Environmental comparison of different scenarios of energy recovery from organic fraction of municipal solid waste and sewage sludge

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Abstract

Purpose. Two possibilities of biological treatments for organic substrates were considered: i) conventional co-digestion of source sorted organic fraction of municipal solid waste (SS-OFMSW) and sewage sludge (SS) (Scenario 1); ii) preliminary dark-fermentation of SS-OFMSW and SS, followed by a second step of anaerobic digestion (Scenario 2). The calculated environmental impacts were compared with the reference present case of aerobic bio-stabilization of SS-OFMSW and anaerobic digestion of SS (Reference Scenario).

Methods. The methodology adopted for the analysis and evaluation of the environmental impact of the waste treatments is the Life Cycle Assessment (LCA). The functional unit is the total annual amount of entering waste (SS-OFMSW and SS). For conciseness reasons, only values of calculated global warming indicator are reported.

Results. Global warming indicator for the co-digestion scenario is 3.21E+05÷6.39E+05 kg of CO_2 eq. (about 77-88% lower than the reference scenario), while values for dark fermentation scenario are 7.98E+05÷9.84E+05 kg of CO_2 eq. (about 71-64% lower than the reference scenario). The sensitivity analysis showed that the results are significantly influenced by assumed values for the specific gas production.

Conclusions. The simple co-digestion scenario has a better environmental performance in comparison to the case of co-fermentation scenario, mainly because the avoided impacts due to energy recovery and compost production are higher.

Keywords: co-digestion, dark fermentation, life cycle assessment, global warming, specific gas production, bio-hydrogen

1. Introduction

A significant capacity of anaerobic digestion (AD) lays in the wastewater treatment sector. Most of the conventional wastewater treatment plants (WWTPs) use AD for the treatment of the produced sludge by using digesters with spare capacity to face variation in wastewater flow and future population growth [1]. Due to low organic loading and low biogas yields of sludge, energy recovery via anaerobic digestion in WWTPs is typically not sufficient to cover its energy consumption. Anaerobic co-digestion (AcoD) of biodegradable waste with SS is nowadays considered one of the most strategic approaches in waste and wastewater management thus increasing the energy production, reducing costs and facilitating nutrient recycling [1–4]. Among the available substrates that have been tested for AcoD, the SS-OFMSW is an optimum co-substrate in order to improve digestion efficiency of SS because of its readily biodegradability nature [5]. Furthermore, the AcoD of these two substrates could be potentially suitable for biohydrogen production from dark-fermentation (DF). Indeed, due to their considerable alkalinity, SS could be used to control pH in the optimal range for biohydrogen production avoiding drops that can bring to the failure of the process when using only SS-OFMSW [6,7]. Most of the studies on DF were carried out on a laboratory scale with batch, semi-continuous or continuous reactors. No study has applied the DF process at industrial or full scale [8]. Limited studies have been done on pilot-scale applications of DF processes [9–12].

In this study, two possibilities were considered: conventional one-step co-digestion of SS-OFMSW and SS; preliminary dark-fermentation of SS-OFMSW and SS, followed by a second step of AD. In both the cases, energy recovery from the biogas and the hydrogen-rich gas were applied. The environmental impacts calculated for these scenarios were compared with the reference present case of aerobic bio-stabilisation of SS-OFMSW and anaerobic digestion of SS.

The Life Cycle Assessment (LCA) methodology was adopted for the analysis and comparison of the environmental impact of anaerobic waste treatments. Several LCAs studies have been published comparing different treatments of the organic fraction of the waste through AD: most assessed AcoD [13–15], while few evaluated the behaviour of the DF process in comparison with traditional treatment processes [16–18].

2. Materials and methods

The different possibilities were evaluated by LCA. The LCA analysis was carried out, then reported and described according to the LCA phases (EN ISO 14040:2006; EN ISO 14044:2006): goal and scope definition, inventory analysis, impact assessment and interpretation**.**

2.1 Goal and scope definition

Definition of the goal is the first phase of the LCA, in which the purpose of the study is described. It identifies and defines the object of the assessment. The purpose of this LCA is to compare the following three scenarios of treatment for SS-OFMSW and SS.

- ***Reference Scenario*****:** anaerobic digestion of SS (produced biogas is used in a boiler to provide thermal energy for the digester) and aerobic bio-stabilisation of SS-OFMSW;
- ***Scenario #1*****:** anaerobic co-digestion of SS and SS-OFMSW, use of biogas to produce electricity and heat by:
  Scenario #1-ICE: with an internal combustion engine (ICE) for biogas recovery;
  Scenario #1-Turb: with a gas turbine (Turb) for biogas recovery;
- ***Scenario #2*****:** anaerobic co-fermentation by DF process of SS and SS-OFMSW and AD of the dark fermentation residues, use of biofuels by:
  Scenario #2-ICE: where the produced hydrogen-rich gas from the DF is used in a molten carbonate fuel cell (MCFC), while the biogas from the AD is used in an ICE;
  Scenario #2-Turb: where the produced hydrogen-rich gas and biogas are both used in a gas turbine.

The LCA boundaries of the analysed systems include the alternative treatments, pre-treatments, energy production from biogas and from hydrogen-rich gas, transportation and final treatment (i.e. aerobic post-composting) and disposal of residues from the main processes. Inventory data for the production of biogas and hydrogen were retrieved from the experimental data for a specific study case. Within the system boundaries, the production processes for utilities, fuels, chemicals and manufactured materials entering the processes and the generated emissions are included. Impacts caused by the construction of plants are not included within the system boundaries. Recovered materials produced as outputs from the systems, for example compost, electricity and/or heat, were resolved by expanding the system boundaries to include avoided primary productions due to material and/or energy recovery from SS and SS-OFMSW [19,20].

The functional unit adopted for the treatment comparisons is the total amount of SS and SS-OFMSW that can be processed in one year, equal to 189 000 t/y of SS (0.7% TS, 70% TVS) and 15 500 t/y of SS-OFMSW (Table 1 shows the characteristics of the SS-OFMSW).

Inventories for the entering utilities, fuels, chemicals and manufactured materials entering the processes, for substituted products (electricity, fertilizers, inert, etc.), for final disposal of residues to landfill and for wastewater treatment were retrieved from Ecoinvent 3.0.

Table 1 - SS-OFMSW characteristics

SS-OFMSW characterization	%
Organic food	67.28
Organic (non-food)	2.72
Paper	3.60
Cardboard	6.00
High density plastics	2.00
Plastics films	6.00
Textile materials	0.40
Glass	4.00
Ferrous metals	1.00
Non-ferrous metals	1.00
Hazardous	1.00
Inert	5.00
TS waste in input	*37.00*
TVS waste in input	*68.00*

2.2 Inventory analysis

In this LCA phase, the life cycle inputs and outputs of the systems previously defined are collected to perform a quantitative description of flows of materials and energy across the system boundary. Inventory data are gained by modelling the processes and by using literature data and experimental laboratory data.

2.2.1 Reference Scenario

The SS-OFMSW, after a mechanical pre-treatment (bags opening and separation of undesired materials), is sent to the composting in order to produce a good soil improver (compost). For the mechanical pre-treatment process, specific consumptions of 15 kWh/t [21] and 1.3 liters of diesel per ton of processed waste are estimated [22]. The specific production of compost is assumed to be equal to 0.43 kg of compost per kg of SS-OFMSW

[23]. Even though green waste is required to provide the necessary structure to composting piles, here it was assumed not to consider its flow in addition to the process, according to the underlying assumption that it would be aerobically stabilised in any case (with or without the SS-OFMSW). The specific consumption assumed for the aerobic biological stabilization section is 38 kWh/t [22]. The SS, after a first phase of thickening, is directly sent to the anaerobic digester with a TS content of 2%, where the anaerobic reactions allow the production of biogas.

The composting process of digestate is modelled in a similar way to the SS-OFMSW aerobic stabilization (without, the initial phase of pre-treatment). Finally, a total amount of water input of 4100 m^3/y is considered for the polyelectrolyte preparation, which is required in the dewatering section (belt filter press) [24].

Table 2 - Operating parameters of the AD process in the Reference Scenario

Parameters	**Values**
Volume	3000 m^3 [24]
Hydraulic residence time (HRT)	17.84 d
Volumetric organic load (OLR)	0.85 kg TVS/m^3 d
Specific gas production (SGP)	0.289 Nm^3 biogas/kg TVS [5]
Biogas produced	733 Nm^3/d
Volumetric composition of biogas [24]	65% CH_4 0.5% H_2S 32% CO_2 2.5% H_2O
Lower heating value (LHV) biogas	22 750 kJ/Nm^3

For the AD of the sludge, the consumptions of electric energy (EE) and thermal energy (TE) are 111 MWh/y and 2058 MWh/y respectively [24]. Currently, the produced biogas is fed to a boiler producing TE, with 85% efficiency [25], which, however, fails to satisfy the TE demand of the anaerobic digester: 1428 MWh/y are produced and an additional contribution of natural gas equal to 630 MWh/y is estimated.

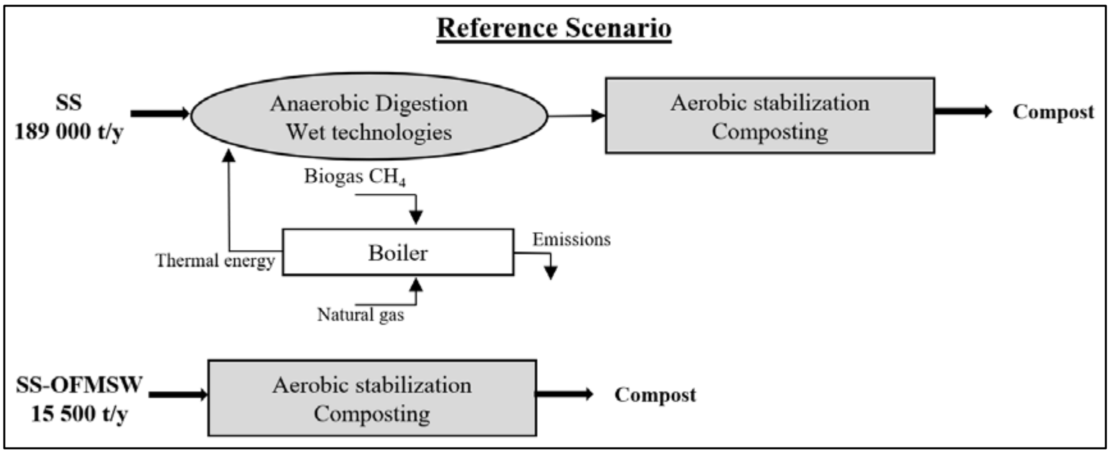

Figure 1 - Organic waste management system in the Reference Scenario

Table 3 - Summary of inventory data in the Reference Scenario

Input	Reference Scenario
Electric Energy [MWh/y]	1438
Natural Gas [MWh/y]	630
Water [t/y]	4100
Polyelectrolyte [t/y] *	14
Diesel [t/y]	17.03
NaOH [t/y] *	0.5
Output	
Electric Energy [MWh/y]	-
Thermal Energy [MWh/y]	-
Compost [t/y]	5930
Supernatant [t/y]	175 929
Waste [t/y]	5365
NO_x [t/y]	0.779
CO [t/y]	0.234
Biogenic CO_2 [t/y]	665
PM [t/y]	0.021

SO_2 [t/y]	0.142

*Polyelectrolyte is used in the dewatering process, NaOH is used for the biogas treatment

2.2.2 Scenario #1

The SS-OFMSW is pre-treated. First, it is processed by an extruder press, and then it is refined, separating mainly plastics and inert, before entering the AD. After the pre-treatment, the SS-OFMSW has 4.8% of TS content. In parallel, the SS moves towards the anaerobic tank with 5% of TS after the thickening.

The operating parameters of the digester are presented in Table 4; the outgoing digestate has a TS content of 2%. The SGP values reported in Table 4 were obtained separately for the SS and SS-OFMSW samples, by laboratory tests. As a matter of fact, the AcoD of SS and SS-OFMSW would lead to a single SGP value, which is expected to improve with respect to the average of the single SGPs. Unfortunately, this value is not available yet: the results will be updated as soon as it will be available from additional laboratory tests.

The final composting process of digestate is modelled in the same way as the Reference Scenario. Finally, a total input of water of 4100 m^3/y and diesel of 20 000 l/y are considered [24]. Diesel is necessary for the SS-OFMSW pre-treatment machines. The water is used for the polyelectrolyte preparation in the sections of dynamic thickening and dewatering (centrifugation), and for the washing of the SS-OFMSW treatment machines. The water consumption is the same as in the previous scenario, basically because the polyelectrolyte requirements are lower, since a more efficient device is here used for the dewatering process (centrifuge).

Table 4 - Operating parameters of the AcoD process in the Scenario #1

Parameters	**Values**
Volume	4500 m^3 [24]
HRT	20.69 d
OLR	1.95 kg TVS/m^3 d
SGP (SS)	0.289 Nm^3 biogas/kg TVS [5]
SGP (SS-OFMSW)	0.678 Nm^3 biogas/kg TVS [5]
Biogas produced	5540 Nm^3/d
Volumetric composition of biogas [24]	65% CH_4 0.5% H_2S 32% CO_2 2.5% H_2O
LHV biogas	22 750 kJ/Nm^3

As described in the scenarios definitions, two alternatives were assumed for the use of biogas:

- a 600 kW power ICE, with EE efficiency of 0.42 and TE efficiency of 0.43 [26];
- a 600 kW power gas turbine, with EE efficiency of 0.33 [27] and TE efficiency of 0.55 [24].

This two energy conversion systems will lead to distinct energy balances because of the different consumption of EE by the two devices and the different production of energy in terms of both EE and TE. Both the engine and the turbine can sustain the energy demands of the plant, allowing the self-sufficiency of the process, being the AcoD energy consumptions equal to 475 MWh/y of EE and 2620 MWh/y of TE, and providing net energy outputs, as reported in Table 5 [24].

For the composting process of digestate, the same specific consumption of the Reference Scenario (38 kWh/t) was assumed.

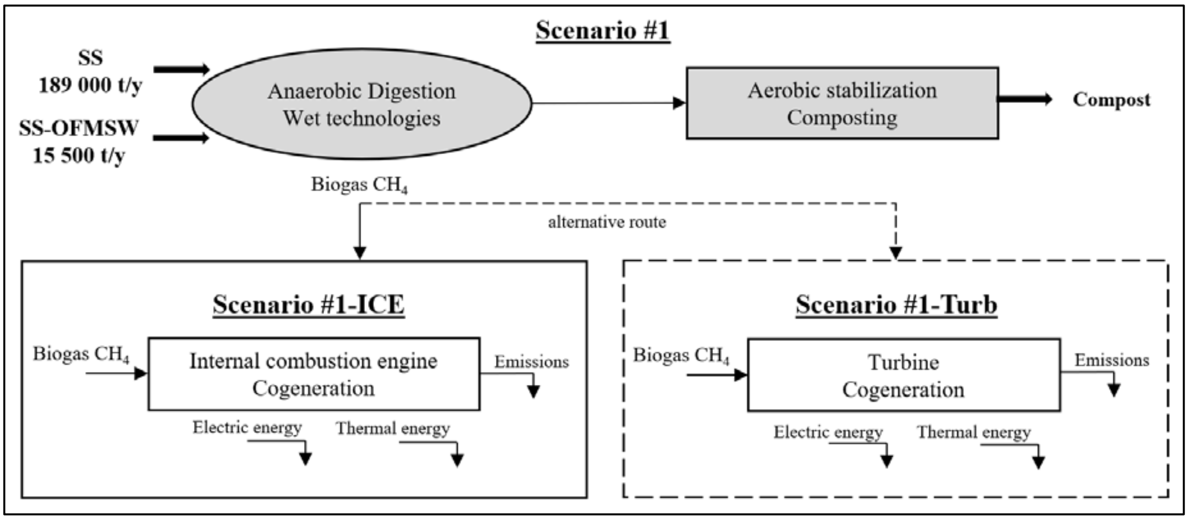

Figure 2 - Organic waste management system in the Scenario #1

Table 5 - Summary of inventory data in the Scenario #1

Input	Scenario #1-ICE	Scenario #1-Turb
Electric Energy [MWh/y]	196	196
Natural Gas [MWh/y]	-	-
Water [t/y]	4100	4100
Polyelectrolyte [t/y] **	19	19
Diesel [t/y]	16.91	16.91
AD13 [t/y] **	3.5	3.5
NaOH [t/y] **	1	1
Output		
Electric Energy [MWh/y]	2523	1518
Thermal Energy [MWh/y]	2348	3473
Compost [t/y]	2223	2223
Supernatant [t/y]	181 541	181 541
Waste [t/y]	5313	5313
NO_x [t/y]	0.458	0.033
CO [t/y]	1.519	0.183
Biogenic CO_2 [t/y]	2526	2526
PM [t/y]	0.035	0.138
SO_2 [t/y]	0.982	0.982

**Polyelectrolyte is used in the thickening and dewatering processes, NaOH and AD13 (mixture of water, carboxylic acids and iron trichloride) are used for the biogas treatment

2.2.3 Scenario #2

The introduction of a DF tank allows to produce hydrogen in the first step of the process. In the following table the operating parameters of the DF reactor are reported.

Table 6 - Operating parameters of the DF process in the Scenario #2

Parameters	**Values**
Volume	818 m^3 [5]
HRT	3.8 d
OLR	10.73 kg TVS/m^3 d
SGP (both SS and SS-OFMSW)	0.06 m^3 biogas/kg TVS [5]
Biogas produced	526.5 Nm^3/d
Volumetric composition of biogas [5]	45% H_2 65% CO_2
LHV hydrogen-rich gas	5 735 kJ/Nm^3

The introduction of the fermentative production of hydrogen step changes some values in the following AD step: HRT changes to 20.76 d, OLR becomes 1.80 kg TVS/m^3 d and biogas produced is 5102 Nm^3/d. For the DF process, a consumption of EE equal to 78 MWh/y and a consumption of TE equal to 2290 MWh/y are considered [24]. For the AD, the energy consumptions are 489 MWh/y of EE and 1007 MWh/y of TE. In this case, the energy recovery from the hydrogen-rich gas and the biogas can be accomplished, according to the two sub-scenarios reported in Figure 3, by:

- hydrogen-rich gas in a MCFC with an EE efficiency of 0.45 [5] (heat recovery by MCFC is not considered); biogas in a 600 kW power ICE, with EE efficiency of 0.42 and TE efficiency of 0.43 [26];
- hydrogen-rich gas and biogas in a 600 kW power gas turbine, with EE efficiency of 0.33 [27] and TE efficiency of 0.55 [24].

Both the configurations can sustain the energy demands of the plant, allowing the self-sufficiency of the process and the net energy output

For the composting process of digestate the same specific consumption of the Reference Scenario equal to 38 kWh/t was assumed.

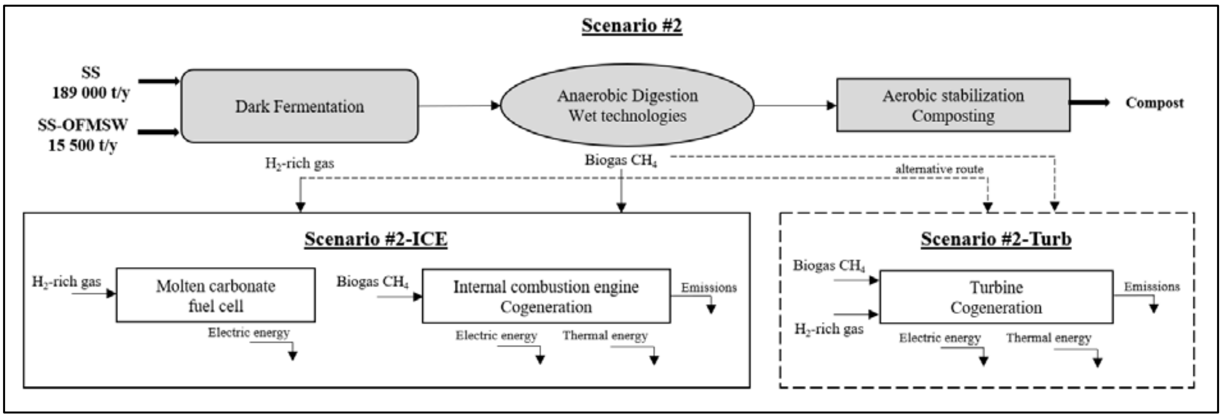

Figure 3 - Organic waste management system in the Scenario #2

Table 7 - Summary of inventory data in the Scenario #2

Input	Scenario #2-ICE	Scenario #2-Turb
Electric Energy [MWh/y]	185	185
Natural Gas [MWh/y]	-	-
Water [t/y]	4100	4100
Polyelectrolyte [t/y] ***	18	18
Diesel [t/y]	16.91	16.91
AD13 [t/y] ***	3	3
NaOH [t/y] ***	1	1
Output	Scenario #2-ICE	Scenario #2-Turb
Electric Energy [MWh/y]	2183	1215
Thermal Energy [MWh/y]	1279	2811
Compost [t/y]	2099	2099
Supernatant [t/y]	181 767	181 767
Waste [t/y]	5313	5313
NO_x [t/y]	0.422	0.030
CO [t/y]	1.399	0.169
Biogenic CO_2 [t/y]	2330	2330
PM [t/y]	0.032	0.127
SO_2 [t/y]	0.904	0.904

***Polyelectrolyte is used in the thickening and dewatering processes, NaOH and AD13 (mixture of water, carboxylic acids and iron trichloride) are used for the biogas treatment

2.2.4 Avoided energy production and stack emissions

The produced energy is primarily used to satisfy the needs of the processes, while the electrical surplus is fed into the electricity grid and the thermal surplus is supposed to be sold to a thermal user located near the plant.

The Ecoinvent records used for inventory of the EE and TE are *Electricity, medium voltage {IT}* and *Heat, central or small-scale, natural gas {Europe without Switzerland} | heat production, natural gas, at boiler modulating <100kW.*

The stack emissions for the energy conversion devices were calculated according to the characteristic emission factors reported in the next table.

Table 8 – Energy conversion devices emission factors

Emission	Boiler	ICE	Turbine
NO_x	4480 kg/(10^6) Nm^3 CH_4 [28]	250 mg/Nm^3 [26]	18 mg/Nm^3 [27]
CO	1344 kg / (10^6) Nm^3 CH_4 [28]	8.29E-04 kg/Nm^3 [29]	100 mg/Nm^3 [27]
CO_2*	2.75 kg CO_2/kg CH_4	2.75 kg CO_2/kg CH_4	2.75 kg CO_2/kg CH_4
PM	121.6 kg/(10^6) Nm^3 CH_4 [28]	1.91E-05 kg/Nm^3 [29]	115.2 kg/(10^6) Nm^3 CH_4 [30]
SO_2*	1.88 kg SO_2/kg H_2S	1.88 kg SO_2/kg H_2S	1.88 kg SO_2/kg H_2S

*The emissions of CO_2 and SO_2 are calculated through the stoichiometric factor

For the global warming impact calculation, two types of CO_2 should be distinguished: **fossil CO_2**, deriving from the combustion of plastics, coal, oil, natural gas; and **biogenic CO_2,** emitted from bioenergy sources, such us renewable biomass, organic waste, and cuttings pruning. Bioenergy produces biomass combustion emissions that are considered carbon-neutral because carbon is generated by the natural carbon cycle. The biogas and hydrogen-rich gas in this study are of renewable origin, and the CO_2 produced by their combustion will not be accounted for global warming calculations. Under the current Kyoto Protocol and in accordance with several programs for greenhouse gas emissions, the potential of bioenergy to reduce greenhouse gas emissions is acknowledged.

2.2.5 Use of compost

For the compost obtained by the aerobic bio-stabilization of the different substrates (SS-OFMSW; SS digestate; SS-OFMSW and SS digestate, etc.), the characterization in terms of nutrients (nitrogen N, phosphorus P and potassium K) was not available for the specific cases. Additionally, no information was found about the eventual change in the content of N, P and K of the digestate before and after the composting process. For this reason, the composition in terms of N, P, K of the dry digestate was assumed for the deriving compost, too.

For the compost produced by the aerobic stabilization of the single SS-OFMSW in the Reference Scenario a typical distribution of nutrients from literature was considered.

Table 9 - Nutrient characteristics of the digestate and compost [31]

	N (as TKN) [g/kgTS]	P (as P_2O_5) [g/kgTS]	K (as K_2O) [g/kgTS]
Dry Digestate	50	40	4
SS-OFMSW Compost	18	30	18.5

According to current Italian situation, it was assumed that 25% of the produced compost is used in gardens substituting peat (1 m^3 of compost - 680 kg - substitutes 1 m^3 of peat - 300 kg), 68% is used in agriculture substituting mineral fertilisers (the amount was calculated on the basis of nutrient contents of the compost) and 7% in environmental reclamations without any substitution [32]. The Ecoinvent records used for the inventory of the peat and the nutrients replacement are *Peat moss {RoW}| peat moss production, horticultural use*, *Nitrogen fertiliser, as N {GLO}| field application of compost*, *Phosphate fertiliser, as P_2O_5 {GLO}| field application of compost*, *Potassium fertiliser, as K_2O {GLO}| field application of compost*.

3. Results and discussion

This section presents the results for the global warming impact (100-year time horizon, IPPC 2007). A more comprehensive Life Cycle Impact Assessment (LCIA) was performed using a well-established midpoint LCIA method - the CML-IA baseline V3.02 / EU25 method, developed by the Institute of Environmental Sciences of the Leiden University [33], but for conciseness reasons, only global warming is presented below.

The results for global warming per functional unit (the total annual amount of SS-OFMSW and SS) are reported in Table 10 for the various scenarios. Table 10 shows that the AcoD system has, in terms of avoided impacts, better behaviour than the co-fermentation system. At the same time, due to the net produced energy, the use of an engine presents better environmental performance than the use of a turbine.

Table 10 - Global warming results of the assessment

	Global Warming [kg CO_2 eq.] per total annual amount of SS-OFMSW and SS	Percent deviation compared to Reference Scenario
Reference Scenario	2.74E+06	-
Scenario #1-ICE	3.21E+05	-88%
Scenario #1-Turb	6.39E+05	-77%
Scenario #2-ICE	7.98E+05	-71%
Scenario #2-Turb	9.84E+05	-64%

Figure 4 shows the contributions of the sub-processes to global warming, for each scenario. The highest contributions to direct impacts (positive values) are given by landfilling of waste.
As it can be seen in Figure 4, the DF process in the co-fermentation scenarios implies higher impacts than the case of AcoD. This is because the DF tank integrated with the anaerobic digester for the biogas production requires more TE to maintain the process temperature. This affects the production of energy by the two different energy conversion devices and the resulting avoided impacts. The contribution given by the electric and thermal energy are respectively 6.12E-01 and 2.65E-01 kg CO_2 eq. per kWh of produced energy.

Moreover, the aerobic stabilization process may lead to avoided impacts due to the substitution of peat and nutrients. The peat substitution allows an avoided impact of 1.32E+00 kg CO_2 eq. per kg of peat replaced, about the nutrients 1.15E+00 kg CO_2 eq. per kg of N, 5.86E-01 kg CO_2 eq. per kg of P_2O_5, 4.57E-01 kg CO_2 eq. per kg of K_2O.

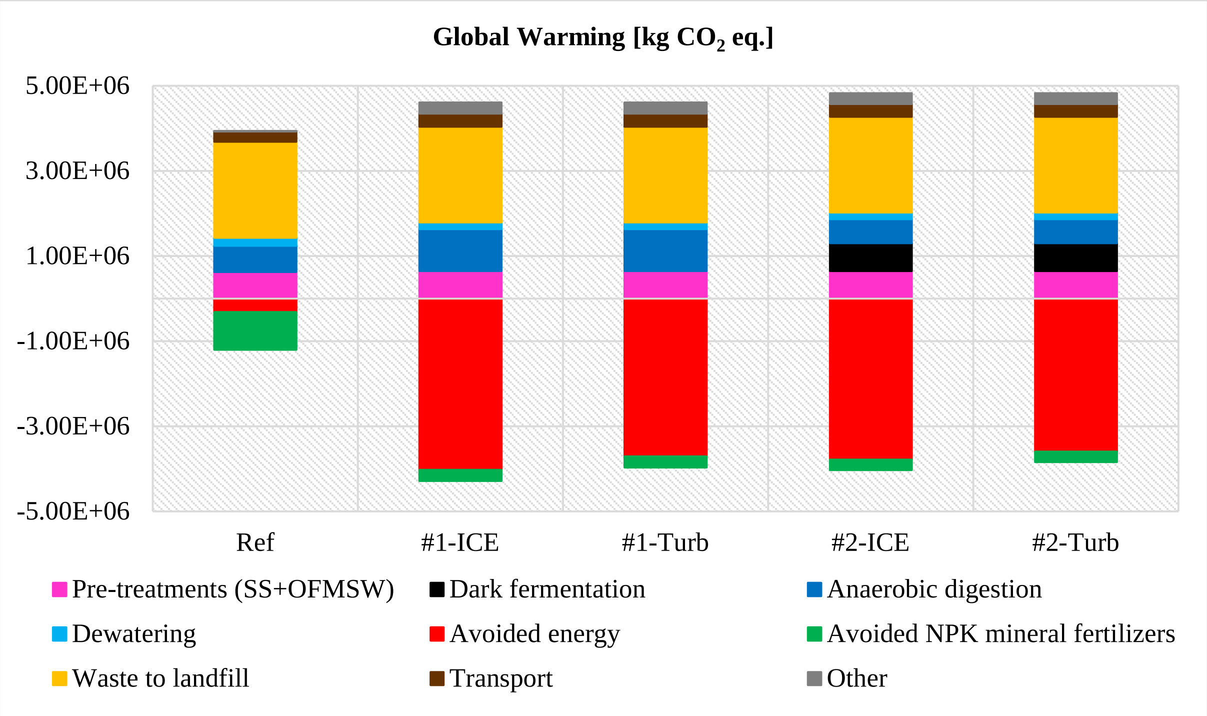

Figure 4 - Sub-processes global warming impacts

3.2 Interpretation and sensitivity analysis

In general, from the interpretation of the impact assessment it is possible to say that the use of an ICE involves higher emissions and a lower TE recovery compared to the use of a turbine (as it is possible to see in Figure 4); however, the generation of EE from an engine is much higher which will lead to a higher environmental performance from the ICE. In the co-fermentation scenario, the coupling of an ICE with a MCFC does not bring a significant benefit in terms of EE, on the contrary the production of electricity through MCFC is very limited. This is because the production of hydrogen-rich gas is not very high. From the comparison between the AcoD and the DF processes, it appears that the production of hydrogen-rich gas does not seem very advantageous. As a matter of fact, the energy recovery is lower and the amount of digestate sent to composting is lower as well, obtaining less compost and consequently less avoided impacts for the agricultural use.

The purpose of the sensitivity and uncertainty analysis is to verify how the results of the impact analysis respond to the variation of the values of some parameters whose uncertainty could have more marked effects on the obtained results. For example, in the field of AD and biological processes in general, working with experimental data on SGPs, by nature subject to variability especially related to the transition from a laboratory scale to a real scale, a sensitivity analysis on this parameter seems to be necessary, in order to better evaluate the possibilities of energy recovery both in terms of EE and TE.

3.2.1 Sensitivity Analysis to the Specific Gas Production (SGP)

A sensitivity analysis to the specific production of biogas and/or hydrogen-rich gas was performed to understand how robust are results conclusions. The values assumed in paragraph 2 for the SGP were obtained from laboratory tests and can be influenced by numerous factors that can vary the yield of the process. Table 11 shows the values of the SGP assumed in the sensitivity analysis. A variation of 10% was considered for the reference values (according to literature data [2][34]) used in section.

Table 11 - SGP variation

	Decrease -10%	Reference value	Increase +10%
Anaerobic digestion SGP [Nm^3 biogas/kgTVS]	0.568	0.631	0.694
Dark fermentation SGP [Nm^3 biogas/kgTVS]	0.054	0.06	0.066

Table 12 shows that higher SGP, there is lower global warming for all the cases. As a matter of fact, for an increasing of the amount of biogas/hydrogen-rich gas, the energy production is higher.

Table 12 - Sensitivity of global warming indicator with respect to a SGP +- 10% variation

	Global Warming [kg CO_2 eq.]		Difference of the percent deviation compared to the reference cases	
	Decrease -10%	**Increase +10%**	**Decrease -10%**	**Increase +10%**
Reference Scenario	2.74E+06	2.74E+06	-	-
Scenario #1-ICE	7.47E+05	-1.01E+05	+15%	-16%
Scenario #1-Turb	8.79E+05	4.00E+05	+9%	-8%
Scenario #2-ICE	1.17E+06	4.40E+05	+14%	-13%
Scenario #2-Turb	1.19E+06	7.81E+05	+8%	-7%

4. Conclusions

The LCA results show that the simple co-digestion scenario has a better environmental performance in comparison to the case of co-fermentation scenario, mainly because the avoided impacts due to electricity and thermal energy recovery are higher. Moreover, the amount of digestate sent to composting in the co-fermentation scenarios is also lower in the co-fermentation scenario, thus obtaining less compost and consequently leading to less avoided impacts. Among the compared cogeneration systems, the internal combustion engine has the best performance since the avoided impacts from energy recovery are higher (more electricity is generated for a similar amount of total energy), in spite of the internal combustion engine has higher stack emissions per unit of volume of combusted biogas. In general, the results show that all the scenarios of co-digestion and co-fermentation present energy self-sufficiency not requiring external energy supply. The sensitivity analysis showed that the LCA results are significantly influenced by the assumed values for the SGP. Some preliminary laboratory tests, performed in a semi-continuous reactor instead than in batch tests, already showed that the dark fermentation step can improve the performance of the following anaerobic digestion one, by increasing the SPG by about 15%. If such an increase will be confirmed in the future, the inventory data will be updated and an improvement in scenarios with dark fermentation is expected.

Acknowledgments

Bio2Energy project – funded by Tuscany Region (IT) – is fully acknowledged. Pedro Marques and Fausto Freire acknowledge support from the FEDER and *Fundação para a Ciência e Tecnologia* (FCT) in Portugal through projects PTDC/AGR-FOR/1510/2014 (POCI-01-0145-FEDER-016764) and PTDC/AAG-MAA/6234/2014 (POCI-01-0145-FEDER-016765).

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