Economically sustainable system for multi-waste management: the "Mixed Plant" concept

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Abstract

The pace of life in today's society has led to an increase in the consumption of resources, particularly those with a short lifecycle. This in turn has resulted in an exponential increase in the quantity of waste going to landfill. In parallel to this, intensified livestock farming has meant an increase in livestock waste, which represents a serious environmental problem if not managed appropriately.

This paper proposes a simultaneous solution to the two problems through the application of a new waste management strategy based on the technological development and practical implementation of the "Mixed Plant" concept. The ultimate aim of this model is to reduce costs associated with waste treatment processes, thereby optimizing waste management, not only from the environmental perspective, but also from the financial point of view. To this end, it is proposed: 1. Treatment, in the same installation, of different types of waste: municipal, industrial, biomass; 2. Energy and mass integration of individual waste treatment processes to obtain a single integrated process more sustainable; 3. Comprehensive recovery of waste as energy (biogas, syngas and carbon pellets) and slow-release fertilizers (struvite). The "Mixed Plant" concept thus becomes a clear exponent of the circular economy model.

Keywords

Circular economy, heat recovery, two-phase anaerobic digestion, pyrolysis, struvite crystallization.

Introduction

In 2014, the total waste generated in the EU-28 by all economic activities and households amounted to 2,503 million tonnes; this was the highest amount recorded for the EU-28 during the period 2004-2014. Municipal waste (MW) accounts for only 8.3 % of total waste generated, however, it has a very high political profile because of its complex character, due to its composition, its distribution among many sources of waste, and its link to consumption patterns [1].

Nearly half (47.4 %) of the waste generated in the EU-28 in 2014 was landfilled. A further 36.2 % of the waste was sent to recovery operations (recycling). Just over one tenth (10.2 %) of the waste treated in the EU-28 was backfilled, while the remainder was sent for incineration, either with energy recovery (4.7 %) or without (1.5 %). Significant differences could be observed among the EU Member States concerning the use they made of these various treatment methods [2]. Focusing on MW, even though more waste is being generated in the EU-28, the total amount of municipal waste landfilled has diminished. For the period 2005-2016 landfilling has fallen by as much as 5.9 % per year on average.

In order to push this trend, the European Commission has adopted a very ambitious Circular Economy Package and has consequently revised many legislative proposals on waste. The new targets include achieving a recycling rate of 65% by 2030 and imposing a cap on landfilled waste to no more than 10% (as a percentage of weight [3].

This reduction can partly be attributed to the implementation of European legislation, for instance Directive 62/1994 on packaging and packaging waste. Furthermore, Directive 31/1999 on landfill stipulated that Member States were obliged to reduce the amount of biodegradable municipal waste going to landfills. The Directive has led to countries adopting different strategies to avoid sending the organic fraction of municipal waste to landfill, namely composting (including fermentation), incineration and pre-treatment, such as mechanical-biological treatment (including physical stabilization). As a result, the amount of waste recycled rose from 25 million tonnes (52 kg per capita) in 1995 to 71 million tonnes (141 kg per capita) in 2016 at an average annual rate of 5.1 %. The share of municipal waste recycled overall rose from 11 % to 29 %.

Different MW treatment options have different type of impacts; however, environmental soundness of the technology should be accounted in the long time perspective. Pyrolysis and gasification are the technologies which have lower environmental impact than the traditional incineration process. MW pyrolysis and gasification are in development, stimulated by a more sustainable waste-to-energy option. Dong et al. [4] showed that pyrolysis and gasification, in particular coupled with a gas turbine/combined cycle, have the potential to lessen the environmental loadings. The benefits derive from an improved energy efficiency leading to less fossil-based energy consumption, and the reduced process emissions by syngas combustion. This study indicates that the heterogeneity of MW and syngas purification technologies are the most relevant impediments for the current pyrolysis/gasification-based waste-to-energy.

These technologies are also interesting when applied to biomass. Biomass is considered as a renewable energy source because its supplies are not limited [5]. While biomass biological processing is usually very selective and produces a small number of discrete products in high yield using biological catalysts, thermal conversion often gives multiple and often complex products, in very short reaction times with inorganic catalysts often used to improve the product quality or spectrum [6].

Thermal treatment has been applied for thousands of years for charcoal production but it is only on the last 30 years that fast pyrolysis at moderate temperatures of around 400-500 ºC has become of considerable interest. This is because the process directly gives high yields of subproducts which can be used directly in a variety of applications [7].

In parallel to this, intensified livestock farming has meant an increase in livestock waste, which represents a serious environmental problem when managed inappropriately. Animal-based protein consumption has surged worldwide over the last 50 years, rising from 61 g per person per day in 1961 to 80 g per person per day in 2011, and this trend continues nowadays [8]. Such a large increase in demand for livestock products will require more than the simple adaptation of current livestock waste managing and treatment practices as they exist in developed countries.

A wide range of technologies are potentially available to treat manures [9] but few were adopted at farm level on a large scale mainly because of two reasons: high investment and operating costs without an equivalent return to the farmer, and their complexity for the livestock operator [10].

In general, waste is currently treated at specific centers or plants depending on the type of waste in question (livestock, municipal, industrial, etc.). It is not common to treat different waste streams at the same facility meaning that treatment synergies are not availed of. But treatment facilities are complex systems of unit operations and streams, so it is crucial to gain general insights into how mass and energy flow throughout the process and to use these insights as a consistent basis for developing cost-effective waste management solutions [11].

Mass and energy integration strategies are in the focus of many industries because of the economical and environmental benefits they provide [12-14]. In the area of sustainable design, mass and energy integration can be used to lower the consumption of fresh resources and to reduce, and even eliminate, the waste materials discharged to the environment. The objective of an integrated system is to be both, economically and environmentally sustainable. The main advantage of process integration is to consider a system as a whole (i.e. integrated or holistic approach) in order to improve its design and operation.

In this respect, the most innovative aspect of the proposal outlined herein is the sustainable management of a wide range of waste at a single facility, a “Mixed Plant”. The design of this plant includes the identification of energy and mass sources and sinks in order to meet the energy needs of some stages with the energy generated in others, thereby achieving an optimal energy balance in the overall system, and, on the other hand, to valorize all the secondary streams generated during the operation. This cannot be achieved in the same degree when the different waste types are treated at separate plants, as is commonly the case.

This study investigates the advantages of two-phase anaerobic digestion for treating a mixture of livestock and agri-food wastes coupled with of a low-temperature catalyzed pyrolysis system for treating waste biomass and plastic waste. Biogas and syngas are the main products of this integrated approach but also secondary streams as digestate and char will be valorized in the process looking for generating not only energy but also economic revenue.

Proposed technological concept

As mentioned before, waste is usually treated at specific facilities depending on the type of waste managed (livestock, municipal, industrial, etc.), meaning that treatment synergies among the different categories of waste are not availed of. To face this situation, the “Mixed Plant” concept proposes the treatment and recovery, at the same facility, of a wide range of waste types: farm/livestock waste, industrial waste (plastic) and the non-recyclable fraction from waste treatment centers (Figure 1). For energy recovery, the inclusion of an anaerobic digestion system is proposed to convert easily biodegradable organic waste into biogas. Also, a thermo-chemical treatment system is included to transform the non-recyclable waste fraction into syngas.

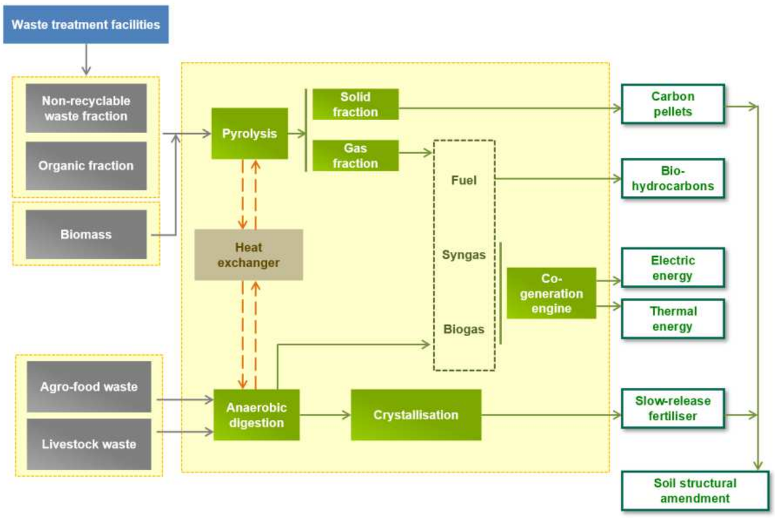

Figure 1. Process diagram with integration of energy and mass flows.

The biogas generated is cleaned prior to being used as a source of primary energy for a combined heat and power engine. Moreover, prior to use, it is mixed with the synthesis gas obtained as one of the by-products of the pyrolysis-torrefaction system. In this way, the blend of gases (biogas and syngas) is the primary fuel source for the CHP engine. Electrical energy and thermal energy are obtained by means of this waste-to-energy process. This is mainly used for the self-consumption of the plant, thereby reducing external energy dependence and ultimately reducing the overall energy costs of the facility. The surplus heat from the engine is mainly used to preheat the mixture to be co-digested prior to feeding the first reactor and, subsequently, to maintain the necessary heat in the digesters so that the temperature of the methanogenesis process is constant and practically independent of the external temperature.

The digest that leaves the methanogenesis reactor is sent to a crystallization block to be converted to struvite (magnesium ammonium phosphate). This process enables the combined recovery of phosphorus (an increasingly scarce element) and nitrogen from the effluent in the form of a compound that can be used in agriculture. Reuse of water and the liquid fraction generated in the process for consumption in the plant and surrounding areas (cleaning of farms, irrigation of crops, etc.) is also an objective.

Pyrolysis sub-products (as tar and charcoal) have been analyzed in order to study the possibility of its pelletization and use as an energy product.

Materials and methods

A pilot plant fulfilling the scheme appearing in Figure 1 has been designed and constructed in the facilities of the Municipal Waste Treatment Center of Botarell (Tarragona). The plant is prepared for the treatment of 1t h^{-1} of waste. The description of the different treatment lines is as follows:

Biological treatment line:

Two-phase anaerobic digestion is the system chosen for the anaerobic co-digestion of manure and other waste streams from the agro-food industry. There is evidence that a two-phase digestion design, where acidogenesis takes place in one digester and methanogenesis in another, with the two systems operating in series, can achieve up to 25% better operating performance than that of traditional digestion systems using perfectly mixed reactors [15-17]. The reason why this two-phase system works better is that the bacterial populations involved in the different stages of anaerobic degradation are very varied and require different development conditions (e.g., pH). This cannot be achieved in a single digestion tank. For this reason, the anaerobic digestion block comprises of a continuous stirred tank acidification reactor (AR, 450 mm inner diameter and 700 mm height), a continuous stirred tank methanogenic reactor (MR, 800 mm inner diameter and 1,200 mm height), and a digested effluent tank. The acidogenic and methanogenic reactors were constructed with 1:5 volumetric ratios to maintain shorter hydraulic retention time (HRT) in the AR as comparable with longer HRT in the MR. Both systems were fitted with thermostats, temperature control, pH, temperature and pressure sensors, gas flowmeter and variable speed mixing system.

Prior to entering the acidogenesis digester, the organic waste is shredded to favor contact with the microorganism (smaller size of waste = greater surface area exposed to microorganism = greater treatment effectiveness), and homogenized in a tank to provide a feed of uniform composition to the digestion system. For this reason, the organic waste pretreatment block includes a shredder and a homogenisation tank (800 mm inner diameter and 1,200 mm height), which can also be used to carry out the hydrolysis process outside the acidogenesis reactor should this be required by the process. Biogas production was monitored using two wet gas flow meters. Biogas composition was analyzed with a Varian CP-4900 Micro-GC with a thermal conductivity detector.

The digestate is conducted to a fluidized bed crystallization reactor for the production of struvite. The reactor has a total volume of 50 L and is composed of two concentric tubes (outer tube: 215 mm inner diameter and 1,900 mm height; internal tube: 160 mm inner diameter and 1,450 mm height) ending in a superior bagging to allow the sedimentation of the crystals.

Thermochemical treatment line:

The low-temperature catalyzed pyrolysis system is basically made up of a main block for thermal treatment in controlled conditions. The length of the rotary-kiln pyrolyzer is 0.85 m and its internal diameter is 0.30 m. In this study, the kiln rotation rate was adjusted to 3 rpm and temperature varied in the range from 350 to 550°C. The equipment developed in this work enables waste-to-energy by thermal treatment in the presence of specific catalysts, of: biomass of different types (forest or agricultural), organic waste (from cities, farms and/or non-food crops), plastics (of different composition), wood, paper and board, and tetra-brick. Ultimately, the system developed enables the energy recovery of urban waste (basically, a combination of all the aforementioned elements) and industrial waste, based on the pyrolysis-torrefaction-gasification process concept.

During the operation, the pyrolysis gases are sent to a cyclone to remove the particles contained in the syngas, and after this element, the syngas passes through a vertical condensing tower. The clean gas is recovered, and sent to the gasometer to be mixed with the biogas generated in the biological line, obtaining a gas-mix ready for use (directly or previously compressed in gas bottles).

For the waste streams and products, total and volatile solid concentration (TS, VS), chemical organic demand (COD), total organic carbon (TOC and TOC soluble), ammonium nitrogen, total Kjeldahl nitrogen (TKN and TKN soluble), phosphate, fat content, pH and conductivity were determined following Standard Methods [18] recommendations. Ammonium nitrogen and phosphate were analyzed colorimetrically with an UV-Visible Spectrophotometer (Shimadzu, UV-1603, Japan). Metals, macro and micronutrients were measured with an Inductively Coupled Plasma Optical Emission Spectrometer (Varian, 720-ES, US).

C, N, H and S contents in waste samples were determined by UNE-CEN/TS 15104 EX with a LECO Truspec CHN(S) elemental analyzer. Oxygen content was not measured directly but was estimated assuming that no other elements were present in the wastes.

The phytotoxicity index was determined through a mobility inhibition assay with Daphnia magna. *Salmonella* and *Escherichia coli* presence was analyzed by streaking on Petri dish.

Wastes intended for thermal treatment were previously submitted to a thermogravimetric analysis in a DTG-60H Shimadzu instrument (Japan) determining the lower and higher heating values (LHV, HHV).

Results

Biological treatment line

The digestion module has operated with a mixture of local waste streams: pig manure (PM), chicken manure (CM) and vegetable waste (VW), 40/40/20 w/w. The system started up with the addition of acclimated inoculum (70 L in the acidic reactor and 362 L in the methanogenic reactor) proceeding from an anaerobic digestion plant treating pig manure.

During the experimental period, the system operated in semi-continuous regime at a temperature of 35ºC, keeping the acidic reactor at an average pH of 5.5 ± 0.5 and a HRT of 2 -3 days, and the methanogenic reactor at an average pH of 7.2 ± 0.5 and a THR of 17 - 18 days.

After three months of operation the organic loading rate (OLR) introduced into the system was approximately 3 kg VS m^{-3} d^{-1} (Figure 2) with a volatile solids removal yield of 70% and a biogas production of 0.35 m^3 CH_4 per kg VS removed (Figure 3).

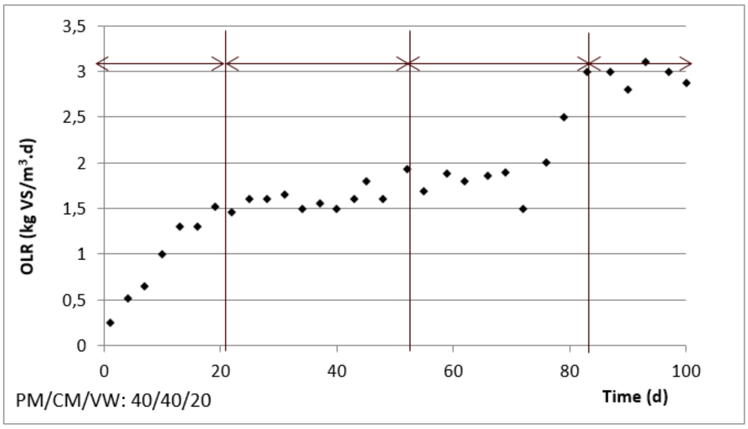

Figure 2. Organic load evolution during the experimental period.

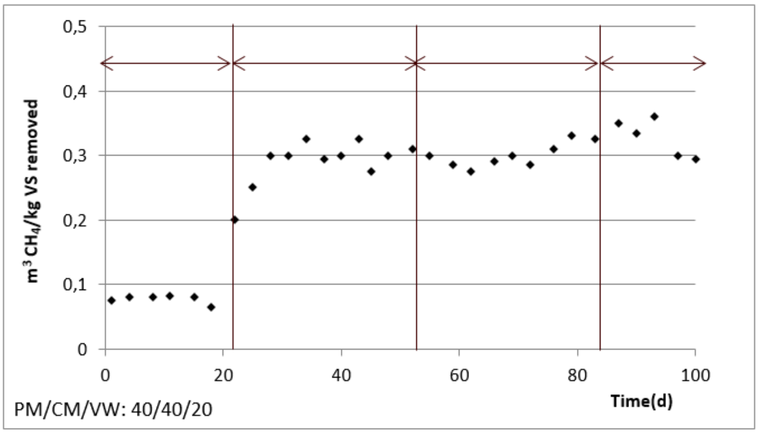

Figure 3. Methane production during the experimental period.

The biogas generated in the process has an average composition of 65% methane, 34% CO_2 and 1% other gases (H_2S <0.1%, H2 <0.5%, N_2 <0.4%). The energy content of this current is 6.0-6.5 kWh m^{-3}.

It should be noted that the process of anaerobic co-digestion of pig manure, poultry manure and vegetable waste showed a good behavior, without producing operational problems.

The obtained digestate was characterized in order to determine its potential as organic amendment (Table 1). The conclusion is that it is suitable for agronomic valorization. As it can be seen, it has a phytotoxicity of less than 25 Equitox m^{-3}, which means, according to, for example, Spanish legislation (legislation of the Community of Madrid (Law 10/1993), or of the Community of Murcia (Law 3/2000)) that this digestate can be considered as a non-toxic discharge for the environment. It is worth noting the total absence of *Salmonella* and *E. Coli*, the low content of metals and the presence of remaining organic matter and nutrients (N, K and P), which increases its potential value as a fertilizer.

Table 1. Digestate characterization.

Conductivity (mS cm^{-1})	14.91		K (mg L^{-1})	239
pH	7.75	**Macronutrients**	Ca (mg L^{-1})	815
COD (mg L^{-1})	6,870		Mg (mg L^{-1})	23
TOC (mg L^{-1})	1,917		Fe (mg L^{-1})	14.94
TOCs (mg L^{-1})	1,883		Co (μg L^{-1})	342
TKN (mg L^{-1})	688		Mn (mg L^{-1})	2.60
TKNs (mg L^{-1})	292	**Micronutrients**	Cu (μg L^{-1})	339
Nitrates (mg L^{-1})	13,07		Zn (mg L^{-1})	2.68
Nitrites (mg L^{-1})	7.36		Mo (μg L^{-1})	37.11
TP (mg kg^{-1})	137		Se (μg L^{-1})	47.23
C/N	2.8		Ni (μg L^{-1})	49.42
Fitotoxicity	< 25	**Heavy metals**	Cr (μg L^{-1})	22.52
Salmonella	nd		Cd (μg L^{-1})	< 10
Escherichia Coli	nd		Pb (μg L^{-1})	8.18

nd: not detected.

Struvite production

A series of experiments were performed in the crystallization reactor with the digestate proceeding from the two-phase anaerobic digestion to produce struvite under different operational conditions, as shown in Table 2.

Table 2. Design of experiments for struvite production at 20 ºC.

Experiment	**Ratio Mg/P**	**Ratio N/P**	**pH**	**Air flow (NL min^{-1})**
1	1.0	4.0	9.0	2.0
2	1.0	8.0	10.5	6.0
3	1.0	12.0	12.0	12.0
4	1.5	4.0	10.5	12.0
5	1.5	8.0	12.0	2.0
6	1.5	12.0	9.0	6.0
7	2.0	4.0	12.0	6.0
8	2.0	8.0	9.0	12.0
9	2.0	12.0	10.5	2.0

In addition to the digestate, the necessary amount of magnesium salt and phosphorus salt was added to the reactor in each experiment to fix the corresponding Mg/P and N/P ratio according Table 2. The magnesium salt used was $MgCl_2 \cdot 6H_2O$, while the phosphorus salt was $NaH_2PO_4 \cdot 12H_2O$. Finally, since the pH of the samples was around 7.5 it was necessary to add a concentrated alkali (50% NaOH solution) to raise the desirable pH value.

Once the reactor charge was finished, air was introduced in the system reaching the flow rate previously set. The system was operating during one hour. After this time, struvite crystals were harvested and dried at 55 ºC during 24 h. Figure 4 shows the reaction yield obtained for each experience. The yield is calculated taking into account the amount of crystal obtained and the amount that would theoretically be obtained for a crystallization reaction with 100% conversion. The quantity theoretically obtained has been calculated according to the stoichiometry of the reaction, with respect to the limiting reagent.

The highest yield obtained in the crystallization reaction has been for experiments number 5 (90.0%) and number 7 (95.4%). The most influential factors in the process are the Mg/P ratio and the pH. For the tested interval, the ratio N/P and air flow are the factors that influence to a lesser extent the process from the technical point of view, but from the economic point of view, the optimum values are N/P=8 and 2 NL min^{-1} flow rate.

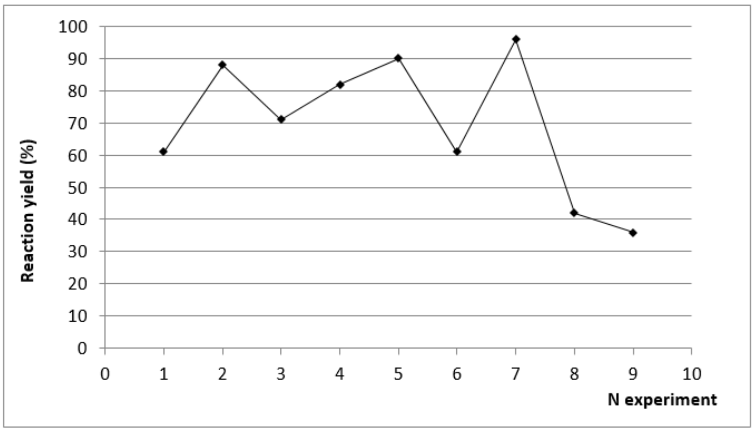

Figure 4. Struvite crystallization yield.

Thermochemical treatment line

The thermochemical line was fed with 50 kg h^{-1} of a mixture of waste streams with the following average composition: waste biomass 15%, organic fraction not suitable for anaerobic digestion 15%, plastic waste 50% and other industrial waste 20%. The mixture had a maximum particle size of 3 mm and 10% humidity and a LHV of 20,172 J g^{-1}. The Table 3 shows the elemental composition of the feeding entering the pyrolyzer.

Table 3. Elemental composition of waste mix entering the pyrolyzer.

% N	% C	% H	% S	% Cl	% O	% Ash
1.16	48.47	7.89	0.16	0.63	26.03	15.66

The product yields of solid, liquid, and gas from the process at an operational temperature of 420-450 ºC in the pirolyzer were, respectively, 9%, 4.8% and 86.2%, with an average energy consumption of 7.3 kWh. The analysis to the gas fraction reveals the composition gathered in Table 4.

Table 4. Pyrolisis gas composition.

Basic paramenters		Organic fraction (C1-C6)		Calculated parameters	
O_2	8 %	Methane	67.223 %molar	Gas specific density[1]	0.7218
H_2S	70 mg L^{-1}	Ethane	4.392 %molar	Gas real density[1]	0.9322
NH_3	< 1 mg L^{-1}	Propane	2.023 %molar	LHV (dry basis)	8.45 kWh m^{-3}
SH_2	7,300 mg L^{-1}	i-Butane	0.557 %molar	Higher Wobbe index	11.01 kWh m^{-3}
NO	250 mg L^{-1}	Butane	0.662 %molar		
NOx	250 mg L^{-1}	Î-Pentane	0.036 %molar		
TOC	30,900 mgC Nm^{-3}	Pentane	0.036 %molar		
CO	> 10.000 mg L^{-1}	Hexane and >C6	0.034 %molar		
CO_2	0.414 % molar	Nitrogen	24.623 %molar		
AOX	< 0.05 mg L^{-1}	VOCs	< 200 mg L^{-1}		

[1] The reference for the calculation is air density at 1 atm and 0 °C.

[2] The Higher Wobbe index (HWI) is defined as HHV.Gs$^{-1/2}$ where Gs is the gas specific density.

The Wobbe Index is a measure of the interchangeability of fuel gases and their relative ability to deliver energy. It gives an indication of whether a turbine or burner will be able to run on an alternative fuel source without tuning or physical modifications. Taking into account that the HWI for natural gas is around 15 kWh m^{-3} [19], the gas fraction generated in the pyrolyzer could be considered a gas fuel with good energy potential.

The analysis of the solid fraction that leaves the plant under the experimental conditions set has given the following average results: 58.31% C, 6.76% H, 12.70% O, 1.17% N, 0.26% S and Cl 1.06%. The LHV of this stream is 23,193 kWh kg^{-1}, which makes it a product with interesting energy potential as coal pellets.

Finally, the liquid fraction has a very low pH (around 1.2), what is justified by its composition, being benzoic acid (1,289 mg L^{-1}), acetic acid (1,710 mg L^{-1}) and fenol (689 mg L^{-1}) the main components of this stream, apart from water. This fraction is generated due to the water content in the raw waste entering the pyrolyzer (around 4 %).

Gas streams valorization

As it has been mentioned before, two gas streams are generated in the integrated process: biogas with an average content of 65% methane equivalent to an energy content of 6.0-6.5 kWh m^{-3}, and syngas with an average content of 67% methane, 4% of ethane, 2% of propane and 2% of other hydrocarbons, equivalent to an energy content of 8.5 kWh m^{-3}.

These streams, since they contain other components besides those cited that can affect the engine and shorten its useful life, cannot be sent directly to the engine. The solution is to submit them to a gas cleaning stage composed of a cyclone and a vertical condensing tower. The clean gas has the following characteristics: particulate matter content less than 5 mg m^{-3}, tar content less than 500 mg m^{-3} and H_2S content less than 50 mg m^{-3} what indicates that the gas is suitable for valorization in a combustion engine.

The engine used in this case is a commercial engine originally designed to work with compressed natural gas but that has been modified, in the frame of this research, to operate with the mixture biogas/syngas.

The initial tests of the engine fed with the syngas/biogas mixture have been positive since they have confirmed that the system is stable, maintains revolutions during the operation and that the electrical performance varies between 30 and 35%, which is equivalent to 2.5-2.9 kWh m^{-3} of renewable electricity generated, values similar to those obtained by other engines when operating with natural gas.

With these initial data it is estimated that the future energy production in the Mixed Plant by means of the valorization of the gaseous flows can cover more than 70% of the energetic needs of the whole facility.

Energy process integration

In order to study potential savings in the Mixed Plant by processes integration, a simplified Pinch analysis was carried out. The first was the identification of the process streams as hot and cold streams. The possible heat exchange will be limited by the approach temperature between them. In this case, the streams of the process and their thermal properties are shown in Table 5.

Table 5. Streams thermodynamic properties.

Stage	Stream	T out (ºC)	T in (ºC)	Mass flow (kg h^{-1})	Heat capacity (kcal kg^{-1} $ºC^{-1}$)	ΔH (kcal h^{-1})
Anaerobic digestion	Hot	37	20	0.83	1.199	6,99
Pyrolysis	Hot	400	20	500	0.336	63,000.00
Crystallization	Cold	20	37	0.81	1.199	-6.82
Gas cooling	Cold	37	400	360	0.295	-70,144.12

Using the Pinch analysis method, the energy integration of the main streams was achieved. Comparatively with the thermochemical line, the capacity of the anaerobic digestion stage is very small, so its energy input is low. Therefore, only the streams with sufficient energy potential to be used in a viable way have been taken into account (pyrolysis and gas cooling), for the energy integration study. The heat exchanged between the process streams was calculated and the minimum energy to provide as heating and to remove as cooling was determined, resulting 37,323.56 and 2,843.68 kcal h^{-1}, respectively. The temperature of closest approach between the hot and cold curves is 25 ºC (Pinch point). According the Pinch methodology, this temperature is where the design of the heat exchange network is most constrained, that is, where energy use optimization can be achieved by using heat exchangers to recover heat between hot and cold streams [20]. The temperature difference is minimal at the Pinch point (ΔT_{min}). According to the study carried out, the optimum value of the ΔT_{min} from a technical and economic point of view is 20 ºC.

Conclusions

During this work a new waste integrated management model, more environmentally and economically sustainable and easy to transfer to any location, has been developed. The "Mixed Plant" concept, including a biological treatment together with a thermal treatment, allows the management and valorization at the same facility, of a wide range of wastes. The energy integration of the main streams in the whole process leds to an optimization of the utility global consumptions. The model includes the generation of a gaseous stream of high

calorific power, mix of biogas and syngas, suitable for combustion engines. Also the following, results are possible to achieve:
- 70% saving of the costs of heat and electricity generation in the integrated system compared to traditional bio-digestion and pyrolysis operating in separate facilities.
- 100% valuing of the effluent produced in the anaerobic process as a slow release fertilizer, which offers advantages of reduced toxicity to plants and losses of nitrogen and phosphorus to the soil.
- 100% valuing of the products generated in the process of thermochemical treatment as coal pellets.
- To reduce, the environmental impact associated with the deposition in landfills of the non-recyclable fraction from waste treatment centres.

The results obtained from this study provide fundamental information for scaling up a high-performance integrated “Mixed Plant” in the future.

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