day determined by the daily blended flow in *tons/day* and the maximum capacity in *tons/cycle*, the cycle duration in *hours/cycle*, and the average power in *kWe*.

$$elCons_k = cycles \left[\frac{c}{d}\right] * 0.5 \left[\frac{h}{c}\right] * 365 \left[\frac{d}{y}\right] * 60\ [kW_e]$$

4. Dewatering unit, which consumption is computed through the digestate flow rate in *tons/day*, the processing capacity in *tons/hour* and the average power in *kWe*, that depend on the digestate TS content.

$$elCons_k = \frac{digestate\left[\frac{t}{d}\right]}{capacity\left[\frac{t}{h}\right]} * 365\left[\frac{d}{y}\right] * power\ [kW_e]$$

5. Insufflation fans of the composting area, which consumption is the product of the electricity usage per ton of compost in *kWh/ton* and the finished compost output in *tons/day*.

$$elCons_k = compostProd\left[\frac{t}{d}\right] * 365\left[\frac{d}{y}\right] * 133\left[\frac{kWh}{t}\right]$$

Table 18: electric consumption parameters of the cost evaluation for each component.

electric consumption		
electricity price [€/kWh]	0.2	
feeding belts		
average feeding rate [t/h]	10.8	90% of 2 tons/10 min
sawdust belt feed power [kWe]	12	2 belts of 7.5kW each at 80% setpoint
digester hydraulic appliances		
average power [kW$_e$]	13.5	on average 1 motor of 15kW at 90% setpoint
equivalent working hours [h/d]	6	
power boost for high viscosity [%]	150%	when adding green waste into the digester
blending cycles		
blender max capacity [t]	6	
blending cycle duration [h]	0.5	
blender electric power [kW$_e$]	60	
dewatering cycles		above 16% TS a second unit is added in series
processing flow rate [t/h]	8/5	for digestate below/above 16% TS content
dewatering electric power [kW$_e$]	6/15	for digestate below/above 16% TS content
composting insufflation fans		
specific compost elCon [kWh/t]	133	internal data aggregation

3.4.3.2. Fuel consumption

It is associated with the usage of wheel loaders, the vehicles utilized to handle green waste and composting material. It is calculated through the cost of diesel oil, assumed at 1.5 €/L, and the average diesel consumption per handled cubic meter of 0.152 L/m^3, computed from internal data. The yearly volumes in $m^3/year$ to be handled depend on the integrated mass balance and determine the actual vehicle usage and fuel consumption cost.

$$c_{fuel} = totalVolume\left[\frac{m^3}{y}\right] * 0.152\left[\frac{L}{m^3}\right] * 1.5\left[\frac{€}{L}\right]$$

The volume estimate is differentiated for green waste and composting material. The green waste only needs to be handled once, from the storage area to the blender. On the contrary, every composting batch is handled four times, from the blending storage area to the bio cells, to the maturation aisle, to the sieving stage, to the final finished compost area.

Table 19: fuel consumption parameters of the cost evaluation.

fuel consumption		
movimentation rate [mc/h]	82.5	4 hours to unload a full bio cell of 330 m3
vehicle consumption [L/h]	12.5	200 L/d with a daily average usage of 16h
fuel price [€/L]	1.5	
composting number of travels [u]	4	

3.4.3.3. Thermal consumption

It is the active cost of the pasteurization equipment used to upgrade to End of Waste (EOW) the liquid filtrate obtained from digestate dewatering.

Since the thermal power is provided by the plant CHP unit, the actual cost is the avoided profit loss of the biomethane that has not been sold, composed by the incentive certificate (CIC) and the grid injection earning.

It is calculated through the biomethane avoided earning of 0.81€/m^3, the biomethane LHV of 10 kWh_{th}/m^3, and the CHP thermal efficiency estimated at 80%. Knowing the daily working hours of the pasteurizer (15 and 13 *hours/day*) and average thermal power (113 and 155 *kW*) differentiated for colder and warmer seasons, the thermal request and biomethane consumption is estimated.

$$c_{th} = \frac{heatingDemand\left[\frac{kWh_{th}}{y}\right]}{80\% * 10\left[\frac{kWh_{th}}{m^3}\right]} * 0.81\left[\frac{€}{m^3}\right]$$

Table 20: thermal consumption parameters of the cost evaluation.

thermal consumption		
available thermal power [kW$_{th}$]	113/155	winter/summer
max number of batches [u/d]	4/6	winter/summer
batch capacity [t/u]	7.5	
CHP thermal efficiency [%]	0.8	
biomethane LHV [kWh$_{th}$/m^3]	10	
methane missed earning [€/m^3]	0.81	assuming CIC of 0.61 €/ m^3 and a grid tariff of 0.2 €/m^3

3.4.3.4. Manpower salary

It accounts for the workforce related to blending cycle management and to material handling. The first is associated with the time spent on blender loading and unloading procedures, computed as a fraction of the total blending cycle duration in *hours/year.*

Material handling concerns the working time of the plant operators driving the wheel loaders. Analogously to the fuel consumption, the cost is computed estimating the required handling time over the year, with the procedure explained above. The yearly hours are then multiplied by the after-tax wage, the gross value disbursed by the plant operator, assumed of 20 €/$hour$.

$$c_{manpower} = (blenderTime * 30\% + handlingTime)\left[\frac{h}{y}\right] * 20\ [\frac{€}{h}]$$

Table 21: personnel salary parameters of the cost evaluation.

manpower salary		
manpower time requirement [%]	30%	of blender cycle management
gross manpower salary [€/h]	20	

3.4.3.5. Material purchase

It includes the supply of green waste to be mixed with digestate in the blending cycles and of irrigation water used in the composting process.

$$c_{purchase,k} = totalMass_k\left[\frac{t}{y}\right] * price_k\ [\frac{€}{t}]$$

The green waste is conferred to the plant up to a maximum amount of 3000 *ton/year,* generating a gate fee earning of 20 €/ton. Unfortunately, with semi-wet digestate a much greater quantity is required, in the order of 10000 to 15000 additional *ton/year,* purchased at the price of 50 €/ton and representing a major cost fraction.

Irrigation water has a much lower cost estimated at 5 €/m^3, which can be avoided by installing the pasteurizer and recirculating the sanitized FSP filtrate.

3.4.3.6. Material disposal

It includes disposal cost of the reject, the dewatering filtrate and the over sieve compost.

$$c_{disposal,k} = totalMass_k\left[\frac{t}{y}\right] * disposalCost\ [\frac{€}{t}]$$

The filtrate is classified as contaminated wastewater and disposed for the fee of 80 €/m^3, representing a major cost entry for the plant. It can be avoided with the installation of the pasteurizer.

Composted material is sieved to guarantee a proper grain size of the end product. Most of the over-sieve material is recirculated in the blending cycle as structuring material, while a minor fraction is disposed as solid organic waste with a 100 €/t.

Hammer mill reject is considered an even more contaminated waste, because it did not pass through degradation in the digester, and is disposed of for 120 €/t.

3.4.3.7. Material sale

It includes the sale of finished compost and of soil conditioner obtained from filtrate pasteurization, with predicted market values of 20 €/t and 2 €/t respectively. The earning is represented in the NPC as a negative cost.

$$c_{sale,k} = -\ totalMass_k \left[\frac{t}{y}\right] * price_k \left[\frac{€}{t}\right]$$

The two streams are secondary plant output produced in limited quantity, having an overall small impact on the plant economics.

Table 22: material prices parameters of the cost evaluation.

material purchase	
green waste conferral price [€/t]	-20
green waste purchase price [€/t]	50
irrigation water cost [€/m3]	5
material disposal	
over sieve disposal [€/t]	100
wastewater disposal [€/m3]	80
material sale	
compost selling price [€/t]	-20
pasteurised soil conditioner [€/m3]	-2

4 Data collection

4.1. Sampling at the plant

In January, a full characterization of the plant operations was conducted, to be considered representative of winter operation.

4.1.1. Pre-treatment of OFMSW

The OFMSW composition was only qualitatively investigated by opening a few randomly selected bags. A major fraction of fruit peels (mainly oranges) was found, together with a significant amount of vegetables' scraps and napkins, coherently with the winter season. A few plastic, glass bottles, and medicine containers were also found. It is reasonable to state that food waste comes with a good separation quality, since most of the material is organic. However, the presence of non-biodegradable plastic bags, impurities, and slowly degradable matter not available to the bacteria, determines an contaminants level of 25%, according to the plant personnel.

Subsequently, the outputs of the hammer mill separator were characterized, running on the organic and reject streams a fibres-plastics separation, a TS, and a VS test on the organic fraction only. The separation rate is expressed as dry weight of fibres and plastics per total fresh sample weight.

Table 23: characteristics of treated organic and hammer mill reject.

	TS	VS	VS/TS	fibres dm%	plastic dm%	dry fibres %	dry plastics %
ORG HM	37.6%	36.3%	96.5%	37.5%	0.0%	99.9%	0.1%
REJECT	52.6%	-	-	45.3%	7.3%	86.2%	13.8%

Results show an effective organic separation with 99.9% fibres in the organic stream, but also an important drag effect in the reject, with 86% of the dry matter being fibrous.

4.1.2. Digestate

Table 24: measured characteristics of three samples of digestate.

	density [t/m^3]	pH	FOS [mg/L]	TAC [mg/L]	FOS/TAC	TS [%]	VS [%]	VS/TS [%]
DIG OUT	0.98	8.37	7.5	20.9	0.36	13.8%	7.5%	54.3%
DIG MID		8.49	9.9	21.5	0.46			
DIG OUT	1.00	8.45	6.9	21.1	0.33	14.4%	7.5%	52.1%
DIG MID	1.04	8.38	7.7	21.3	0.36	13.3%	6.8%	51.1%

Digestate samples are extracted after discharging approximately 40 L of fluid, to obtain a material as homogeneous and representative as possible. TS, VS, pH, FOS, TAC content were measured.

Investigating the differences between digestate taken from the middle and the outlet section, the FOS/TAC of DIG OUT was lower than DIG MID as expected.

4.1.3. Post treatment of digestate

To analyse the behaviour of digestate dewatering and blending process, density and TS assessment is carried out on the involved streams. They include the digestate (average of direct measures), the Filter Screw Press cake, and the blended mixture, giving an indication on the effectiveness of the blending recipe.

Table 25: measured characteristics of fresh and dewatered digestate, and of blended mixture.

	density [t/m^3]	TS [%]
DIGESTATE	1.00	13.8%
CAKE FSP	0.88	39.6%
BLENDED	0.40	-

Dewatering appears to be very effective, reaching the upper value of the obtainable TS range (25-40%) of the FSP cake. Such value is a consequence of the high solid content of the digestate of 14%. Accordingly, the density of the blended material also coincides with the minimum advisable value of expected density range (0.4-0.65) of Table 4.

4.1.4. Composting

To monitor the composting process, soil activity and soil quality analysis are performed on material in different stage of maturation. A full sampling of the biological activity of the maturation building was conducted, with temperature and biogas measurements on four sampling points for each one of the twelve aisles. The results are collected in Table 53 and summarized in Table 26.

Table 26: measured characteristic of composting and composted soil grouped by type

Maturation stage	**CH4 [%]**	**CO2 [%]**	**O2 [%]**	**H2S [ppm]**	**temp [°C]**	**TS [%]**
Good aerobic activity	0.02-0.27	10.1-18.3	3.0-7.6	1-2	41-51	44.30%
presence of anaerobic activity	20-35	35-50	0.1-0.3	100-300	26.50	
high temperature conditions	0.12-0.24	0.25	20.5	1	77-79	
finished compost	6.4	30	0.01	46	43.7	63.9

In Table 27: measured chemical quality of composting and composted soil. , the chemical quality analysis performed on maturation material in good aerobic activity and on finished compost:

Table 27: measured chemical quality of composting and composted soil.

	pH (H2O)	pH (KCl)	NO2- (mg/L)	NO3- (mg/L)	NH4+ (mg/L)
MATURATION	8.74	8.48	5	50	0.1-0.4

FINISHED COMPOST	8.49	8.3	25	500	0.5

4.2. Historical plant data

Similarly to the sampling conducted in January, a periodical characterisation of the plant streams is carried out since the first start-up in June. The historical data collection allows to extract average monthly values and to give an interpretation of the development of biological processes occurring in the plant.

4.2.1. Seasonal variations of waste quality

The OFMSW characteristics on which the plant is designed, indicated in the primary design document known as Process Flow Diagram (PFD), are reported in Table 28:

Table 28: expected characteristics of OFMSW used to design the plant.

PFD OFMSW characteristics	value
TS – Total Solids (105°C)	28%
VS/TS - Volatile Solids ratio	75%
Contaminants content	10%
BMP value to treated organic	> 600 m^3/t_{VS}
Bulk Density	650 kg/m^3

The contaminants content is expressed as the sum of the mass fractions of paper, plastic, glass, metals, and grit in the OFMSW composition. Such analysis is not regularly performed and there is no recorded evidence, but the waste received on-site shows a contaminants level higher than expected, up to 25%.

Much easier is instead to characterize the stream of organic waste fed in the digester after the mechanical pre-treatment. Sampling and analysis campaigns are regularly carried out, allowing to detect seasonal variations of the delivered waste composition.

Table 29: historical monthly average characteristics of treated organic waste.

	Average TS	Average VS	Average VS/TS
jun-22	22.2%	17.0%	76.7%
jul-22	30.8%	23.5%	76.1%
aug-22	41.9%	18.3%	43.6%
sept-22	30.4%	24.5%	80.5%
oct-22	25.3%	21.4%	84.6%
nov-22	37.3%	28.9%	77.5%
dec-22	35.4%	27.3%	77.0%
jan-23	34.2%	28.2%	82.4%

The TS and VS content is measured through proximate analysis. The average August TS is way higher than the adjacent months, probably due to measurement inaccuracy, also resulting in an unreasonably low VS/TS ratio.

To increase the reliability of numbers adopted in the models, the August VS/TS ratio is assumed equal to the average between July and September. VS is kept constant, and TS accordingly reduced. Overall, the adjusted seasonal trend is shown in Figure 33.

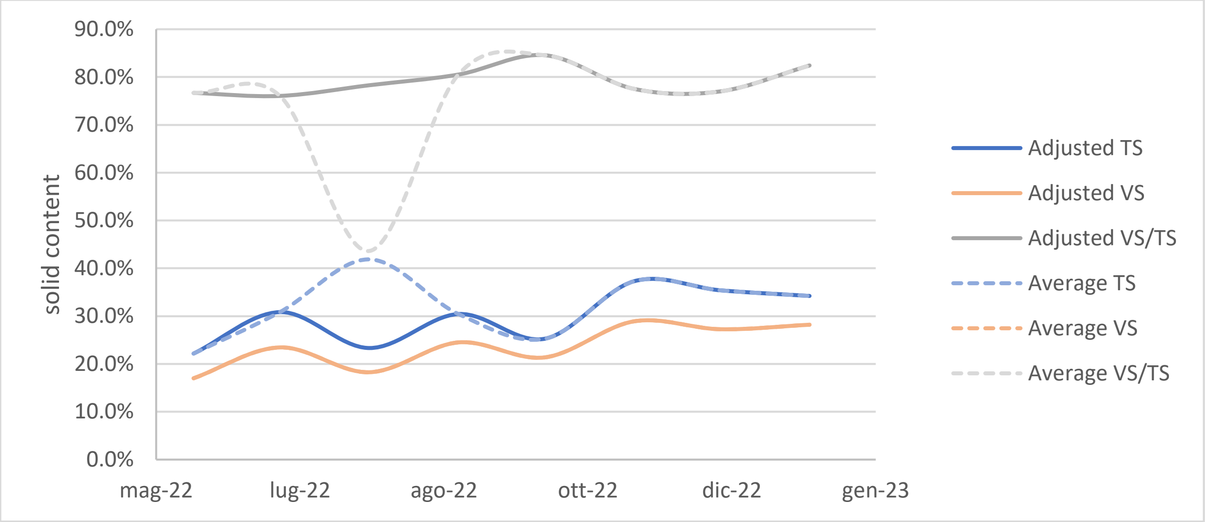


Figure 33: treated organic - graphical comparison of measured and adjusted characteristics.

During the summer months the waste shows a lower solid content (26.7%), due to the larger consumption of fruit and vegetable increasing the moisture content of the incoming waste, contrarily to the winter months (33.0%). In terms of total average on eight months, the received waste quality appears to be very close to the expected one.

Table 30: expected, seasonal and total averages of treated organic characteristics.

	Average TS	Average VS	Average VS/TS
PFD	30.0%	24.3%	81%
jun-sept	26.7%	20.8%	77.9%
oct-jan	33.0%	26.4%	80.0%
total average	29.9%	23.6%	79.1%

4.2.2. Digester feeding

The OFMSW is conferred to the plant, stored in the reception pit, and gradually displaced to the mechanical treatment where the impurities are removed from the organic stream (ORG) then fed into the digester. Delivery and consumption might differ, resulting in increasing and decreasing reception pit levels. According to the plant records, the hammer mill separation rate is 75.5% and consequently about 25% of the treated OFMSW is discarded in the reject stream.

Table 31: historical monthly average of OFMSW conferral, treatment, and net feeding.

[t/month]	Delivered OFMSW	Consumed OFMSW	Produced ORG	Fed ORG	ORG/OFMSW
Jul-22	1525	1151	876	838	76%
Aug-22	1439	1141	934	909	82%
Sep-22	1233	1179	800	745	68%

Oct-22	588	798	615	566	77%
Total	1196	1067	806	765	**75.5%**

Feeding data include the mass daily fed into the reactor, out of which the weekly or monthly average is computed. The substrate available to the microbial communities is estimated multiplying the monthly average of VS content by the fresh fed mass. HRT and OLR are computed assuming 1600 m^3 of digester volume and 0.9 ton/m^3 of organic substrate density.

Table 32: historical monthly average of feeding data, HRT and OLR.

	ORG feed [t/d]	VS%	VS feed [t/d]	HRT [d]	OLR [kg_{VS}/m^3d]
jun-22	12.7	17.0%	2.2	113.6	1.3
jul-22	27.8	23.5%	6.5	51.8	4.1
aug-22	28.9	24.0%	6.9	49.8	4.3
sept-22	25.1	24.5%	6.1	57.5	3.8
oct-22	31.4	21.4%	6.7	45.8	4.2
nov-22	31.4	28.9%	9.1	45.8	5.7
dec-22	27.3	27.3%	7.5	52.7	4.7
jan-23	44.5	28.2%	12.6	32.3	7.9

Biogas yield is measured as the ratio of the average daily biogas production and the average daily fed substrate, during the considered period of time. From June to October the feeding automatization was weight-based, while it switched to time-based in the following months. During the second period, the actual loading rate was approximately 90% lower with respect to the initial estimation of 2 tons per 10 minutes. Therefore, a 0.9 correction factor is applied in the biogas yield calculation of November to January.

Table 33: historical monthly average characteristics of biogas production and yield.

	VS feed [t/d]	ORG feed [t/d]	biogas prod. [m^3/d]	biogas prod. [t/d]	biogas yield [m^3/t_{VS}]	biogas yield [m^3/t_{ORG}]
jun-22	2.2	12.7	1968	2.5	886	155
jul-22	6.5	27.8	5588	7.0	907	201
aug-22	6.9	28.9	5726	7.1	1085	198
sept-22	6.1	25.1	6647	8.3	1169	265
oct-22	6.7	31.4	7339	9.2	1093	234
nov-22	9.1	31.4	6691	8.3	736	213
dec-22	7.5	27.3	5926	7.4	788	217
jan-23	12.6	44.5	8225	10.3	655	185
total	7.0	28.6	6014	7.5	862	210

Biogas production and yield are plotted in Figure 34. Organic feed and biogas production columns report measured values. VS feed column is the product between the organic feed and its average monthly VS content, while biogas yield is the ratio of biogas production and feed columns. The volumetric biogas production is converted into mass flow rate through the density of 0.00125 ton per cubic meter.

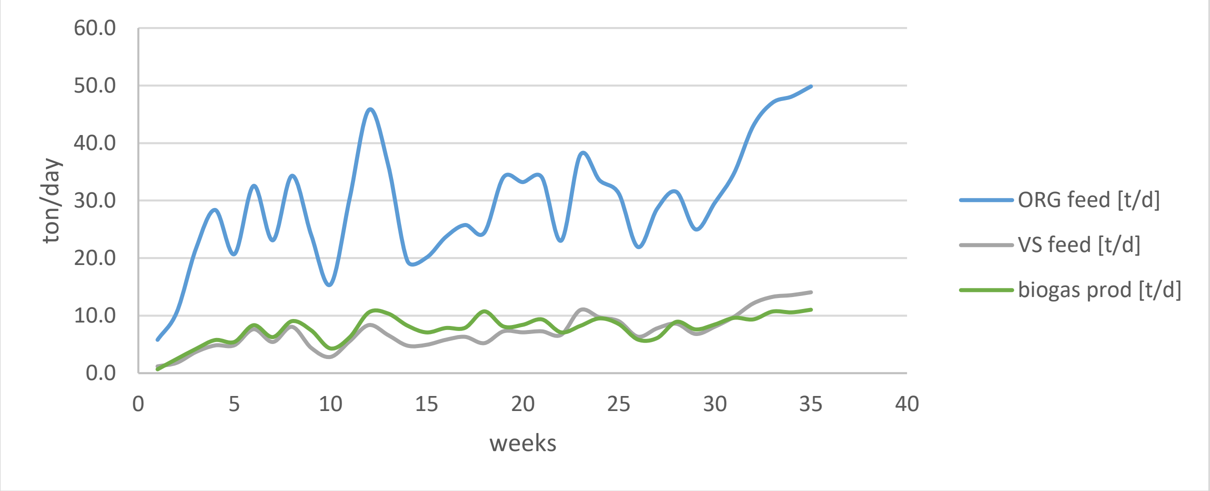


Figure 34: graphical trend of organic feeding and biogas production.

Here, the biogas production line is frequently above the VS feed line, indicating that organic matter injection is lower than its removal. Since this is physically impossible, it is likely that VS content is underestimated, due to a volatilization of degradable matter during the desiccation furnace heating [44].

In Figure 35 the biogas yield with respect to fresh mass feeding and VS intake are plotted.

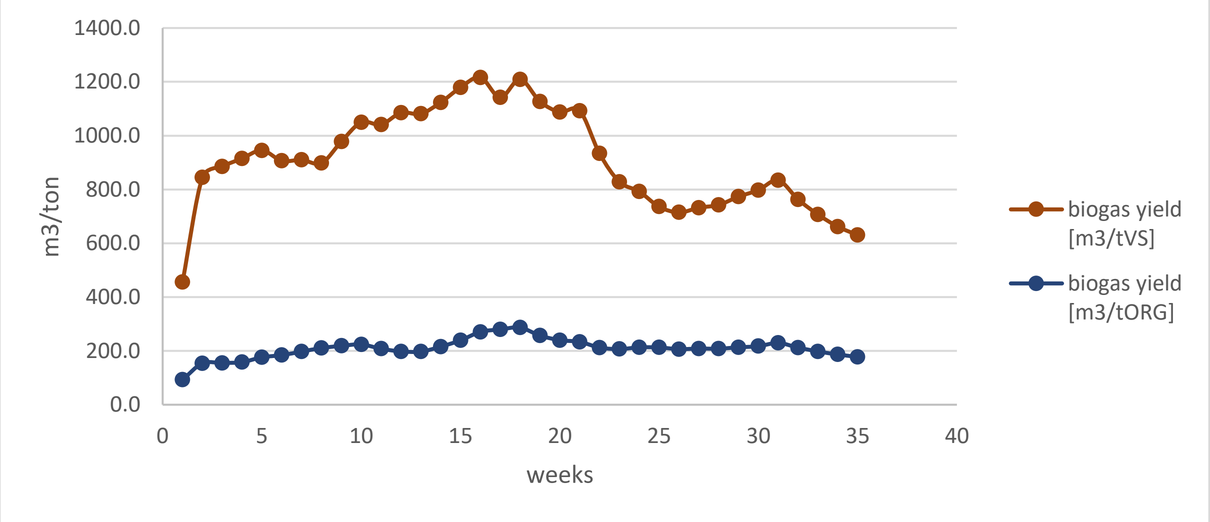


Figure 35: graphical trend of biogas yield on fresh mass and VS basis.

The curve referred to fresh organic waste appears more stable and overall more reliable than the one referred to VS degradable matter, which is multiplied by inaccurate average VS measurements. Also, biogas yield peaks of 1200 m^3/t_{VS} are out of the range indicated in the literature of OFMSW dry AD [9]. The reported biomethane content in the biogas flow has a stable value ranging between 57 and 58%, and therefore yield curves of biomethane production are approximately a scaled version of the biogas ones.

4.2.3. Digestate effluents

Digestate is extracted from inlet, middle and outlet sampling ports, and VS, TS, VS/TS, pH, FOS, TAC, FOS/TAC, density are measured.

Results are plotted in Table 34 grouped by different extraction ports.

Table 34: historical monthly average characteristics of digestate from IN-MID-OUT ports.

	month	IN	MID	OUT
TS	jun-22	10.2%	-	10.6%
	jul-22	10.4%	10.6%	7.1%
	aug-22	11.6%	11.0%	10.7%
	sept-22	11.9%	12.8%	13.2%
	oct-22	13.3%	12.7%	16.1%
	nov-22	15.1%	14.3%	13.9%
	dec-22	13.2%	13.9%	13.5%
	jan-23	14.1%	15.0%	14.9%
VS/TS	jun-22	64.0%	-	82.7%
	jul-22	73.6%	71.4%	87.0%
	aug-22	63.8%	66.6%	59.6%
	sept-22	60.3%	67.4%	62.6%
	oct-22	60.8%	58.6%	65.4%
	nov-22	62.7%	59.0%	60.4%
	dec-22	53.2%	51.3%	49.4%
	jan-23	52.0%	65.5%	56.7%
pH	jun-22	7.87	-	7.92
	jul-22	8.07	8.02	8.03
	aug-22	8.12	8.10	8.13
	sept-22	8.12	8.11	8.14
	oct-22	8.11	8.15	8.13
	nov-22	8.15	8.26	8.27
	dec-22	8.30	8.39	8.32
	jan-23	8.31	8.39	8.38
FOS/TAC	jun-22	0.33	-	0.32
	jul-22	0.28	0.28	0.29
	aug-22	0.28	0.28	0.28
	sept-22	0.30	0.30	0.29
	oct-22	0.38	0.37	0.41
	nov-22	0.49	0.47	0.42
	dec-22	0.50	0.48	0.41
	jan-23	0.50	0.43	0.40

From IN to OUT port:

- organic degradation progressively occurs, volatilizing solid matter into gaseous components, and therefore the TS and VS/TS contents are expected to decrease,
- the conversion of VFAs, and the consequent removal of acidic compounds, should lead the pH to increase, and the FOS/TAC ratio to decrease.

The expected biochemical dynamics are not met in the collected data. The average TS and VS/TS contents of the OUT digestate is often higher than the one extracted from the IN and MID ports. Similarly, average pH and FOS/TAC ratio do not behave as expected considering samples from the inlet to the outlet sections.

The inaccuracy of the results most likely depends on the scarce representativeness of the samples, characterized by a high variability. Causes can be the digestate recirculation, and the low homogenization and stratification of the substrate in the digester, depending on an inadequate mixing equipment for the excessively liquid condition of the digestate.

Overall, the results are not reliable in the representation of the AD dynamics. Collected data can instead be useful to describe the average digester characteristics.

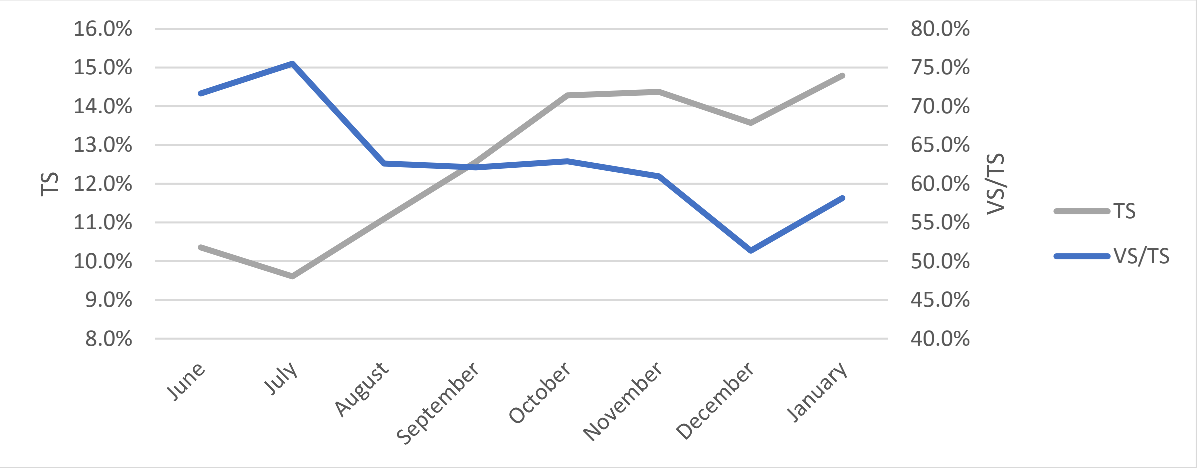


Figure 36: graphical trends of digestate TS and VS content.

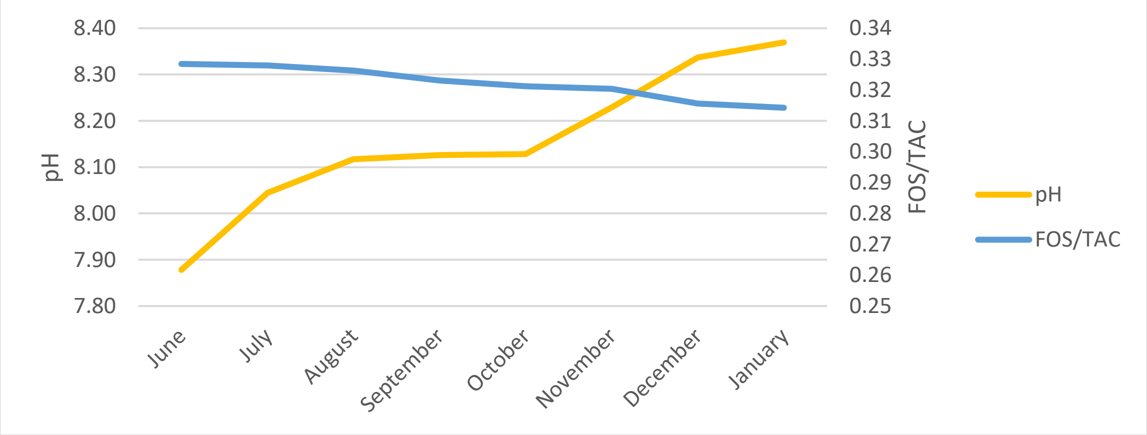


Figure 37: graphical trends of digestate pH and FOS/TAC characteristics.

Table 35: historical monthly average characteristics of digestate from all sample ports.

	month	TS	VS/TS	pH	FOS (x1e3)	TAC (x1e3)	FOS/TAC	density
ALL	June	10.4%	71.7%	7.88	3.1	9.4	0.33	
	July	9.6%	75.5%	8.04	3.1	9.5	0.28	
	August	11.1%	62.6%	8.12	3.2	9.7	0.28	
	September	12.6%	62.1%	8.13	3.2	9.9	0.30	0.96
	October	14.3%	62.9%	8.13	3.2	10.1	0.39	0.99
	November	14.4%	60.9%	8.23	3.3	10.3	0.45	0.97
	December	13.6%	51.4%	8.34	3.3	10.6	0.46	0.99
	January	14.8%	58.1%	8.37	3.4	10.8	0.43	1.00

In Figure 36, the average Total Solid content clearly increases from June to January, a sign of an increasingly dry organic waste fed into the digester, as also reported in the previous paragraphs. The decreasing VS/TS ratio indicates a VS removal efficiency improving over time, linked with the adaptation of microbial colonies, stabilization, and optimization of the biochemical process.

Similarly, in Figure 37 the increasing pH and decreasing FOS/TAC ratio are signs of rising VFAs conversion, spontaneous part of the plant start-up and ramp-up process.

Nonetheless, digestate TS is too low for the declared dry operations, with significant and negative impacts on the post-treatment and composting process. Solutions are the extension of blending capacity, the inclusion of a digestate dewatering stage, or the addition of finely grinded green waste in the digester, as it will be discussed in the next chapter.

Density is very close to 1 kg/L and can be assumed constant. Nonetheless, a literature search was carried out to find more accurate density correlations, investigating biogas digestate [51] and animal manure [52]. A plant TS-density correlation was developed crossing the available data, and then compared with the literature ones.

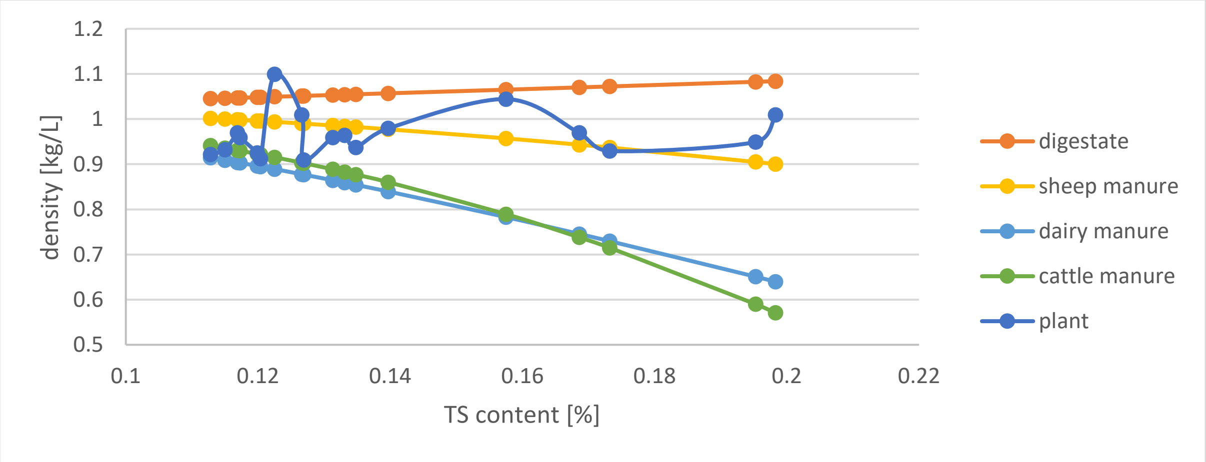


Figure 38: comparison of digestate TS-density correlations from literature and internal data.

The trendline of the curve obtained from plant data is similar to the literature curve of the digestate [51] depicted in orange, with the only difference of an intercept of -0.088, resulting in the correlation:

$$\rho(TS) = -0.088 + \frac{0.998}{1 - 0.00345\,TS}$$

With the density expressed in t/m^3, and the TS content in percentage points.

4.2.4. Other streams

On-site measurements of blender ingredients characteristics are reported below:

Table 36: average characteristics of compost, over sieve, blending ingredients and mixture.

	VS	TS	density
recirculated compost	-	0.65	0.50
recirculated over sieve	-	0.62	0.464
green waste pre-mix	-	-	0.218
blended mixture	0.31	0.45	0.59

Dewatering streams characteristics are reported according to the adopted screen size:

Table 37: average characteristics of the Filter Screw Press output streams.

FSP	VS	TS
cake 0.75 mm	0.22	0.31
filtrate 0.75 mm	0.05	0.10
cake 1.00 mm	0.22	0.34
filtrate 1.00 mm	0.06	0.11

Finally, average features of the leachate collected from the reception pit:

Table 38: average characteristics of leachate.

Leachate	VS	TS	pH
tot average	4.4%	7.5%	5.64

5 Problem statement

The plant of the case study was conceived as a dry AD facility, and the digestate post-composting process was sized accordingly. In the first six months of operation, the digester behaved as a semi-wet system, discharging excessively liquid digestate and negatively impacting downstream technical aspects and the overall plant profitability. The problem will be analysed by investigating causes, consequences, and possible solutions, with the support of mass balance modelling and data collection.

5.1. Causes

Possible co-causes are identified in the digester design, in the quality of the incoming OFMSW, in the pre-treatment process and in the biological transitory of the start-up.

5.1.1. Process design

The plant is sized to process 24000 tons per year of waste, feeding both the treated organic and the leachate collected from the OFMSW reception pit, with 53.4 and 3.1 *tons/day* respectively. These daily flow rates are fed as input parameters in the digester steady state model, according to the waste characteristics reported in the PFD, and the biogas and digestate output streams are calculated by applying the mass balance of 3.2.2.1.

Three different VS conversion and biogas output were calculated considering:

1. a biogas potential of 750 m^3/ton$_{VS}$, as assumed in the preliminary design (PFD),
2. a VS removal efficiency of 75%, being a mid-high value for similar plants,
3. a VS removal efficiency of 50%, being a low value for similar plants.

Table 39: results of steady state digester model with design input data.

	INPUT			OUTPUT: CASE 1		OUTPUT: CASE 2		OUTPUT: CASE 3	
	ORGANIC	LEACHATE	FEED	BG	DIG	BG	DIG	BG	DIG
MFR [t/d]	53.4	3.1	56.5	12.2	44.3	10.5	46.0	7.4	49.1
TS [t/d]	16.0	0.2	16.3		4.1		5.8		8.8
VS [t/d]	13.0	0.1	13.1		0.9		2.7		5.7
TS [%]	30%	8%	28.8%		9.2%		12.6%		18.0%
VS [%]	24.3%	4.8%	23.2%		2.1%		5.8%		11.6%
BGP [m3/tVS]				750		642		456	
$\eta_{rem_{VS}}$ [-]					91%		75%		50%

The design outlet digestate conditions do not match the declared dry AD behaviour:

- In case 1, digestate shows an excessive VS conversion, with very low outlet TS content of 9% and an unreasonably high VS removal of 91%
- In case 2, a reasonable conversion leads to a 12% TS digestate, comparable with a semi-dry behaviour, with 15% loss on the design biogas production.
- In case 3, dry AD conditions are met, but with a 40% loss on biogas yield.

Without even taking into consideration the actual operations, the reactor behaves as a wet digester already in the preliminary plant design. Dry digesters can stand a high OLR reaching great biogas yields, but also requiring a significant TS uptake to guarantee a proper solid concentration in the reactor. Therefore, the preliminary assumption of a high conversion rate is not out of context, but possibly a poor solid content of the food waste is the reason of the issue.

The recorded biogas production ranges between 600 and 1200 m^3/ton_{VS}. Such numbers might be overestimated due to underestimation of VS content as explained in 4.2.2, but on the other hand the average value is considerably above the expected design potential.

5.1.2. Pre-treatment

The hammer mill separation filters out, together with the plastics, a large fraction of bulky and fibrous organic material. The majority of slowly and non-degradable solid fraction is not made available in the organic stream, and consequently the vast majority of feeding substrate is highly fermentable, boosting the removal of solids and contributing to the liquid conditions of the digestate.

To address the issue, different hole diameters were tested, from 7 to 70 mm, but without observing significant improvements in the drag effect phenomena, since elongated fibres won’t pass through the metallic screen regardless of the screen size.

An improvement could be made through the installation of a reject separator machine that, by isolating plastics from fibrous material, could allow the recirculation of the lignocellulosic fraction in the other phases of the process, for instance the compost blending stage.

5.1.3. Feeding ramp-up

At the first plant startup, the feeding ramp-up took longer than expected due to equipment’s technical issues and delay in bureaucratic authorizations. A low feeding rate, at fixed digester volume, results in an increased HRT, which consequently boosts the biochemical conversion efficiency. The higher the VS removal efficiency, the lower the retention capacity of solid matter in the digester, favouring excessive liquefaction of the digestate.

In Figure 39, the HRT is computed through the weekly average feed of treated organic waste, assuming an operational digester volume of 1600 m^3 and a density of 0.9 t/m^3 for the organic waste. Additionally, OLR is computed using the average monthly VS.

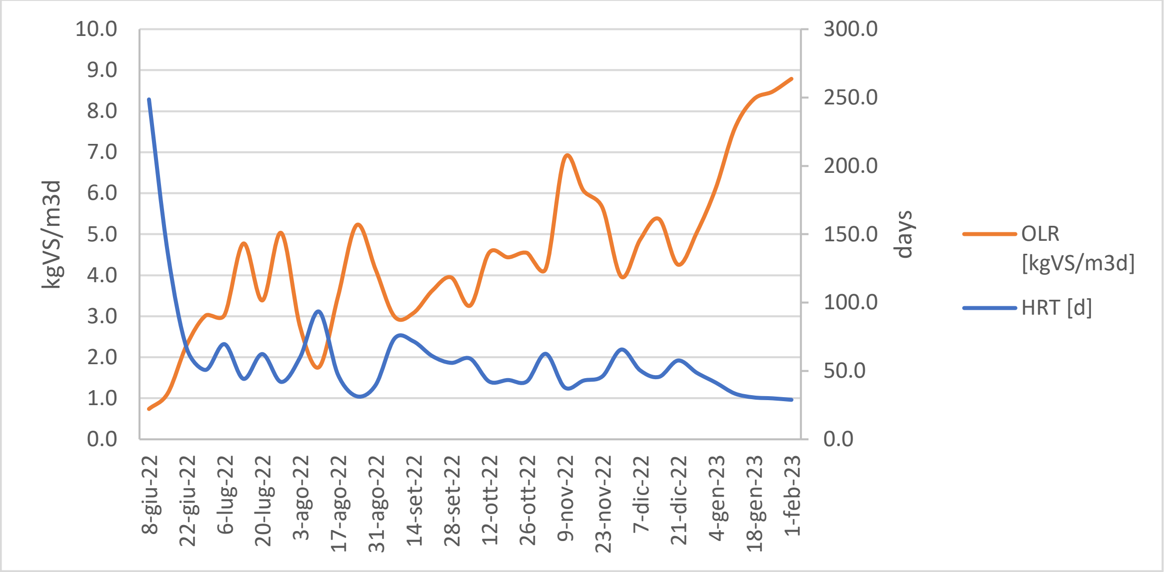


Figure 39: historical weekly HRT and OLR.

Overall, excluding the first 8 ramp-up weeks, the average HRT is 45 days with an OLR of 4.9 $kg_{VS}/m^3/d$. The design HRT of 32 day is not reached before November, and similarly the design OLR value of 7.3 is only seen starting from January. HRT ranges between 60 and 27 days, while OLR between 4 and 10 $kg_{VS}/m^3/d$.

Overall, semi-wet digester conditions could not be avoided with the expected food waste characteristics, because this is how the reactor should work according to the preliminary design. The situation was negatively influenced by the delayed feeding ramp-up, that kept too high HRT and too low OLR for a long time, limiting solids uptake and accumulation, and by the removal of fibrous non-degradable matter operated by the hammer mill, allowing the passage of the putrescible fraction only.

5.2. Consequences

5.2.1. Digester

A dry digester is expected to have high solids content, and consequently a high viscosity that keeps in suspension the lighter and heavier elements that would otherwise float or precipitate. A wet digester is instead more susceptible to such homogenisation issues because of its liquid digestate, reason why it is equipped with a powerful mixing system. When a reactor designed for dry AD operates under semi-wet or wet conditions, the agitators are inadequate, and the insufficient mixing could penalize the biogas production due to thermal stratification and uneven VS and COD distribution.

A plant experiment showed how an extraordinary boost in mixing was shortly followed by an unexpected biogas production. Indeed, increasing the mixing operating hours can improve the homogenization issue, but not the stratification problem which is related to low viscosity of the substrate and can only be solved ensuring a more solid digestate.

5.2.2. Post-composting

Designed as a dry process, the expected digester TS is 17 to 20%, on which the digestate treatment and composting process are sized. A lower solid content of the digestate affects the mixing ratios of the blending recipe, requiring a higher quantity of structuring material, and resulting in greater volumes to be handled and composted.

The system is impacted in terms of time, space, energy, manpower requirement and purchase expenses. Each ton of blended mixture requires handling, irrigation, forced aeration, and an adequate residence time. The building is sized to ensure a proper duration of the composting process considering the design volumetric flow rate. An increased mixture production implies that the minimum residence time is not met, penalizing the quality of the final product.

5.3. Solutions

Different types of solutions can be adopted to deal with the post-composting process, either acting downstream or upstream of the digester.

5.3.1. Second blender

A second blender can be added in parallel to double the treating capacity in case of high volumetric flow rates. The time required by the plant operators to deal with the blending cycles would be halved.

Furthermore, it would increase the redundancy and the reliability of the overall system, avoiding unforeseen stops due to equipment failure, being the blender a critical component subject to wear and tear.

5.3.2. Dewatering

A dewatering unit would split the semi-liquid digestate into a drier flow, discharged into the blender, and a liquid one, pasteurized or disposed of.

Not only the FSP cake would be very concentrated, reducing the mixing ratio of required structuring material, but it would also drastically shrink in terms of mass flow rate, which overall decreases the volume of material sent to composting. Advantages are the lower handling costs and energy expenditure, but the compost production will also be significantly reduced. Furthermore, for the lower uptake of vegetal additives, it would reduce the C/N ratio [53].

A digestate up to 14% TS can be processed in a single simpler unit, while for higher solid contents in the range of 17% to 25% a more advanced machine will be needed. The two units would operate in series, the second one processing the filtrate of the first one to maximize the capture rate of the solid fraction.

5.3.3. Sawdust feeding

The root of the issue is the insufficient injection of solid matter in the digester, linked with a poor contribution of the organic waste. An alternative solution to handle the low TS content of the digestate could be to act upstream and directly increase the solid concentration in the digester by feeding finely grinded green waste mixed with the treated organic. The fine material, hereby referred as sawdust, would be obtained by grinding fibrous green waste and sieving below 20 mm, expecting a low density and a TS content of 60-70%. Such approach would:

- Reduce the amount of structuring and absorbing material of the blender recipe,
- Increase the uptake of solid and slowly degradable matter, increasing viscosity in the digester and reducing homogenization and stratification issues associated with sedimentation.

6 Results

The results of different activities are reported in the chapter, namely the investigation of the biochemical processes occurring in the digester, the feasibility study of sawdust feeding in the digester, the economic assessment of the installation of the reject separator, and the aggregated economic comparison of different plant configurations adopted to deal with the issues of the post-composting process.

6.1. Solid content measurements inconsistency

Steady state and dynamic digester models are fed with design parameters and historical data. The dynamic model allows to predict the solids concentration trend and the duration of the transient, after which the results coincide with the steady state model.

In Figure 40, the behaviour of the plant start-up according to the design parameters.

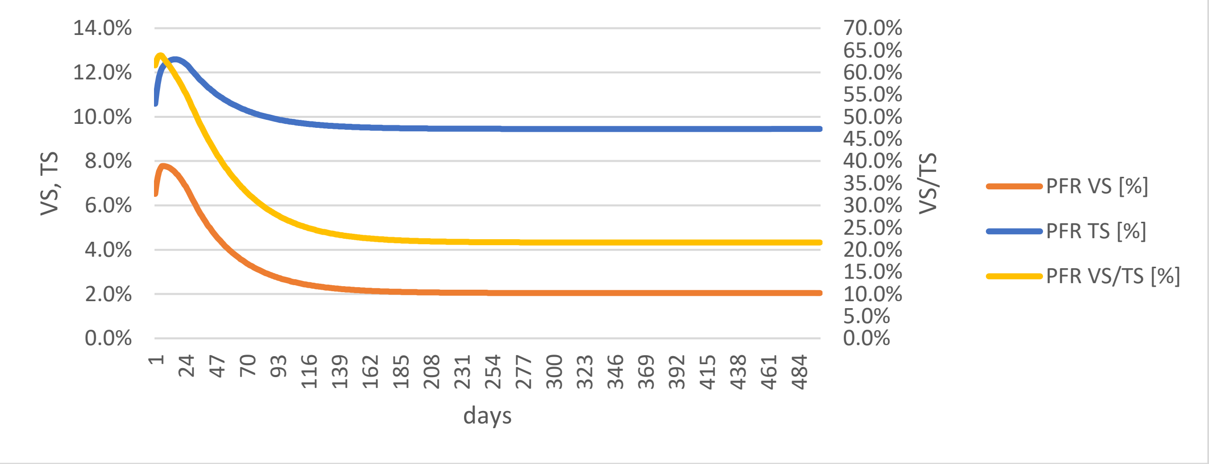


Figure 40: digester solid concentration - start-up transient with design input data.

At the end of the transient, the digester stabilizes at 9% TS and 2% VS, as also described in Table 39, revealing a reactor design incoherent with the declared dry process behaviour.

6.1.1. Steady state model

Analysing the historical data, a series of measurements inconsistencies is found. In fact, a critical aspect of the sampling campaigns is the robustness of the collected data. Some procedures are less reliable than others, and because of intrinsic errors the measurement values are systematically inconsistent with the real measured quantities.

In the plant under analysis, the most reliable measurements are the biogas production and the organic feeding rate, directly detected by simple devices as flowmeters and loadcells. Contrarily, the TS and VS content are determined through a sequence of operations that include high temperature desiccation, and the values are likely to be underestimated due to a volatilization of organic compounds during the heating phases [44].

In the digestate, this underestimation factor has a minor impact, because of the lower residual content of degradable matter. Instead, it is expected to have a greater effect on the fresh organic waste, because of its highly putrescible state.

The average seasonal data are tested in the steady state digester model.

Table 40: measured seasonal average characteristics of fed organic and outlet digestate.

	organic - measured average				digestate - measured average		
	TS	VS	TS/VS	BGP	TS	VS	TS/VS
jun-sept	26.7%	20.8%	77.9%	221	10.9%	7.4%	67.4%
oct-jan	33.0%	26.4%	80.0%	212	14.3%	8.3%	58.4%

Using the measured feeding characteristics of Table 40, the model returns extremely low and negative solid contents of the digestate, which has no physical meaning. Reversely, the organic feeding TS is computed that would return a digestate TS equal to the measured average of Table 40.

Table 41: adjustment of organic feeding characteristics according to incoherent model results.

	digestate - model result		organic feeding adjustment		
	TS	VS	TS theorical	TS measured	Theor./meas.
jun-sept	-1.0%	-9.1%	35.3%	26.7%	132.6%
oct-jan	9.1%	0.2%	36.8%	33.0%	112.6%

These values are 33% and 13% higher than the measured ones for warm and cold season respectively, suggesting an underestimation up to 30%. The average seasonal adjusted solid contents of 35.3% and 36.8% will be adopted in the integrated mass balance.

6.1.2. Dynamic model

The daily historical data are tested in the dynamic digester model, comparing the predicted biogas production and digester solid contents with the measured ones.

Comparing the predicted biogas yield with the actual one, the modelled biogas production closely follows the actual one, with cumulative predicted value (1504244 m^3) being 100.3% of the measured one (1500358 m3).

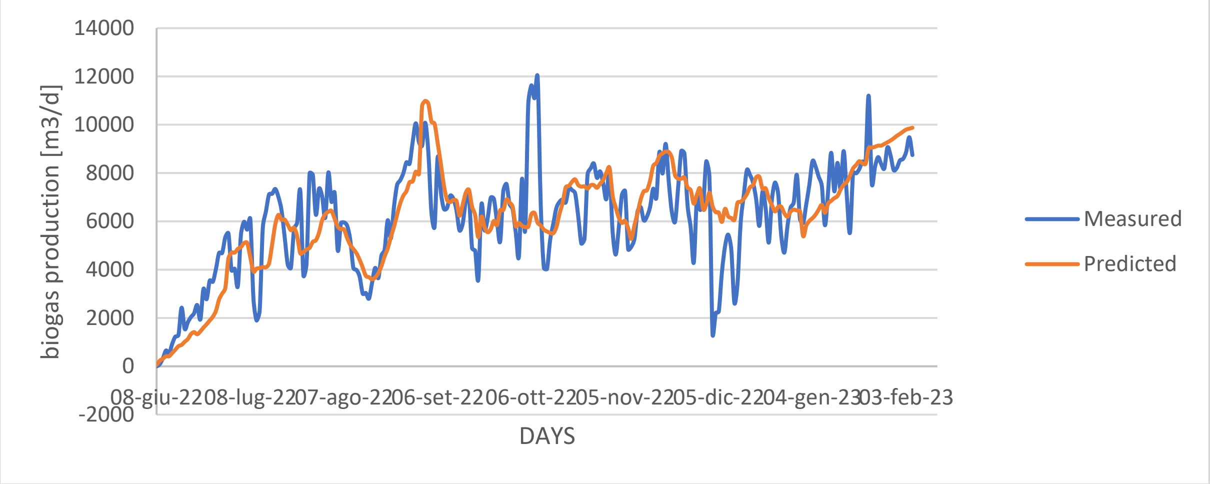


Figure 41: graphical trend of measured and model predicted biogas production.

At the beginning, the prediction underestimates the real production, probably due to the longer real HRT that led to higher yields per ton of substrate. Similarly, a sort of phase shift is visible until October. In terms of biochemical conversion, the model can be considered reliable.

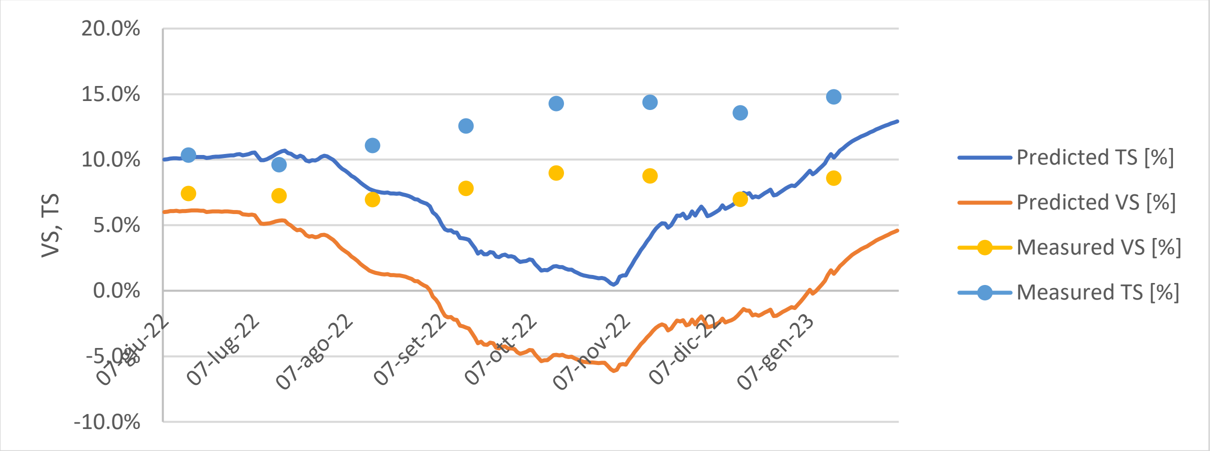


Figure 42: graphical trend of measured and predicted digester solid concentration.

The solid concentration prediction is instead not realistic, as the VS content drops to negative values, and the trend does not match with the measured monthly average.

Since the VS removal is associated with the modelled biological conversion, which is instead reliable, the model failure could depend on the underestimation of the TS and VS values of the organic feeding stream, as already seen for the steady state model. The input solid content is lower than the one actually fed in the digester, in particular in the months between July and November.

Summarizing, concerning data reliability, the priority is given to the biogas yield and the digestate measurements. The organic feeding TS and VS values are adjusted to meet the measured biogas production and digestate quality.

6.2. Feasibility of sawdust feeding

It is estimated the amount of grinded green waste to be fed into the digester to reach a solid content of 18%.

Grinded vegetal material TS is characterised through three collected samples, obtaining (on a rainy day) an average value of 60.8%. It can realistically range between 60% and 70% depending on the relative humidity of the air in the storage area.

The mixing ratio of sawdust and digestate blend is forecasted, applying mass balance of total mass and moisture content, considering digestate TS varying between 12% and 17%, and sawdust TS between 60% and 70%.

Table 42: sawdust-digestate ratios according to variable solid contents.

mix TS	sawdust TS		
17%	60%	65%	70%
12%	10.4%	9.4%	8.6%
13%	8.5%	7.7%	7.0%
14%	6.5%	5.9%	5.4%
15%	4.4%	4.0%	3.6%
16%	2.3%	2.0%	1.9%
17%	0.0%	0.0%	0.0%
dig TS	SAWDUST RATIO		

mix TS	sawdust TS		
18%	60%	65%	70%
12%	12.5%	11.3%	10.3%
13%	10.6%	9.6%	8.8%
14%	8.7%	7.8%	7.1%
15%	6.7%	6.0%	5.5%
16%	4.5%	4.1%	3.7%
17%	2.3%	2.1%	1.9%
dig TS	SAWDUST RATIO		

mix TS	sawdust TS		
19%	60%	65%	70%
12%	14.6%	13.2%	12.1%
13%	12.8%	11.5%	10.5%
14%	10.9%	9.8%	8.9%
15%	8.9%	8.0%	7.3%
16%	6.8%	6.1%	5.6%
17%	4.7%	4.2%	3.8%
dig TS	SAWDUST RATIO		

The mixing ratio of the digestate is complementary to the sawdust one. A 6 to 8 % sawdust mass fraction in the digester would ensure a digester TS of 17% to 19%, considering a wide range of qualitative variation of the digestate. An average mass fraction of 7% is chosen.

- To reach and maintain the given sawdust concentration, a regular sawdust flow must be mixed with the feeding stream and injected in the digester.
- The organic feed must be maximized to ensure the gate fee earning, and therefore with the additional sawdust intake the inlet flow rate will increase.
- The operative digester volume must be kept constant at 1600 m3, and to do so a higher digestate rate must be discharged as well.

Consequently, maintaining the same volume but increasing the inlet flow, the resulting HRT will decrease.

Starting from a digester volume of 1600 m^3 and a digestate density of approximately 1 t/m^3, the sawdust concentration of 7% on mass basis corresponds to 112 tons. This quantity is supplied and maintained during a 30-day retention cycle with a daily flow rate of 3.7 tons.

The initial feeding rate is increased from 53.3 to about 57 tons, with a sawdust ratio in the feeding stream of approximately 6.5%. The HRT is reduced from 30 to 28 days.

Sawdust injection is tested in the dynamic model, starting from the design parameters:

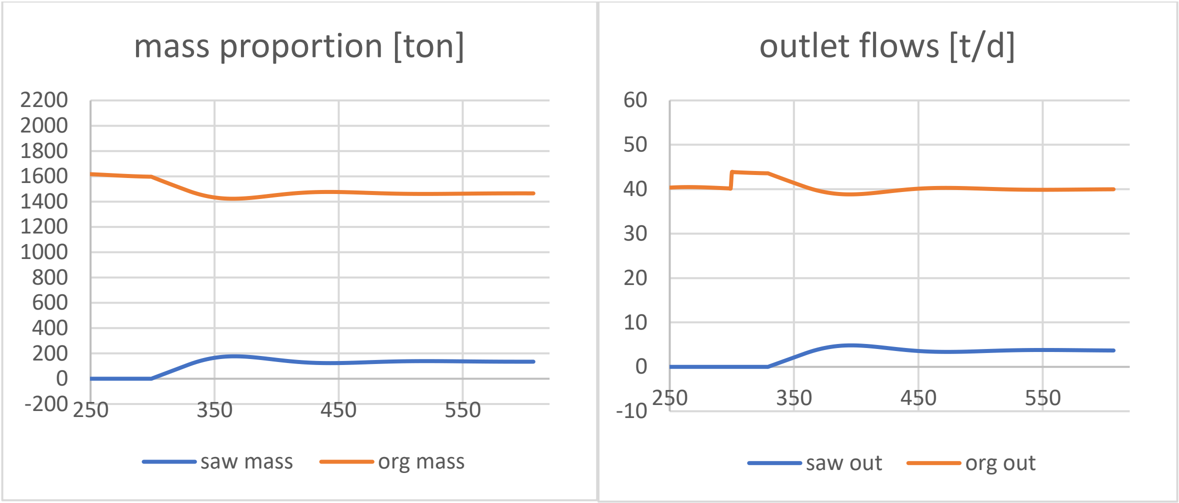


Figure 43: dynamic model results of sawdust feeding.

The sawdust content in the digester is 8.4% in mass, despite it's only 6.5% of the feeding flow, since part of the organic feed leaves the digester under the form of biogas. A minimum sawdust degradation will occur, and it is reasonable to slightly oversize the injected amount.

Seasonal OFMSW variations affect digestate quality, and the feeding system must be oversized to guarantee a sufficient sawdust intake in case of extra liquid digester conditions. The worst considered case is with 54 tons/day of organic waste at 25 % TS, requiring 20 tons/day of sawdust to get a 18% TS digestate output.

Similarly, variations of the sawdust quality affect the required flow rate. Table 43 assumes 54 tons/day of organic waste at 35% TS and a BGP of 205 m^3/tonORG.

Table 43: sawdust feeding requirements at varying sawdust solid content.

DIG TS		sawdust flow rate [t/d]					
		4	5	6	7	8	9
sawdust TS [%]	45%	15.75%	16.40%	17.01%	17.60%	18.17%	18.72%
	50%	16.20%	16.95%	17.66%	18.35%	19.00%	19.63%
	55%	16.65%	17.50%	18.31%	19.09%	19.83%	20.54%
	60%	17.11%	18.05%	18.96%	19.83%	20.66%	
	65%	17.56%	18.60%	19.61%	20.57%		
	70%	18.01%	19.16%	20.25%			

Sawdust density is much lower than the digestate one, and it might be a critical issue in terms of volumetric flow rate in the limited digester volume. However, its equivalent density when mixed with digestate is very close to the liquid one.

An open question to be investigated is how the sawdust will impact the biochemistry. The concentration ramp should be slow enough for microorganisms to adapt, but further testing is preferrable.

6.3. Convenience of reject separator

The component is modelled to assess the economic impact of its installation, comparing differential operational costs with and without the reject separator.

The yearly reject, fibres and plastics streams are computed using the model of the separator introduced in chapter 3, with the parameters displayed in Table 44.

Table 44: reject separator model results in yearly flow rates.

mass balance	OFMSW	reject	plastics	fibres
separation rate [t/t_{OFMSW}]		24.3%		
% dry matter of reject			27%	73%
removal efficiency			90%	10%
flow rate [t/y]	24000	5830	919	4911
TS [%]		37.6%	75%	31%
TS [t/y]		2192	689	1503

The estimated reject production amounts to about 6000 tons per year, divided in about 5000 and 1000 tons of fibres and plastics respectively if the separator is installed.

Case 1 does not include the component. The hammer mill reject cannot be disposed as it is but requires a bio-drying stage to remove excess moisture, increasing its TS content from 35-40% to 50-55%. The drying is carried out in the maturation building, using the same aeration equipment of the composting material, but adopting a different insufflation cycle duration. The considered costs are the:

- Electricity cost of insufflation,
- Reject disposal cost.

Case 2 includes the reject separator. The plastics do not require bio-drying because the separated stream has TS of 75% according to the machine manufacturer. There is an additional separator electric consumption, and the fibres are recirculated as structuring material in the blending stage. The considered costs are the:

- Investment cost of purchase and installation of the machine,
- Electric consumption of the machine,
- Plastics disposal cost,
- Avoided (negative) cost of green waste purchase.

The economic comparison is carried out with the NPC method introduced in chapter 3.4, with constant annuities amortized in a 20-year period with a CRF of 0.117.

Table 45: technical and economic parameters of the separator economic assessment.

Separator investment cost [€]	200000		*bio drying cycle duration [h]*	56
electricity cost [€/kWh]	0.2		*average insufflation power [kW]*	13.9
reject disposal cost [€/t]	120		*reject/plastics density [t/m3]*	0.65
green waste cost [€/t]	0-50		*maturation aisle volume [m3]*	420
pre-treatment hours [h/y]	4380		*separator average power [kW]*	15

The insufflation electricity consumption is computed using the average insufflation power, the cycle duration, and the number of cycles per year calculated as the ratio of yearly volume to dry by the volume of the maturation aisle.

The separator electric consumption is given by the average power of similar machines [54], and the yearly working duration assumed equal to the pre-treatment functioning time of 12 hours per day, 365 day a year.

Table 46: economic assessment of the adoption of the separator in 20 years lifetime.

	Case1	case2
Investment [k€]	0.0	200.0
annuities		
Bio drying insufflation electricity [k€/y]	3.3	0.0
separator electric consumption [k€/y]	0.0	13.1
waste disposal [k€/y]	501.2	105.3
avoided green waste cost [k€/y]	0.0	-247.7
free green waste		
total annuity [k€/y]	505	118
NPC [k€]	4295	1008
pay green waste 50 €/t		
total annuity [k€/y]	505	-129
NPC [k€]	4295	-901

The green waste purchase cost is considered null or 50 €/t in two different scenarios. The NPC is lower by installing the reject separator, regardless of the avoided cost of structuring material. In fact, the major cost entry is the disposal of reject or plastics, and the separator will reduce to a sixth the amount of material to dispose.

Therefore, the installation of the reject separator is recommended.

6.4. Techno-economic comparison

With the digester operating in the current semi-wet conditions, the facility is not financially self-sustaining. The rationale for the techno-economic comparison is to determine the most cost-effective plant configuration, considering the costs associated with the digestate post-treatment and composting process.

6.4.1. Plant configurations

The assessment will take into consideration eight plant configurations, implementing the combinations of the possible solutions presented in chapter 5.3, namely the installation of a second blender, of a dewatering unit, of a pasteurizer, and the sawdust feeding.

1. Base case (preliminary design), including a high number of blending cycles, and large volumes of green waste and composting mixture,
2. A second blender is added to the base case, increasing the blending capacity, reducing the number of cycles but still involving high composting volumes,
3. A dewatering unit is added to the base case, reducing number of cycles, the volumes of green waste and of composting mix, while liquid filtrate is disposed,
4. A pasteurizer is added to case 3, recycling the filtrate in the composting process, cutting disposal expenses and irrigation water consumption,
5. As case 1 with the addition of sawdust feeding, to keep digester TS at a constant value of 18% and to reduce homogenization and sedimentation issues,
6. As case 2 with the addition of sawdust feeding,
7. As case 3 with the addition of sawdust feeding, but requiring a second dewatering unit to handle digestate above TS of 16%,
8. As case 4 with the addition of sawdust feeding and of a second dewatering unit.

Table 47: additional components present in each plant configuration.

cases	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
sawdust feeding	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE	TRUE	TRUE
second blender	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE
one dewatering unit (16% TS)	FALSE	FALSE	TRUE	TRUE	FALSE	FALSE	FALSE	FALSE
two dewatering units (18% TS)	FALSE	FALSE	FALSE	FALSE	FALSE	FALSE	TRUE	TRUE
Leachate disposal	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE	FALSE
Leachate pasteurization	FALSE	FALSE	FALSE	TRUE	FALSE	FALSE	FALSE	TRUE

6.4.2. Technical assessment

The integrated mass balance is adopted to compute the plant streams:

- The organic waste feeding characteristics are the same for each configuration, corresponding to the adjusted seasonal averages reported in Table 48,
- Green waste flow rate to the blender is set for each configuration to guarantee a blended mixture humidity below 45% and a density below 0.55 t/m^3.
- In cases 5 to 8, sawdust feeding flow rate is set to guarantee a digestate TS of 18% regardless of the seasonal variations.

Table 48: organic feeding seasonal characteristics adopted in the integrated mass balance.

	TS	TS/VS	BGP [m^3/t]
summer	35.3%	77.9%	221
winter	36.8%	80.0%	212

The main streams are showed below, differentiated for the cases with and without the FSP dewatering and the sawdust feeding. The presence of the second blender or of the pasteurizer do not affect the mass flow rates, but only the operative costs.

The yellow cells represent the external variable inputs, set to obtain a specific quality of the digestate and of the blended mix. The green cells are the target characteristics of the material sent to composting.

Table 49: integrated model significant results.

		winter				**summer**			
case		**1**	**3-4**	**5**	**7-8**	**1**	**3-4**	**5**	**7-8**
				sawdust				**sawdust**	
			FSP		**FSP**		**FSP**		**FSP**
sawdust	*mass [t/d]*	0.0	0.0	3.3	3.3	0.0	0.0	6.2	6.2
green waste	*mass [t/d]*	54.0	9.3	59.0	10.1	55.5	9.3	62.0	10.7
digestate	*mass [t/d]*	39.8	39.8	43.0	43.0	39.2	39.2	45.2	45.2
	TS [%]	14.3%	14.3%	18.0%	18.0%	10.9%	10.9%	18.0%	18.0%
digestate/cake to the blender	*mass [t/d]*	39.8	8.0	43.0	8.6	39.2	7.8	45.2	9.0
	TS [%]	14.3%	25.0%	18.0%	22.5%	10.9%	19.0%	18.0%	22.5%
blended mixture	*density [t/mc]*	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
	humidity [%]	54.2%	51.3%	52.7%	52.2%	55.0%	53.5%	52.7%	52.2%
	vol [mc/d]	232.4	43.7	255.8	47.0	234.9	42.7	268.9	49.8

The presence of the dewatering unit allows to reduce the green waste consumption by a factor of 5 to 6, abating a huge fraction of one of the major costs. The presence of the sawdust ensures a dry digestate and improves the digester conditions, but on the other hand, it has almost no effect on the blending and composting process, except for increasing the digestate flow rate to the blender and the volume of the mixture.

It is worth to observe by how much the volumetric flow rate to the bio cells, 40 to 256 m^3 per day, exceeds the maximum allowed value of 107 m^3 per day, according to the preliminary design. In fact, without dewatering unit, the composting residence time must be reduced by a factor greater than 2.

6.4.3. Economic assessment

The assessment is carried out at constant OFMSW input and biogas output, considering the additional or avoided differential costs related to digestate post treatment and composting section of each configuration. All the modelled costs are introduced in chapter 3.4.

The investment and maintenance costs of each component are reported in Table 50.

Table 50: fixed costs for each additional component.

Additional components	**C.Inv [k€]**	**O&M [%]**	**O&M [k€/y]**
sawdust feeding	179	5%	9
second blender	271	15%	41
one dewatering unit (16% TS)	357	10%	36
two dewatering units (18% TS)	775	12%	93
Leachate disposal	0	0%	0
Leach. pasteurization	381	7%	27

The greater investment consists in the purchase and installation of the double dewatering unit, that also includes the piping works to connect the digester to the machines to the blender. The greater maintenance cost, in percentage terms, is the blender, because it is the most susceptible to impurities brought by the green waste.

Table 51: fixed costs for each configuration.

cases	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***
Investment Costs [k€]	0	271	357	739	179	451	954	1336
amortized investment costs [k€/y]	0	14	18	37	9	23	48	67
Maintenance Costs [k€/y]	0	41	36	62	9	50	102	129

The investment and maintenance costs of each configuration are computed as the sum of the costs for each component that is additional with respect to the initial layout. The values of Table 50 are multiplied by the values of Table 47 to obtain the configurations costs of Table 51. The major costs correspond to cases 4 and 8, with the larger number of extra components.

Operational costs are differentiated for winter and summer.

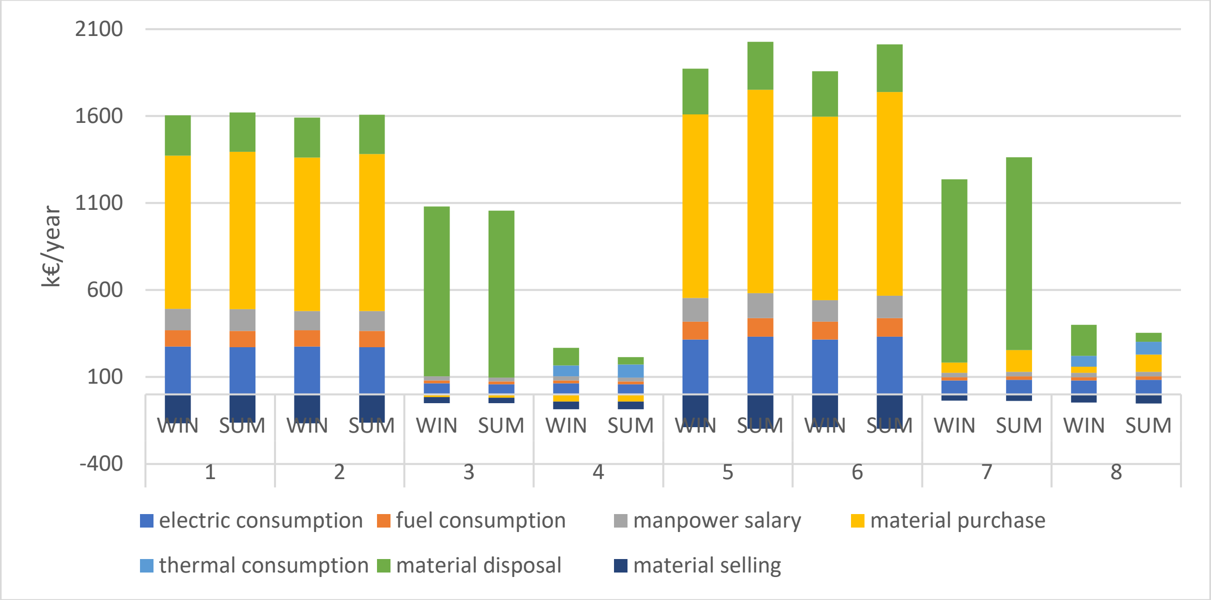


Figure 44: variable costs for each configuration in winter and summer operations.

General considerations:

- The most significant item is the material disposal cost, mainly related to dewatering filtrate in cases 3 and 7, reason why it would be convenient to install the pasteurizer.
- Closely following the material purchase cost, associated with the green waste required in the blending section, being a major entry in cases 1, 2, 5, and 6. Such configurations do not imply dewatering, have liquid digestate, require a lot of blending additives and generate large volumes to be composted.
- The same cases show a relevant electricity cost, mostly represented by the compost insufflation consumption, also linked to the large composting volumes to be aerated as showed in Figure 45.

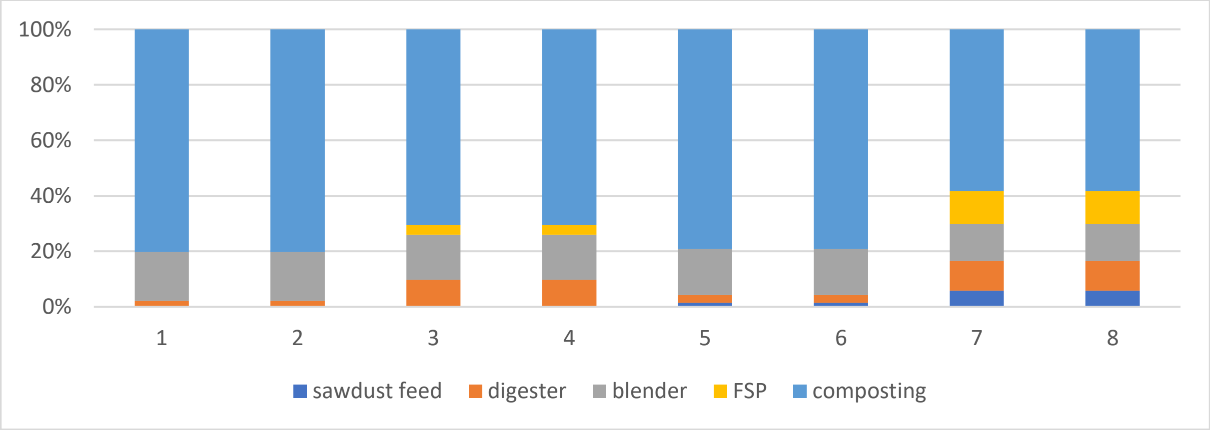


Figure 45: electricity costs share for each configuration.

- Higher material purchase and electricity costs are observed in cases 5 and 6, with respect to cases 1 and 2, because the sawdust feeding increases the volume of digestate to be structured, consequently boosting the composting volumes.
- The negative costs are the earnings from material sale, mainly compost, but having a negligible impact on the economics of the digestate post-treatment. With dewatering, the material purchase cost can be negative because the green waste conferral fee covers and exceeds the purchased expenditure.

Specific seasonal considerations:

- The material purchase cost is always higher in the summer version of the respective configuration, since the digester solid content is lower, requiring larger amounts of absorbing and structuring materials.
- The same cannot be said for the disposal costs, that are sometimes higher in winter because the pasteurizer treating capacity is lower, having less available thermal power.

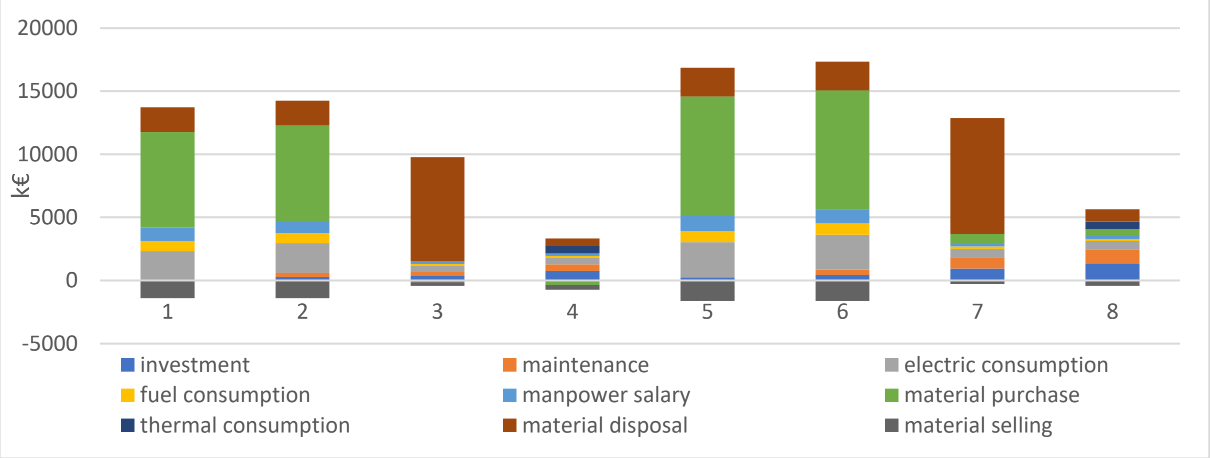


Figure 46: Net Present Cost for each configuration.

The total NPC is calculated as the sum of the investment and of the annuities on the plant lifetime, resulting in the graph of Figure 46.

- The lowest cost option is the case 4, with digestate dewatering and filtrate pasteurization, but without sawdust feeding. However, the FSP rejects 80% of the digestate mass flow rate and 65-75% of the solid content, therefore losing an important fraction of the organic matter that could have been recovered in the form of compost.
- Case 8 is the second-best configuration, it is not as competitive as case 4, but in the analysis the equivalent costs of sedimentation in the digester is not accounted, which can change the perspective.
- Cases 5 and 6 solve the issue of semi-wet conditions by processing a digestate at 18% TS but are not as convenient as expected. In fact, the limiting factor in

the blending recipe is the density of the digestate that does not change significantly with the solid content, and therefore the required green waste is as high as the base case.

- In every configuration the investment cost is negligible if compared to the operational costs, especially of material disposal and purchase.

6.4.4. Sensitivity analysis

A sensitivity analysis is performed on the total NPC, reducing the market price of green waste. The gate fee of 20 €/t conferral remains unchanged, and the plant still receives a earning for the first 3000 tons per year of received green waste.

Table 52: sensitivity analysis of total NPC at variation of green waste purchase price.

total NPC [k€]	1	2	3	4	5	6	7	8
GW 50 [€/t]	12325	12841	9330	2591	15209	15713	12584	5214
% reduction (0%)	0%	0%	0%	0%	0%	0%	0%	0%
GW 40 [€/t]	10879	11395	9296	2557	13437	13940	12368	4998
% reduction (20%)	-12%	-11%	0%	-1%	-12%	-11%	-2%	-4%
GW 30 [€/t]	9433	9949	9263	2524	11664	12168	12153	4783
% reduction (40%)	-23%	-23%	-1%	-3%	-23%	-23%	-3%	-8%
GW 20 [€/t]	7987	8503	9229	2490	9892	10396	11938	4567
% reduction (60%)	-35%	-34%	-1%	-4%	-35%	-34%	-5%	-12%

The response of NPC is always lower than the percentage of green waste price variation. NPC reduction is significant in cases 1, 2, 5, 6, being the configurations with the highest requirement of structing material, but it is enough to make dewatering inconvenient without a pasteurizer.

7 Conclusions

This work studies the operations and analyses the data of a dry-process biogas plant located in Apuglia, focusing on the specific problem of the semi-wet conditions in the digester, with the objective of answering the following research questions: what are the causes and the consequences of this issue in terms of technical and economic performances? Which are the plant modifications that could reduce the negative impacts on the plant profitability?

The main cause is identified with the digester preliminary design, combined with a delayed feeding ramp-up and an excessive removal of lignocellulosic fibres occurring in the pre-treatment. In fact, according to the mass conservation principle, the design does not allow to reach dry conditions, resulting in 9% TS digestate with the forecasted characteristics of the OFMSW. Simultaneously, the slow ramp up extended the HRT from a design value of 30 to an average of 45 days, favouring excessive hydrolysation and conversion of volatile solids, while the pre-treatment prevented the feeding of the solid slowly degradable matter that could counteract the excessive degradation phenomenon.

The consequences are observed in the digester and in the post-composting process. A low solid content of the digestate implies a low viscosity, leading to floating and sedimentation of light and heavy particles respectively, overall causing thermal and chemical stratification that might endanger the biological stability. A proof of the lack of homogenisation is the low representativeness of digestate samples extracted from different points of the reactor. A Plug Flow Reactor is not designed to handle the low viscosity, it is equipped with inadequate mixing equipment, and furtherly suffers from this condition.

A liquid digestate requires more absorbing and structural materials to reach a proper density and TS of the blended mixture sent to post-composting. This implies larger volumes to be handled, aerated, irrigated, and composted, not allowing for a sufficient composting time due to a limited space availability. With the nominal blender capacity, the duration of the blending cycles can reach 12 hours per day, requiring care of the plant personnel. Economically, a liquid digestate implies a heavy impact in terms of structuring material to be purchased at a high cost, together with the increasing handling and electric costs related to the larger volumes involved. Another major entry is the disposal fee of liquid and solid reject streams.

Solutions to limit the negative economic impacts on the post-composting can be applied upstream or downstream the digester. In the pre-treatment section, a separator can be installed to split the hammer mill reject in its plastics and organic fractions, to reduce the disposal cost of plastic reject and to recirculate the fibres in the blender recipe. Inside the reactor, the viscosity and solid content can be increased by feeding finely grinded gardening waste, to guarantee a 18% TS. Downstream solutions are the increase of blending capacity by installing a second blender, and the addition of a dewatering stage to separate a concentrated semi-solid stream to be sent to the blender. A pasteurizer can significantly decrease the disposal cost of dewatering filtrate.

Numerical results are obtained from the modelling of plant components and from the adoption of average data recorded on-site. A data inconsistency was found in the TS and VS content of the organic waste, possibly due to volatilization of degradable matter during the measuring procedure. An underestimation of up to 30% makes the values incompatible with either the mass conservation equations of the models and with the digestate TS measures.

Sawdust feeding equipment was sized to guarantee 18% TS in the digester at varying digestate conditions. The concentration in the digester should range between 6-8%, supplied with a daily sawdust flow comprised between 4 and 6 tons per day, with a maximum capacity of 20 t/d to account for extremely liquid conditions.

Economically, the installation of a reject separator is convenient, considering the huge disposal fee of contaminated plastics of 120 €/t. Then, considering eight possible plant configurations combining the installation of a second blender, a dewatering stage, and sawdust feeding, the aggregated differential costs are calculated and compared. The gate fee of the collected OFMSW and the earnings from biomethane sale are not considered since they are the same for each case.

The least-expensive configuration involves a dewatering stage and a pasteurizer, to upgrade the contaminated filtrate to an End of Waste soil conditioner; the sawdust feeding is not included. Despite being the best option economic-wise, the FSP rejects 80% of the digestate mass flow rate and 65-75% of the solid content, therefore losing an important fraction of the organic matter that could have been recovered in the form of compost.

The injection of finely grinded green waste does not appear as convenient as expected, because it increases the digestate volume discharge, and it does not influence the density, that is the limiting factor in the definition of the structuring material requirement of the blending recipe.

Limitations of the modelling are the missing spatial characterisation of the digester model, which leads to the assumption of material homogeneity, incorrect in a Plug Flow Reactor (PFR), and unable to represent the biochemical dynamics along the HRT. Regarding the economic analysis, it is reported the lack of methodologies to evaluate the impact of complex phenomena such as the sedimentation and stratification in the digester, which could give further economic value to the sawdust feeding strategy. Another useful implementation would be the combined reliability of the installed components, since a higher number of machines increases the risk of failure and associated cost of unforeseen stop.

Direct implications for the plant owner are the recommendation to install the reject separator, and to include the pasteurizer in the dewatering stage planning, since the investment of nearly 400 k€ is recovered in half a year by avoiding 900 k€/y of filtrate disposal cost. It is suggested to test the partition of dewatering, with different fractions of the digestate flowing into the FSP, analysis the effects on the blending of a mixture of cake and liquid digestate.

Further research valuable for the plant owner is an accurate characterisation of the digestate TS-density correlation to better estimate the economic impact of varying the blending recipe. A punctual study on the C/N ratio of the blended ingredients and mixture could improve the quality of the composting process. Sawdust feeding must be accurately evaluated by considering the impact on the biochemical processes and the equivalent avoided cost of solving the sedimentation issues. A deeper study of the solid content (TS, VS) measuring procedure could be carried out to obtain more coherent data.

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A Appendix A

Table 53: soil activity sampling of the maturation aisles.

aisle	CH4 [%]	CO2 [%]	O2 [%]	H2S [ppm]	temp [°C]	Comments
1.1	0	0.45	20.7	1	25	Burned on the surface, biological death
1.2	0.02	0.28	21.0	0	28.1	Compact, hard clods, with mushrooms and roaches
1.3	0	0.55	20.6	0	41.1	Softer, with vapour release
1.4	0	0.3	20.5	0	30.5	More compact on surface, without vapour release
1	**0.01**	**0.38**	**20.7**	**0.00**	**33.23**	
2.1	0	0.4	20	0	29	Fresh material, little vapour
2.2	0.01	0.6	20	0	41	
2.3	0	0.5	20.3	0	37.5	Very compact, little vapour
2.4	0	1.5	18.7	0	45.5	Lot of plastics, without vapour
3.1*	20-35	35-50	0,1-0,3	100-300	26.5	*First measurements showed very high CH4 content
3.1	0.3	0.7	20.5	2	26.5	Extremely fresh and wet material, full of flies.
3.2	0.1	0.5	20.5	1	30.5	
3.3	0.07	0.41	20.45	1	64.5	Much drier and fibrous material, without plastics, with high temperatures and significant vapour relase
3.4	0.03	0.36	20.35	1	77	
4.1	0.12	0.26	20.49	1	78.8	Soft soil, with many plastics
4.2	0.05	0.24	20.44	1	65.6	Darker and softer soil
4.3	0	0.26	20.44	1	62.7	White stains (mold/ashes) on the surface, clods
4.4	0.02	0.3	20.42	1	69.7	Dry, fibrous, little vapour release, mushrooms
4	**0.05**	**0.27**	**20.45**	**1.00**	**69.20**	
5.1	0.16	0.25	20.53	0	57.3	Very dirty material, lots of plastics, significant vapour release
5.2	0.22	0.25	20.53	0	48.4	
5.3	0.21	0.25	20.53	0	51.1	
5.4	0.18	0.26	20.53	0	51.5	
5	**0.19**	**0.25**	**20.53**	**0.00**	**52.08**	
6.1						Soft, loamy, clean soil, without plastics, little vapour release, presence of mushrooms roaches and spiders.
6.2						
6.3	0.24	0.25	20.48	0	76.6	
6.4	0.19	0.25	20.5	0	66.6	
7.1						Very similar to the previous aisle, 6,7, and 8 make up a plateau
7.2						

7.3						
7.4						
8.1						
8.2						
8.3						
8.4	0.04	1.43	19.35	0	52	
9.0						Hammer mill reject in biodrying
10.0						
11.1						missing
11.2	0	10.12	7.62	1	41	Woody, structured, and compact soil
11.3	0.02	5	16	1	37.5	Compact soil with spiderwebs
11.4	0.27	18.27	3	2	51.1	Softer soil, most biologically active part of the area
12.1	0.02	0.48	20.83	0	48.6	Fresh, soft, humid soil, high vapour release.
12.2	0.02	4.55	15.1	3	71.1	
12.3	0.03	1.17	19.58	1	51.7	
12.4	0.04	6.3	13.47	1	67.5	
compost .1	2.08	26.94	0.01	89	49.2	Biologically active material without oxygen and very high methane content
compost .2	6.4	30	0.01	46	43.7	
compost .3	1.1	27	0	121	65	
compost .4	8.4	33.1	0	89		
compost	**4.50**	**29.26**	**0.01**	**86.25**	**52.63**	

Except for aisle 11, the composting piles do not show a significant carbon dioxide production, symbol of an aerobic oxidation carried out by the microbial community. The piles are heterogeneous, with fresh, humid material with multiple forms of fungal and animal life, and dry, structured, fibrous material, conglomerated in compact clods and presenting white stains on the surface, possibly ashes generated from self-combustion.

Finished compost, unexpectedly, shows an almost null oxygen content, with very high methane and carbon dioxide composition, as well as high temperatures up to 65°C.

Table 54: Weekly average feeding conditions and biogas production.

	VS feed [t/d]	ORG feed [t/d]	OLR [kgVS/m3d]	HRT [d]	biogas prod [m3/d]	biogas prod [t/d]	biogas yield [m3/tVS]	biogas yield [m3/tORG]
8-giu-22	1.2	5.8	0.7	248.6	538.8	0.7	455.8	93.0
15-giu-22	1.8	10.6	1.1	135.9	1980.9	2.5	844.3	153.8
22-giu-22	3.7	21.7	2.3	66.5	3384.7	4.2	885.5	155.2
29-giu-22	4.8	28.4	3.0	50.7	4616.6	5.8	915.3	158.4
6-lug-22	4.9	20.7	3.0	69.6	4354.9	5.4	945.3	176.3
13-lug-22	7.6	32.6	4.8	44.2	6688.9	8.3	906.8	184.4
20-lug-22	5.4	23.1	3.4	62.4	5027.4	6.3	909.8	197.5
27-lug-22	8.1	34.3	5.0	42.0	7252.8	9.0	898.4	210.7
3-ago-22	4.4	24.0	2.7	60.0	5960.8	7.4	978.1	218.8
10-ago-22	2.8	15.4	1.8	93.4	3442.5	4.3	1049.3	224.0
17-ago-22	5.6	30.4	3.5	47.3	5013.2	6.3	1041.5	208.1
24-ago-22	8.4	45.8	5.2	31.5	8486.0	10.6	1084.6	198.1
31-ago-22	6.6	36.2	4.1	39.8	8308.8	10.4	1081.5	197.5
7-set-22	4.8	19.5	3.0	73.8	6628.4	8.3	1123.2	215.5
14-set-22	4.9	20.1	3.1	71.6	5681.4	7.1	1179.0	239.3
21-set-22	5.8	23.7	3.6	60.8	6295.9	7.8	1216.3	270.5
28-set-22	6.3	25.8	3.9	55.9	6321.8	7.9	1141.9	279.9
5-ott-22	5.2	24.4	3.3	59.0	8613.7	10.7	1209.0	286.5
12-ott-22	7.3	34.1	4.5	42.3	6507.8	8.1	1127.1	257.1
19-ott-22	7.1	33.2	4.4	43.4	6740.1	8.4	1087.9	240.0
26-ott-22	7.3	34.0	4.5	42.3	7496.0	9.3	1092.7	233.5
2-nov-22	6.7	23.0	4.2	62.5	5688.6	7.1	933.7	212.6
9-nov-22	11.0	38.0	6.9	37.9	6595.8	8.2	828.6	206.8
16-nov-22	9.7	33.5	6.1	42.9	7635.6	9.5	792.3	213.3
23-nov-22	9.0	31.2	5.6	46.1	6844.7	8.5	736.1	212.8
30-nov-22	6.3	21.9	4.0	65.7	4680.3	5.8	714.6	206.6
7-dic-22	7.8	28.6	4.9	50.4	4901.1	6.1	732.2	208.7
14-dic-22	8.6	31.5	5.4	45.7	7158.9	8.9	742.6	208.2
21-dic-22	6.8	25.0	4.3	57.6	6101.1	7.6	773.3	213.4
28-dic-22	8.1	29.6	5.1	48.6	6789.6	8.5	797.6	217.4
4-gen-23	9.8	34.8	6.1	41.4	7712.1	9.6	833.9	229.6
11-gen-23	12.1	43.0	7.6	33.5	7499.5	9.4	763.0	212.3
18-gen-23	13.3	47.0	8.3	30.6	8591.6	10.7	706.9	198.1
25-gen-23	13.6	48.1	8.5	29.9	8479.5	10.6	662.0	186.7
1-feb-23	14.1	49.9	8.8	28.9	8843.9	11.0	630.2	177.8
TOTAL	7.9	31.6	4.9	45.5	6196.1	7.7	927.1	220.9

Table 55: operating costs of the plant configurations differentiated for winter and summer.

	1		2		3		4		5		6		7		8	
	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM	WIN	SUM
electric consumption	**275**	**271**	**275**	**271**	**63**	**58**	**63**	**58**	**316**	**332**	**316**	**332**	**80**	**84**	**80**	**84**
sawdust feed	0	0	0	0	0	0	0	0	5	5	5	5	5	5	5	5
digester	6	6	6	6	6	6	6	6	9	9	9	9	9	9	9	9
blender	48	48	48	48	11	9	11	9	53	55	53	55	11	11	11	11
FSP	0	0	0	0	2	2	2	2	0	0	0	0	9	10	9	10
composting	221	217	221	217	44	41	44	41	250	263	250	263	47	49	47	49
fuel consumption	**93**	**94**	**93**	**94**	**17**	**17**	**17**	**17**	**103**	**108**	**103**	**108**	**19**	**20**	**19**	**20**
green waste	16	16	16	16	3	3	3	3	18	19	18	19	3	3	3	3
compost mix	77	78	77	78	15	14	15	14	85	89	85	89	16	17	16	17
manpower salary	**124**	**125**	**112**	**113**	**24**	**23**	**24**	**23**	**136**	**142**	**123**	**129**	**25**	**27**	**25**	**27**
blender cycles	24	24	12	12	5	4	5	4	26	27	13	14	5	5	5	5
g.w. Movim.	17	18	17	18	3	3	3	3	19	20	19	20	3	3	3	3
comp. Movim.	82	83	82	83	15	15	15	15	91	95	91	95	17	18	17	18
material purchase	**882**	**903**	**882**	**903**	**-16**	**-20**	**-40**	**-40**	**1056**	**1170**	**1056**	**1170**	**59**	**124**	**35**	**98**
g.w. Conferral	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60	-60
g.w. Purchase	836	863	836	863	20	20	20	20	987	1095	987	1095	95	158	95	158
irrigation w.	106	101	106	101	24	20	0	0	129	135	129	135	24	26	0	0
thermal consumption	**0**	**0**	**0**	**0**	**0**	**0**	**63**	**74**	**0**	**0**	**0**	**0**	**0**	**0**	**63**	**74**
pasteurizer	0	0	0	0	0	0	63	74	0	0	0	0	0	0	63	74
material disposal	**230**	**227**	**230**	**227**	**976**	**959**	**100**	**43**	**261**	**275**	**261**	**275**	**1054**	**1108**	**178**	**51**
FSP	0	0	0	0	930	916	54	0	0	0	0	0	1005	1057	129	0
oversieve	230	227	230	227	46	43	46	43	261	275	261	275	49	51	49	51
material selling	**-166**	**-163**	**-166**	**-163**	**-33**	**-31**	**-45**	**-46**	**-188**	**-198**	**-188**	**-198**	**-35**	**-37**	**-47**	**-53**
compost	-166	-163	-166	-163	-33	-31	-33	-31	-188	-198	-188	-198	-35	-37	-35	-37
soil condit.	0	0	0	0	0	0	-12	-15	0	0	0	0	0	0	-12	-16

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List of Symbols

Variable	Description	SI unit
$\boldsymbol{M}$	Mass flow rate	kg/s
$\boldsymbol{V}$	Volumetric flow rate	m^3/s
$\boldsymbol{m}$	Mass	kg
$\boldsymbol{TS}$	Total Solid content	-
$\boldsymbol{VS}$	Volatile Solid content	-
η_{rem}	Removal efficiency	-
ρ	Density	kg/L
$\boldsymbol{BGP}$	Biogas potential	m^3/kg

List of Abbreviations

Acronym	**Abbreviation of**	**Unit (if any)**
ACM	Ammendante Compostato Misto (mixed composted soil improver)	
ACT	Active Composting Time	
AD	Anaerobic Digestion	
BGP	Biogas Potential	[m^3/ton]
BMP	Biomethane Potential	[m^3/ton]
C/N	Carbon to Nitrogen ratio	[-]
CHP	Combined Heat and Power	
COD	Chemical Oxygen Demand	[ml/L]
CRF	Capital Recovery Factor	
CSTR	Continuous Stirring Tank Reactor	
DDM	Degraded Degradable Matter	[%]
DIG	Digestate	
DM	Dry Matter	[%]
EOW	End of Waste	
EU	European Union	
FOS	Flüchtige Organische Säure	[mgCH3COOHeq/L]
FSP	Filter Screw Press	
GHG	Green House Gases	

HM	Hammer Mill	
HRT	Hydraulic Retention Time	[d]
LCA	Life Cycle Assessment	
LCFAs	Long Chain Fatty Acids	
LHV	Lower Heating Value	[J/m^3]
MFR	Mass Flow Rate	[kg/s]
MSW	Municipal Solid Waste	
NPC	Net Present Cost	[€]
NPV	Net Present Value	[€]
O&M	Operations and Maintenance	
ODM	Organic Degradable Matter	[%]
OFMSW	Organic Fraction of Municipal Solid Waste	
OLR	Organic Loading Rate	[kg$_{VS}$/m^3/d]
OPEX	Operational expenditure	
ORG	Treated organic waste	
PFD	Process Flow Diagram	
PFR	Plug Flow Reactor	
RDS	Rate Determining/Limiting Step	
TAC	Totales Anorganisches Carbonat	[mgCaCO3eq/L]
TK	Total Potassium	
TKN	Total Kjeldahl Nitrogen	
TOC	Total Organic Carbon	
TP	Total Phosphorous	

TS	Total Solid	[%]
VFAs	Volatile Fatty Acids	
VFR	Volumetric Flow Rate	[m^3/s]
VOC	Volatile Organic Carbon	
VS	Volatile Solid	[%]
WtE	Waste to Energy	
WWTP	Wastewater Treatment Plant	

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