Life cycle assessment and life cycle costing of advanced anaerobic digestion of organic fraction municipal solid waste

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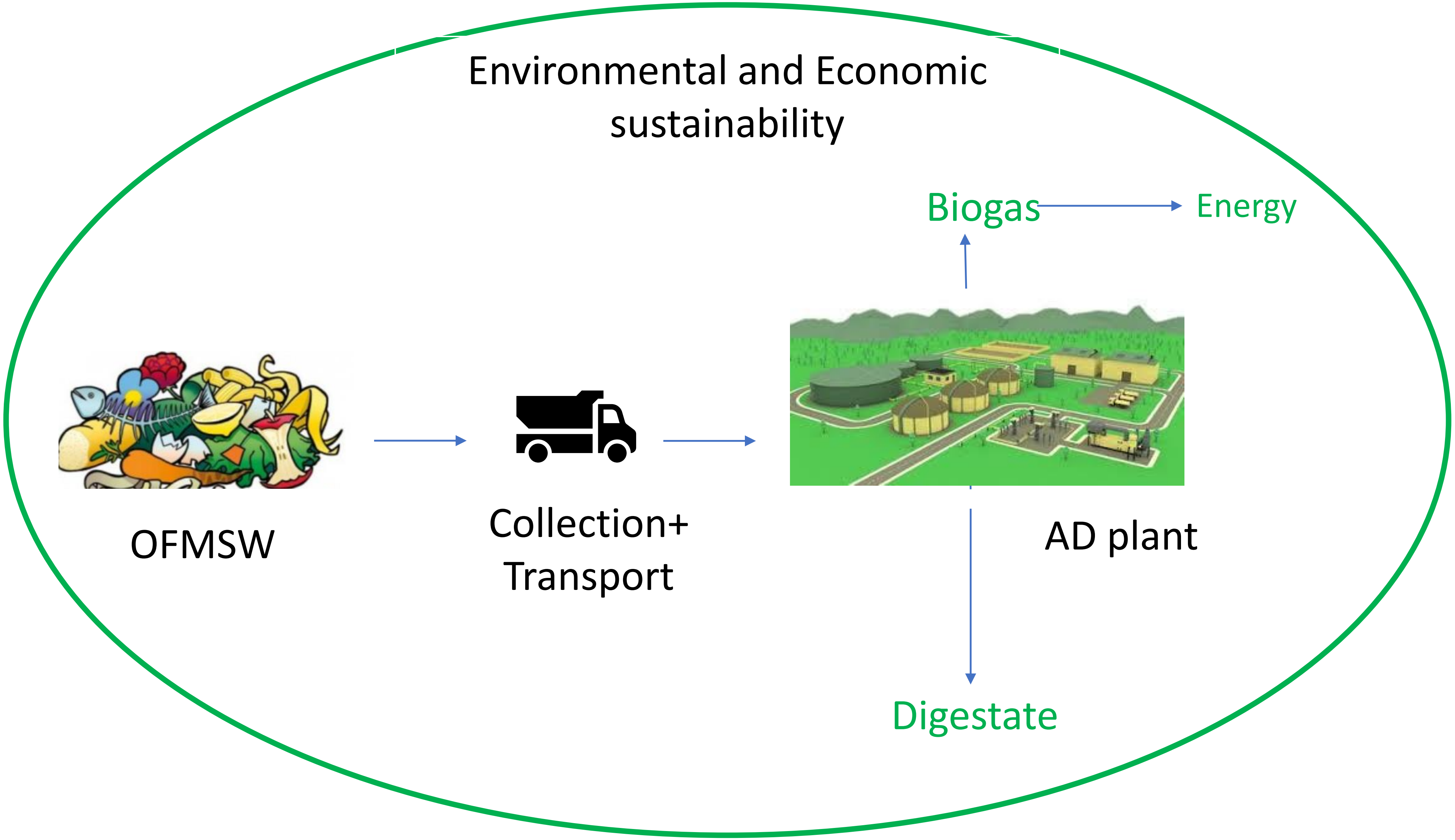
Highlights

- Environmental sustainability and economic profitability of anaerobic digestion (AD)
- Environmental impact drops by increasing S:I ratio and inoculum incubation time
- Capex and Opex drop by increasing the inoculum incubation time and the S:I ratio
- AD at the highest S:I ratio and inoculum incubation time reach the sustainability

Author contributions statement

Authors ‘contributions are detailed in the following. F. Demichelis carried out Life Cycle Assssment (LCA) and Life Cycle Costing (LCC) studies and writes part of the paper. T. Tommasi supported the study of LCA and LCC. F.A. Deorsola contributed to realise the conceptualization, methodology and data curation of the study and contribute to write and review the manuscript. D. Marchisio reviewed the manuscript. G. Mancini reviewed the manuscript. D. Fino realised the conceptualization, methodology and supervision of the study.

Graphical Abstract



Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Life cycle assessment and life cycle costing of advanced anaerobic digestion of organic fraction municipal solid waste

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Abbreviations

AD anaerobic digestion

CAS cow agricultural sludge

ESI energy sustainable index

LCA life cycle assessment

LCC life cycle costing

GWP global warming potential

MBT mechanical biological treatments

MSW municipal solid waste

NPV Net Present Value

OFMSW Organic fraction municipal solid waste

ROI Return On Investment

TS Total solids

VS Volatile solids

WAS Waste activated sludge

Abstract

The aim of this study is the evaluation of the environmental sustainability by means of Life Cycle Assessment (LCA) and economic profitability through Life Cycle Costing (LCC) of the 18 AD configurations carried out on Organic Fraction Municipal Solid Waste (OFMSW) at three S:I ratios (1:2, 1:1 and 2:1) for three different inoculum incubation times (0, 5 and 10 d). The adopted approach was the eco-efficiency perspective, coming from the combination of technical, environmental (LCA) and economic (LCC) perspectives. The main findings of the study were that increasing both the S:I ratio and the inoculum incubation time (5 and 10 days) the environmental impacts decreased, and economic profitability increased. In detail, the lowest values of Climate Change were achieved by the AD performed with both inocula WAS and CAS for 10 days at S:I equal to 2:1: 28.67 and 27.72 kg CO_2 eq respectively. The minimum AD plant size for which all the 18 AD configurations was economically profitable after 5 year of amortisation was 30,000 t/y of OFMSW. Capital and operational costs decreased by increasing the incubation time of the inoculum and the S:I ratio, since higher specific biogas rate was reached, and smaller AD bio-reactor volume were adopted because hydraulic retention time decreased.

The AD plant size, for which maximal revenues and minimal capital and operational costs were detected, was 50,000 t/y OFMSW. Among all the AD configurations, the environmental sustainability and economic profitability were reached by test perfomed with inocula WAS and CAS incubated for 5 and 10 d at the highest S:I ratio 2:1.

Keywords: organic fraction municipal solid waste (OFMSW), anaerobic digestion (AD), Life Cycle Analysis (LCA), Life Cycle Costing (LCC).

Introduction

In 2019, the production of Municipal Solid Waste (MSW) in Europe ranged from 280 kg per capita in Romania to 844 kg per capita in Denmark, and in Italy was equal to 500 kg per capita (Eurostat, 2021). In Europe, the Organic Fraction Municipal Solid Waste (OFMSW) represented an average of 27% of MSW, equal to a generation of 177 million tonnes (Eurostat, 2021). The traditional OFMSW treatments consist in mechanical biological treatments (MBT), thermo-valorisation, composting and anaerobic digestion (AD). Among them, anaerobic digestion (AD) is one of the most efficient and environmentally sustainable techniques for organic waste remediation and valorisation (Ardolino et al., 2018). OFMSW is considered as one of the major contributors to climate change, human health risk and ecosystem damages. OFMSW is a biodegradable waste and so it could potentially be employed in renewable energy production processes. AD of OFMSW is a very attractive option to convert the complex organic matter into a renewable and clean energy source, as biogas. AD is a biochemical process by which complex organic matter are transformed into simple soluble compounds in anaerobic environment. The main benefit of AD is the stabilisation of organic matter and pathogens by converting them into biogas under anaerobic condition. The biogas is a gas mainly made up of methane and carbon dioxide. In detail, AD is a multistep biological process made up of hydrolysis, acidogenesis, acetogenesis and methanogenesis. Hydrolysis is the first and rate-limiting step, since it must reduce both organic matter and high molecular compounds as carbohydrate, proteins and lipids respectively into sugars, amminoacids and fatty acids. The AD of OFMSW is generally carried out at liquid state condition, which means total solids (TS) ranged from 0.5 to 10%. In the present study liquid state AD was carried out, in detail at 6% TS. The AD of organic matter is an environmental sustainable technique since is a carbon neutral process, but it has disadvantages as long retention time, low removal efficiency organic compounds, strong sensibility to the variation of pH, alkalinity, temperature, retention time, nitrogen, carbon availabilities and Carbon Nitrogen (C:N) ratios which affects the AD process stability. To evaluate the environmental sustainability of AD process, several studies of Life Cycle Assessment (LCA) were carried out on AD performed with different organic waste as corn silage, dairy manure, food waste (Martinez-Sanchez et al., 2016) and agricultural waste (Ascher et al., 2020). LCA is a methodology to assess environmental impacts which covers all the life cycle of product and process. The aim of the present study is the evaluation of the environmental sustainability through Life Cycle Assessment (LCA) and economic profitability through Life Cycle Costing (LCC) of the AD configurations tested in (Demichelis et al., under review).

The adopted approach was the eco-efficiency perspective, coming from the combination of technical, environmental (LCA) and economic (LCC) perspectives. In (Demichelis et al., under review) mesophilic AD was performed on real OFMSW supplied by San Carlo Spa (Fossano, Italy) with two inocula, one coming from the mesophilic digestate of waste activated sludge (WAS) provided by SMAT (a wastewater treatment plant in the north of Italy), and the second from the mesophilic digestate of cow agricultural sludge (CAS) supplied by Cascina La Speranza (Candiolo, Italy) at three substrate inoculum ratios (S:I): 1:2, 1:1 and 2:1 for three inoculum incubation times: 0, 5 and 10 days. Two inocula with different origins were selected to improve the C:N ratio, in particular animal sludge matter provided enhancement of C:N and buffering capacity. The main output of the present study was the evaluation of optimal technical feasibility, environmental sustainability, and economic profitability of AD configurations to scale them at the commercial -industrial scales.

2 Materials and methods:

2.1. Environmental sustainability

Life cycle assessment was performed with SimaPro 9.0 software and it was based on ISO 14040 (2006) and 14044 (2006). Ecoinvent 3.0 was employed as database.

2.1.1 Goal and scope:

The goal of LCA was the evaluation of the best anaerobic digestion (AD) configurations among the 18 AD configuration tested in (Demichelis et al., under review).

In the present study, the concept of best AD configuration means the AD configurations which reached the highest technical-performances, the lowest environmental impacts and the highest economic profitability.

The functional unit (FU) was 1 t of wet OFMSW. The produced emissions, the consumed material and the required energy were referred to the FU. The choice of FU equal to 1 t of OFMSW allowed the comparison with other studies available in the scientific literature (Ascher et al., 2020). The boundary conditions included: the collection and the transport of OFMSW to the the AD plant, the transport of inoculum to the AD plant, the AD process and the CHP unit. The OFMSW was collected in the town and then transported to the AD plant.

According to (Demichelis et al., under review) AD was performed in batch feeding at 6%TS on real OFMSW supplied by San Carlo Spa (Fossano, Italy), with two inocula, one coming from the mesophilic digestate of waste activated sludge (WAS) provided by SMAT (a wastewater treatment plant in the north of Italy), and the second from the mesophilic digestate of cow agricultural sludge (CAS) supplied by Cascina La Speranza (Candiolo, Italy) at three substrate inoculum ratios (S:I): 1:2, 1:1 and 2:1 for three inoculum incubation times:

0, 5 and 10 days. Two inocula with different origins were selected to improve the C:N ratio, in particular animal sludge matter provide enhancement of C:N and buffering capacity. Hence, a total of 18 configurations of AD of OFMSW were tested. The AD was performed under mesophilic conditions 37°C with constant mixing at 300 rpm. AD has two outputs: biogas and digestate. The AD configurations adopted the following code: TX_Y_ZZZ, where X can be 0, 5 or 10 days representing the incubation time of the inoculum, Y is the S:I ratio, in detail 1 for S:I=1:2, 2 for S:I=1:1 and 3 for S:I=2:1and ZZZ represents the origin of the inoculum WAS or CAS. Biogas was sent to CHP unit to produce electric energy (η = 0.45) and heat (η = 0.55), while digestate was not valorised, in order to focus the attention only on the benefits coming from biogas-energy valorisation. The adopted approach was from cradle to gate according to (Wang et al., 2020).

2.1.2 Life cycle inventory (LCI)

The LCI defined all inputs and outputs involved in the processes. The primary data came from the study of (Demichelis et al., under review) and in Table 1 these data are scaled up to FU equal to 1 t of OFMSW with a correction factor 0.8 (Perry, 2008). The LHV of methane was assumed equal to 35.9 MJ/m^3 according to (Gonzàlez et al., 2020). In Table 1, six AD configurations were yellow coloured since they were energetically self-sufficient with Energy Sustainable Index higher than 1. The secondary data were taken from Ecoinvent 3.0. and reported in Table 2. According to (Brander et al., 2019) attributional LCA was applied. In detail, attributional LCA means a modelling approach by which inputs and outputs were attributed to the FU of a product system linking the unit processes of the system according to a normative rule. Collection and transport of OFMSW were equal to 20 and 30 km respectively, while the transport of inocula, both for WAS and CAS was equal to 20 km. Expansion system methodology was applied since electric and heat were re-integrated in the AD system.

2.1.3 Life cycle impact assessment (LCIA)

Life cycle impact assessment was performed with the ReCiPe Midpoint (H) method. The AD system was evaluated both as internal processes with energy productions and as external process including OFMSW collection, OFMSW and inocula transportations and energy consumption. Both internal and external processes affected global warming potential (GWP). In the present study, the analysed impact categories were: Climate change (kg $CO_{2\,eq}$), Ozone depletion (kg CFC-11 eq), Human toxicity, (kg 1,4-DB eq), Cancer effects (CTUh), Acidification (molc H+ eq), Terrestrial eutrophication (molc N eq), Marine eutrophication (kg N eq,) and Land use (kg C deficit). The attention will be focused on Climate Change, because in scientific literature several studies were available for comparison.

2.1.4 Interpretation data e sensitivity analysis

The last step of LCA was the interpretation of the results to evaluate the achievement of the goal. A double sensitivity analysis was performed to measure and detect possible variation of AD response on environmental impacts. The first sensitive analysis was performed varying selected parameters as kilometre of transport and collection of OFMSW, since recent studies prove that biomass yield density (t/ha·y) varied with biomass supply distance (km) from biorefinery plant location. In detail, the study of (Golecha et al., 2016) stated a mutual influence and dependency between biomass yield density (t/ha·y) and supply distance (km). The second sensitivity analysis for LCA section was applied changing the low heating value (LHV) of biogas of the 18 tested AD configurations from -2.5 to+2.5% of CH_4 (%v/v) content, according to (Wang and al., 2020).

	Biogas (NL/kgvs)	CH_4 (%)	CO_2 (%)	Inoculum (t)	OFMSW (t)	H_2O (m^3)	Energy produced (kWh)	Energy consumed (kWh)	ESI (-)	EE saved (kWh)	ET saved (kWh)
T0_1_WAS	762.5	64.67	35.33	4.4	1	0.1	106.27	326.7	0.33	-99.19	-121.23
T0_2_WAS	731.24	62.76	37.24	2.2	1	0.47	98.91	226.51	0.44	-57.42	-70.18
T0_3_WAS	708.12	62.53	37.47	1.1	1	0.65	95.43	182.89	0.52	-39.36	-48.11
T0_1_CAS	782.58	66.01	33.99	3.74	1	0.76	111.33	326.7	0.34	-96.91	-118.45
T0_2_CAS	755.89	64.84	35.16	1.87	1	0.8	105.63	191.66	0.55	-38.71	-47.32
T0_3_CAS	748.89	61.74	38.26	0.94	1	0.81	99.65	169.83	0.59	-31.58	-38.6
T5_1_WAS	818.52	61.8	38.2	4.4	1	0.1	109.03	274.43	0.4	-74.43	-90.97
T5_2_WAS	835.95	62.8	37.2	2.2	1	0.47	113.15	217.8	0.52	-47.09	-57.56
T5_3_WAS	932.06	64.5	35.5	1.1	1	0.65	129.57	128	**1.01**	0.71	0.87
T5_1_CAS	840.49	63.82	36.18	3.74	1	0.76	115.61	248.29	0.47	-59.71	-72.97
T5_2_CAS	859.49	65	35	1.87	1	0.8	120.41	165.53	0.73	-20.3	-24.81
T5_3_CAS	948.68	67.57	32.43	0.94	1	0.81	138.16	117.58	**1.18**	9.26	11.32
T10_1_WAS	849.69	67.9	32.1	4.4	1	0.1	124.35	287.5	0.43	-73.42	-89.73
T10_2_WAS	890.96	68.2	31.8	2.2	1	0.47	130.97	121.97	**1.07**	4.05	4.95
T10_3_WAS	994.2	69	31	1.1	1	0.65	147.86	117.58	**1.26**	13.63	16.65

T10_1_CAS	846.41	68.31	31.69	3.74	1	0.76	124.62	222.16	0.56	-43.89	-53.65
T10_2_CAS	892.2	69.85	30.15	1.87	1	0.8	134.32	121.97	**1.1**	5.56	6.79
T10_3_CAS	997.81	70	30	0.94	1	0.81	150.54	117.58	**1.28**	14.84	18.13

Table 1: Primary data of LCI based on (Demichelis et al, under revision) scaled up to the FU = 1t of OFMSW

Transport	Transport, freight, lorry 16-32 metric tons, Euro 6
Electricity	Electricity, high voltage (IT) electricity production oil
Heat	Heat, central or small scale, other than natural gas (CH), heat production at heat pump 30kW
Water	Water from natural resource

Table 2: Secondary data from Ecoinvent 3.0

2.3 Economic analysis

Economic feasibility was studied by Life Cycle Costing (LCC). LCC is an assessment of all costs related to the production of a product or service, considering the whole life cycle from production to usage until disposal. The LCC was carried out in three main modules: data collection, cost estimation and data interpretation. The target of LCC was the evaluation of the economic cost of the whole life cycle of anaerobic digestion process, with the aim to reduce and minimise the cost of production. In this study, the result of LCC is the definition of the economic dimension of the AD process. LCC was performed from the viewpoint of producers. According to LCA (paragraph 2.1.1), the same goal and scope, system boundary and functional unit were adopted to perform LCC to obtain an overall consistent analysis.

LCC was calculated considering capital investment, operational costs, profitability of the anaerobic digestion, Net Present Value (NPV), Return On Investment (ROI) and payback time. The LCC was performed on the minimum AD plant size for which economic profitability was achieved.

2.3.1 Capital cost evaluation

Capital cost (Table3) included the purchase of reactors and facilities for the construction and the installation. The cost of land was not considered since the analysis was not geo-referred. In fact, the target of the economic analysis was the evaluation of the economic profitability of the proposed AD configurations. The tax of interest was equal to 2% with a 5-years of amortization. The amortization was calculated with Eq. 1:

$$A(euro) = C_0 \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (1)$$

where A means the amortization cost, C_o is the capital investment, n the number of years of amortisation and i is the tax of interest.

Technique	Unit	Cost(Euro/unit)	References
Grinder	kg/s	2323.3	(Eurostat, 2021)
Bio-digestor	m^3	2514.7	(Gonzàlez et al., 2020)
Stirrer	kW	46465.3	(Akeberg et al., 2000)
Centrifuge	kg/s	116163.2	(Akeberg et al., 2000)
Heat exchanger	m^2	889.96	(Akeberg et al., 2000)

Table 3: List of capital costs.

2.3.2 Operational cost evaluation

The operational costs (Table 4) included the cost of the collection and transport of OFMSW to the AD plant, the maintenance of the equipment, the disposal of AD residues, the labours and the utilities necessary to run the processes as fuel, steam, heat and electricity.

Technique	Operation	Unit	Cost (Euro/unit)	References
Raw material	Collection of OFMSW	Euro/t	0.21	(ISPRA, 2021)
	Inoculum	Euro/m^3	2.10	(Demichelis et al., 2018)
Water and energy consumption	Process water	Euro/m^3	0.13	(Akeberg et al., 2000)
	Power	Euro/kWh	0.034	(Akeberg et al., 2000)
	Electric power	Euro/MW	5.24	(Wingre et al., 2003)
	Steam boiler	Euro/MW	72.80	(Wingre et al., 2003)
	Steam for AD process	Euro/kg	0.2	(Akeberg et al., 2000)
	Waste disposal	Euro/t	40.00	(ISPRA, 2021)
	Labor	Euro/year	44966.40	(ISTAT, 2021)

Table 4: List of operational costs.

2.3.3 Revenue and evaluation of profitability

The market value of electric energy is 0.20 euro/kWh and thermal energy of 0.201 euro/kWh (Eurostat statistic, 2021). The annual profit was the difference between the revenue and the sum of the amortisation and operational costs.

To complete the evaluation of the profitability the NPV, ROI and payback time were calculated.

NPV (Eq. 2) pointed out the profitability of the AD configuration considering a plant lifetime of 20 years considering a 5% discount for the future cash flows referring to the present value. According to (Pleissner et al., 2016), NPV > 0 means that AD process is profitable.

$$NPV\ (euro) = \sum_{t-1}^{T} \frac{C_t}{(1+d)^t} - C_0 \quad (2)$$

where, C_t is the net cash flow during period *t*, C_0 is the initial capital investment, *t* is the plant lifetime and *d* is the discount rate.

ROI (Eq. 3) was defined as key parameter to evaluate the performance of the profitability of an investment

$$ROI\ (\%) = \frac{Annual\ net\ profit}{Initial\ total\ investment} \cdot 100 \quad (3)$$

In details, to calculate ROI the annual net profit after 5 years of amortization was considered. Payback time states the time required to regain the funds expended in capital costs.

2.3.4 Economic sensitivity analysis

Two sensitivity analysis were performed. The first sensitivity analysis for LCC was performed as sensitivity for LCA, by changing the LHV of CH_4 of the 18 AD configurations tested from -2.5 to+2.5% of CH_4 (% v/v) content, according to (Wang and al., 2020). The second sensitivity analysis was performed by floating the CH_4 price of $\pm$20% according to (Li et al., 2020).

3.Results:

3.1 Environmental sustainability.

Life Cycle Assessment (LCA) was carried out on the 18 AD configurations tested in (Demichelis et al., under review) and the following impact categories were analysed: Climate change (kgCO_2 eq), Ozone depletion (kg CFC-11 eq), Human toxicity, Cancer effects (CTUh), Acidification (molc H+ eq), Terrestrial eutrophication (molc N eq), Marine eutrophication (kg N eq,) and Land use (kg C deficit). Global warming potential (GWP) was significantly affected by OFMSW management practices involving significant GHG emissions. The emissions due to collection and transport of OFMSW, AD of OFMSW and biogas utilisation were summed up. Conventional OFMSW managements were evaluated to underline the pros coming from to the proposed AD management. In details, incineration and landfilling achieved 107 kg CO_2 eq and 209 kg CO_2 eq, respectively, these results agreed with (Cremiato et al., 2018).

In the present study, the reduction of GHG emission was due to the use of produced biogas as thermal energy to heat the bio-digestor. This pro was detected in the AD configurations with Energy Sustainable Index (ESI) major than 1; the AD performed both with inocula WAS and CAS for incubation time of 5 and 10 d at S:I ratios equal to 1: 1 and 2:1 (Table 1, yellow coloured): T5_3_WAS, T5_3_CAS, T10_2_WAS, T10_2_CAS, T10_3_WAS and T10_3_CAS. In Figure 1, the GWP reached by the 6 AD configuration with ESI major than 1 was depicted considering the GWP contribute of each phase of AD process. The highest environmental items were OFMSW and inoculum transport, according to (Golecha et al., 2016).

Since the produced biogas was employed as energy vector part of electric and thermal energy were saved and negative Climate change values were evaluated. It is important to underline that many LCA studies about organic waste, food waste and OFMSW were performed in scientific literature, but it is challenging to make analogies and comparisons due to the different system boundaries, FU, and life cycle impact methodologies.

Moreover, the most adopted AD system is made up of the following units: AD unit, biogas utilisation with a biogas engine and digestate treatment as fertiliser. In the present study, digestate valorisation was not considered since the attention was focused only on pros and cons of biological waste to energy process based on the experimental results achieved in (Demichelis et al., under review). Table 5 depicts that increasing both the S:I ratio and the inoculum incubation time (5 and 10 days) the environmental impacts decreased, since higher amount of OFMSW was valorised and specific production of biogas with higher methane content was achieved. In details, the environmental impacts of AD performed both with inocula WAS and CAS at the lowest S:I (1:2) and lowest inoculum incubation time (0 days), were higher than the ones achieved by the AD performed both with inoculum WAS and CAS with the highest S:I (2:1) and the highest inoculum incubation time (10 days).

	Climate change	Ozone depletion	Human toxicity, cancer effects	Acidification	Terrestrial eutrophication	Marine eutrophication	Land use
Unit	kg CO_2 eq	kg CFC-11 eq	CTUh	molc H+ eq	molc N eq	kg N eq	kg C deficit
T10_3_WAS	28.67	3.9E-03	2.1E-07	0.15	0.20	0.02	50.17
T10_2_WAS	38.19	5.2E-06	2.8E-07	0.19	0.27	0.02	68.67
T10_1_WAS	82.61	1.1E-05	6.4E-07	0.45	0.61	0.05	129.27
T5_3_WAS	37.00	5.2E-06	3.0E-07	0.21	0.29	0.03	59.73
T5_2_WAS	62.36	8.0E-06	4.7E-07	0.34	0.45	0.04	88.75
T5_1_WAS	85.63	1.1E-05	6.2E-07	0.43	0.59	0.05	126.77
T0_3_WAS	50.71	6.4E-06	3.8E-07	0.28	0.37	0.03	68.48
T0_2_WAS	64.37	8.2E-06	4.8E-07	0.35	0.46	0.04	90.42
T0_1_WAS	94.67	1.2E-05	7.1E-07	0.51	0.68	0.06	136.78
T10_3_CAS	27.52	3.7E-06	2.0E-07	0.14	0.19	0.02	47.68
T10_3_CAS	36.33	4.9E-06	2.7E-07	0.18	0.26	0.02	63.96
T10_1_CAS	68.40	9.0E-06	5.1E-07	0.36	0.49	0.04	108.61
T5_3_CAS	30.38	4.1E-06	2.2E-07	0.16	0.22	0.02	50.05
T5_2_CAS	49.23	6.4E-06	3.7E-07	0.26	0.35	0.03	74.67
T5_1_CAS	74.43	9.7E-06	5.6E-07	0.39	0.53	0.05	113.61
T0_3_CAS	47.17	6.0E-06	3.5E-07	0.26	0.34	0.03	64.01

T0_2_CAS	55.25	7.1E-06	4.1E-07	0.30	0.40	0.04	79.67
T0_1_CAS	92.51	1.2E-05	6.9E-07	0.50	0.67	0.06	128.63

Table 5: Environmental impacts of the 18 AD configurations

In detail, the Climate change of AD with inoculum non incubated was + 69.98 %$\pm$ 0.37, Ozone depletion was + 68.29 % $\pm$ 0.24, Human toxicity was +70.61 % $\pm$ 0.40, the Acidification was + 71.41 % $\pm$ 0.47, Terrestrial eutrophication, was + 70.45 % $\pm$ 0.41, Marine eutrophication was + 70.48 % $\pm$ 0.41 and Land use was + 63.12 % $\pm$ 0.27, higher than AD performed with inocula incubated for 10 d at the highest S:I ratio (2:1). We focused more attention on Climate change, since it is the most studied impact category in scientific literature. For the Climate change impact category, the present study considered the contribution of biogenic carbon, with a factor of biogenic CO_2 equal to 1.

In the present study, the highest GWP values were reached by the following configurations: AD performed with inoculum WAS and CAS without incubation (0 day) at S:I ratio equal to 1:2: T0_1_WAS reached 94.67 kgCO_2/t OFMSW and T0_1_CAS achieved 92.51 kgCO_2/t. These results agreed with the study of (Ascher et al., 2020) who performed the AD of food waste both neglecting and considering the biogenic CO_2 and reached -97.27 and 140.50 kgCO_2 eq per 1 t of food waste and with the study of (Jin et al., 2015) which reached 96.97 kgCO_2/t of food waste in mesophilic liquid AD, with S:I ratio equal to 1:2. In Climate change category (Figure 1, in which are reported only the AD configurations with ESI >1), the inoculum played a key role, since decreasing the S:I ratio (1:2) the amount of inoculum increased, increasing the reactor volume and the CO_2 emissions rather than AD configurations with higher S:I (1:1 and 2:1). Moreover, increasing both the S:I ratio and the incubation time, the specific biogas production and the CH_4 content in the biogas increased, with a consequential decrease of CO_2 emissions and thermal energy required to heat the bio-digestor, since biogas was sent to CHP unit. The GWP values of T10_3_WAS and T10_3_CAS were 28.67 and 27.52 kg CO_2, respectively according to (Fei et al., 2021) which reached 29.24 kg CO_2 per 1 t of food waste treated with solid and liquid AD processes. The AD performed both with CAS and WAS incubated for 5 days at S:I equal to 1:2 (T5_1_WAS and T5_1_CAS) agreed with the study of (Fei et al., 2021) which reached 77.9 kg CO_2 per 1 t of food waste treated with solid and liquid AD processes.

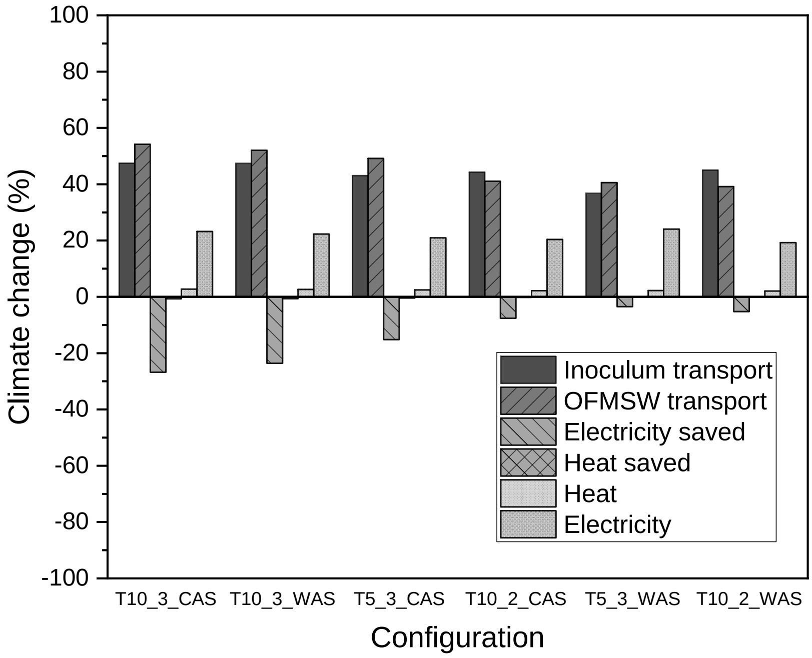


Figure 1: Climate change values of the AD configuration with ESI major than 1

According to (Ascher et al., 2020) the CHP unit contribute to GWP ranged between 20-30% of total GWP estimated.

Usually, dairy waste management consists in stockpiling and land application which caused 307 and 204 kg CO_2 eq per ton respectively, according to (Adghim et al., 2020). In the present study, 9 AD configurations adopted as inoculum the digestate coming from cow agricultural sludge (CAS) and the reached GWP witnessed the positive valorisation of both matrix CAS (as inoculum) and OFMSW (as substrate), which achieved a minimum GWP with T10_3_CAS (27.52 kg CO_2 eq) and maximum T0_1_CAS (92.52 kg CO_2 eq). Moreover, the AD performed with inoculum CAS achieved GWP lower than the one using WAS as inoculum, in the range of – 4.18 to – 16.51%. This trend was in line with the study of (Cristóbal et al., 2018).

Considering the ESI (Table 1) and Climate change values (Table 5 and Figure 1) of all AD configurations with ESI major than 1; the decrease of kgCO_2 eq emissions matched with the increase of ESI values. In terms of kg CO_2 eq released, the best AD configurations were AD performed with both CAS and WAS inoculum incubated for 10 day at S:I ratio equal to 2:1 (T10_3_CAS and T10_3_WAS), AD with both CAS and WAS incubated for 10 d at S:I ratio equal to1:1 (T10_2_CAS and T10_2_WAS), and AD with both CAS and WAS incubated for 5 d at S:I ratio equal to 2:1 (T5_3_CAS and T5_3_WAS). These trends agreed with multi-criteria decision ranking reported in (Demichelis et al., under review) performed with ELECTRE II. The AD performed both with inocula CAS and WAS at the highest S:I ratio (2:1) for the highest inocula incubation time (10 d) reached the lowest Human toxicity, Ozone depletion, Cancer effect, Acidification, Terrestrial eutrophication, Marine eutrophication, and Land uses values. These values agreed with (Fei et al., 2021). These outputs were due to the higher valorisation of OFMSW reached working at higher S:I ratio and the correct disposal of digestate. According to (Martinez-Sanchez et al., 2016) the main contribution to the above-mentioned impact categories was the application of digestate as fertiliser.

3.2.2 Environmental sensitivity analysis

Two sensitivity analysis were performed. The first sensitive analysis was performed varying the following parameters: kilometre of transport and collection of OFMSW, since recent studies prove that biomass yield density (t/ha·y) varied with biomass supply distance (km) from biorefinery plant location. The transport of OFMSW was increased and decreased respectively of plus and minus 10 km. In detail, according to the study of (Golecha et al., 2016) a mutual influence and dependency between biomass yield density (t/ha·y) and supply distance (km) was detected and the trend of GWP of the 18AD configurations did not change, but increasing the transport (km) the GWP increase about 23-18% (Figure 2). The second sensitivity analysis for LCA was applied changing the LHV of biogas of the 18 tested AD configuration of $\pm$2.5% of CH_4 (%v/v) content, according to (Wang et al., 2020). Sensitivity analysis, performed by changing the LHV of CH_4, witnessed that GWP values ranged from –1.68. to +5.65 %, but the trend of the tested 18 AD configurations did not change (Figure 2). To conclude, the environmental analysis proved that increasing both the S:I ratio and the inoculum incubation time the environmental impacts decreased.

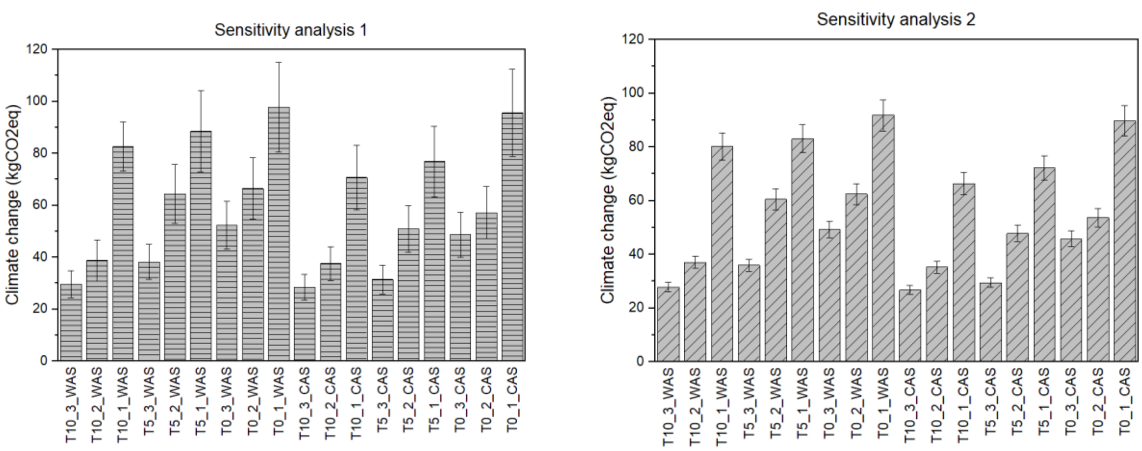


Figure 2: Sensitivity analysis. Sensitivity analysis 1 obtained by changing the transports of inoculum and OFMSW +10 km and -10 km. Sensitivity analysis 2 obtained by changing the LHV of methane, +2.5 % -2.5 %.

3.3 Economic sustainability

To develop economic analysis Life Cycle Costing was performed and a quantitative cost engineering technique was applied, in detail analytical technique, which considers product as a decomposition of a series of elementary operations and activities. In this way, the costs were estimated as a sum of all the components, both for investment and operational costs. The analytical technique was adopted since it was the most accurate and consistent approach for cost estimation, according to (Altavilla et al., 2015).

Value analysis was carried out and it should maximize the difference between value and cost, trying to reduce waste, which is an element or part of the process that does not add value.

Capital and operational costs, revenues, incomes, ROI, NPV and payback time were calculated. The study was carried out on AD plant of 30,000 t of OFMSW per year since it was the minimum size for which all the 18 AD configurations were profitable after 5 years of amortisation.

3.3.1 Capital cost

The AD plant had a service life equal to 20 years and 5 years of amortisation of capital cost according to (Li et al., 2020) AD feed mood was carried out in batch series, since the inoculum played a key role as proved in (Demichelis et al., under review) reaching methane yields +38.2 %v/v higher than traditionally AD of OFMSW. The capital costs included bio-reactor construction, CHP unit, and plant costs, which were both the direct and the indirect costs to realise the plant as buildings, purchase of equipment, instrumentation, and facilities according to (Li et al., 2020).

	HRT (d)	Inoculum (t)	H_2O (m^3)	Working.volume reactor(m^3)	Volume reattor(m^3)
T0_1_WAS	27	132000	2998.88	14849.9	18562.37
T0_2_WAS	27	66000	14000	9900	12375
T0_3_WAS	28	33000	19500	7700	9625

T5_1_WAS	20	132000	2998.88	10999.93	13749.91
T5_2_WAS	18	66000	14000	6600	8250
T5_3_WAS	16	33000	19500	4400	5500
T10_1_WAS	18	132000	2998.88	9899.93	12374.92
T10_2_WAS	16	66000	14000	5866.67	7333.33
T10_3_WAS	16	33000	19500	4400	5500
T0_1_CAS	27	133980	22755.1	16806.16	21007.7
T0_2_CAS	25	66990	23877.55	10072.3	12590.37
T0_3_CAS	27	33495	24438.78	7914.04	9892.55
T5_1_CAS	20	133980	22755.1	12449.01	15561.26
T5_2_CAS	21	66990	23877.55	8460.73	10575.91
T5_3_CAS	15	33495	24438.78	4396.69	5495.86
T10_1_CAS	16	133980	22755.1	9959.21	12449.01
T10_2_CAS	15	66990	23877.55	6043.38	7554.22
T10_3_CAS	19	33495	24438.78	5569.14	6961.42

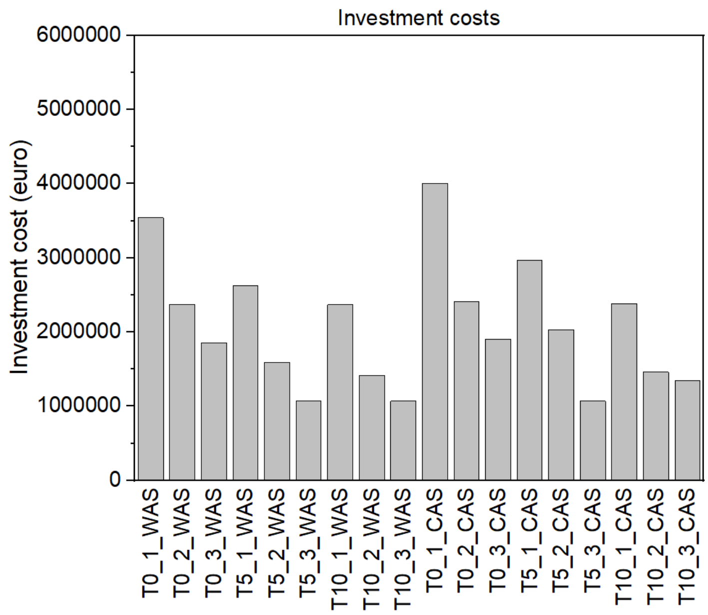
Table 6: Detail of AD plant for size 30,000 t/y (the minimum size economic profitable for all the 18 AD configuration tested).

In Table 6, the features of AD bio-reactor of a plant of 30,000 t of OFMSW per year and 2105.4 t of digestate was reported.

30,000 t of OFMSW per year was studied since was the minimum size for which all the 18 AD configuration were profitable after 5 years of amortisation.

The capital costs of the 18 AD configurations are depicted in Figure 3 as total investment costs (euro) and percentage contribute of each item (%). In detail, increasing the incubation time of the inoculum (5 and 10 d) and the S:I ratio both with CAS and WAS, the bio-reactor size decreased, because the HRT of the process decreased, and consequentially its purchase decreased from 49.00 % (T0_1_WAS) to 35.33% (T10_3_CAS) of total capital cost. Increasing the S:I ratio (1:1 and 2:1) and the inoculum incubation (5 and 10 d) the CHP unit cost contribution increased, since higher biogas rate was achieved. The capital costs of AD performed both with WAS and CAS inocula incubated for 10d at S:I ratio equal to 2:1 agreed with the ones reached by (Patinvoh et al., 2017) with dry AD.

The capital costs of AD performed with inocula incubated for 5 and 10 d at higher S:I ratio (1:1 and 2:1) were like the ones obtained with dry AD (Qian et al., 2015).



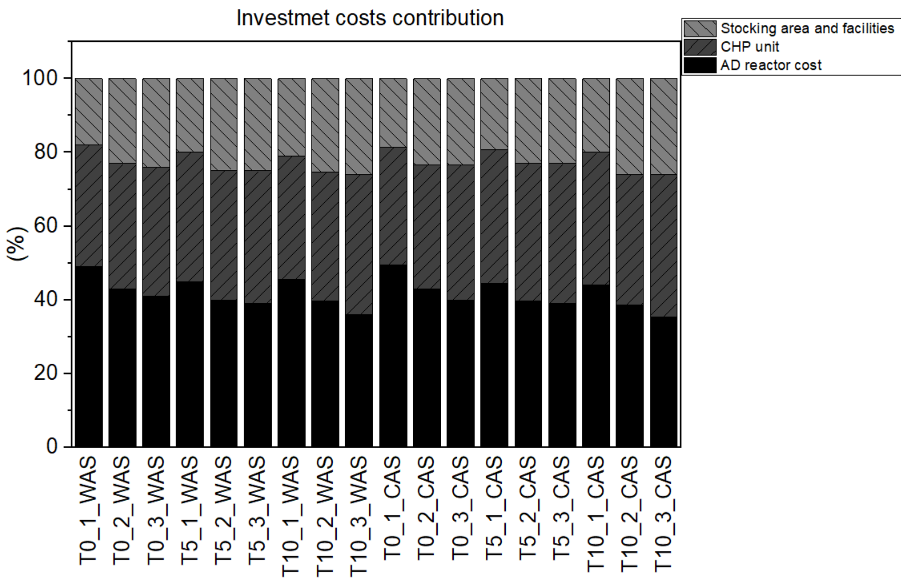


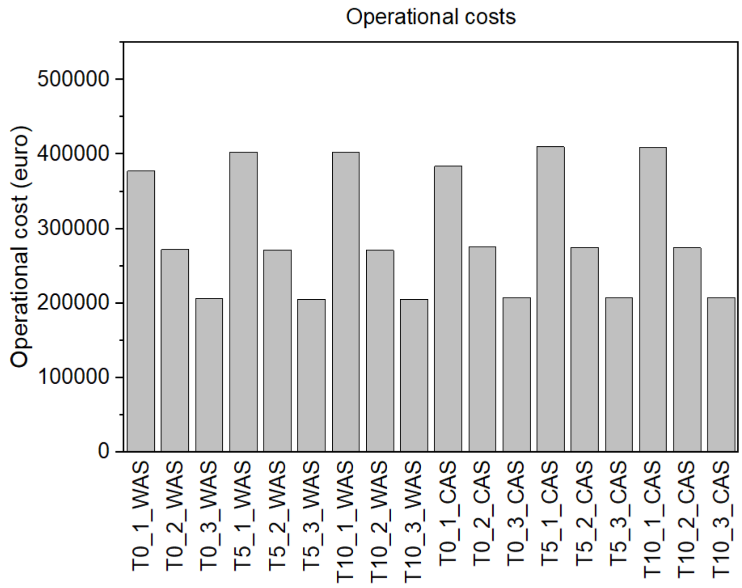
Figure 3: Capital costs (euro) and contribution percentage in capital costs (%)

3.3.2 Operational costs

Operational costs included the cost of the raw material (i.e. transport of inoculum, the collection and transport of OFMSW to the AD plant), the equipment maintenance, the disposal of waste and residues, the labours and the utilities necessary to run the processes as fuel, steam, heat and electricity.

The operational costs of the 18 AD configurations are depicted in Figure 4 as total operational costs (euro) and percentage contribute of each items (%). The costs of raw materials, equipment maintenance, waste disposal and labour costs were constant among the 18 configurations. The key item was the energy (electrical and thermal) costs. In details, two trends were detected. The first trend was: for AD performed with non incubated inoculum the energy required increase by increasing the S:I ratio, since low specific biogas rate and long HRT were reached. This trend agreed with liquid AD performed by (Li et al., 2020).

The second trend was: for AD performed with incubated inoculum, the required energy decreased by increasing the S:I ratio, since high specific biogas rate and short HRT were reached. This trend agreed with (Qian et al., 2015).



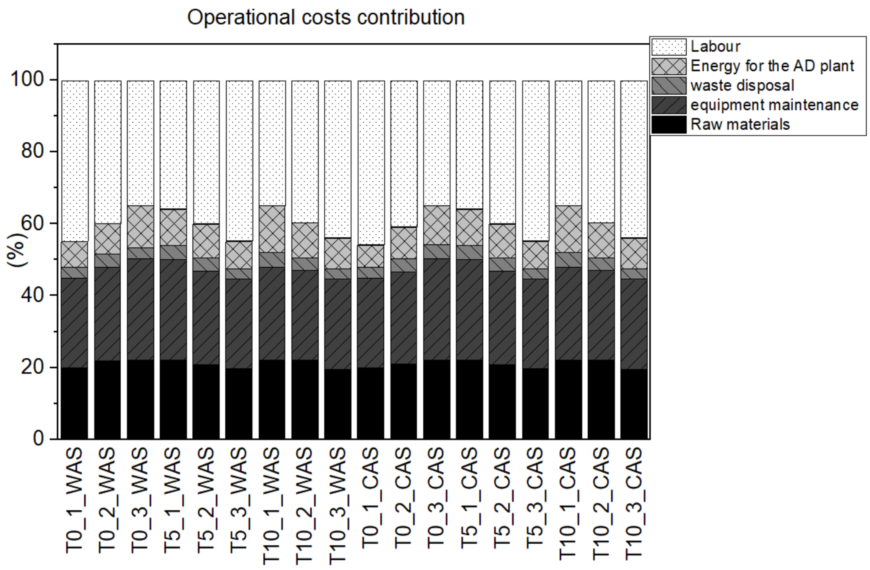


Figure 4: Operational costs (euro) and percentage contribution (%)

3.3.3 Revenues

Figure 5 depicts the incomes of the 18 AD configurations due to the differences between biogas trade and capital and operational costs, before and after 5 years of amortization and ROI after 5 years of amortization. In the first 5 years of life AD plant the only profitable configurations were AD performed with both inocula CAS and WAS incubated for 5 and 10 d at the highest S:I (2:1), respectively: T5_3_WAS, T10_3_WAS T5_3_CAS, T10_3_CAS. After 5 years of amortization all the 18 AD configurations were profitable and among them the most profitable were: T10_3_WAS, T10_3_CAS. followed by T5_3_CAS and T5_3_WAS.

The incomes achieved by these configurations agreed with wet AD performed (Demichelis et al., 2018) for AD plant. To scrutinize the economic assessment of the above mentioned profitable configurations, Net Present Value (NPV), Return of Investment (ROI) and payback time were calculated (Table 7).

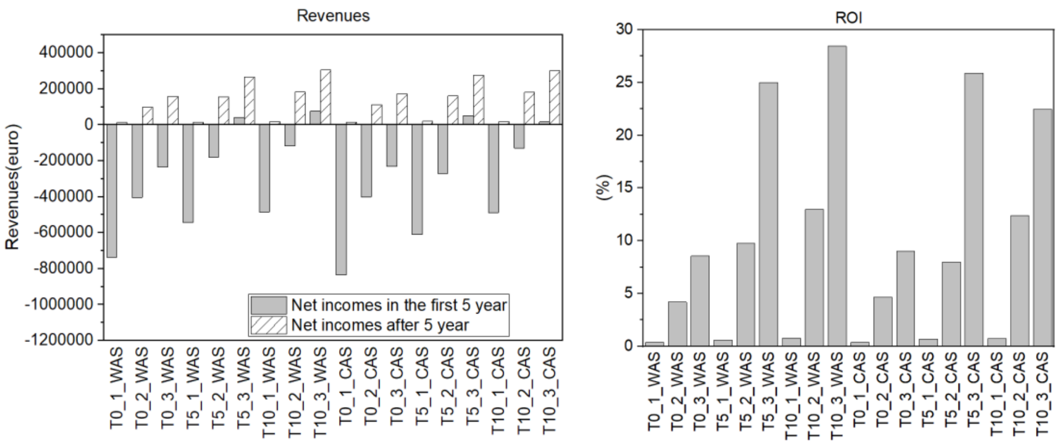


Figure 5: Revenues (euro) and ROI (%)

AD configurations	ROI (%)	payback time (y)	NPV (euro)
T5_3_WAS	24.99	10	2,348,887.37
T10_3_WAS	28.45	11	2,810,068.86
T5_3_CAS	25.89	10	2,467,367.73
T10_3_CAS	22.47	12	2,534,258.31

Table 7: Economic key indicator to evaluate the profitability of the 18 AD configurations

In particular, only four AD configuration (the AD performed with inocula WAS and CAS incubated for 5 and 10 d at the highest S:I ratio) had payback time minor of 20 y (the life service of the AD plant), NPV positive and ROI higher than 20%. Among them, the T5_3_WAS reached best fit NPV, ROI and payback time, respectively 2,810,068.86 euro, 28.45% and 11 y. The minimum size for which all the 18 AD configuration were profitable after 5 years of amortization was 30,000 t/y of OFMSW. To identify the best fit between capital, operational costs and revenues the study of ROI was performed for AD plant size from 20,000 t/y to 100,000 t/y (Figure 6). The best fit of economic assessment was detected for AD plant size equal to 50,000 t/y according to (Demichelis et al., 2018) (Arias et al., 2020).

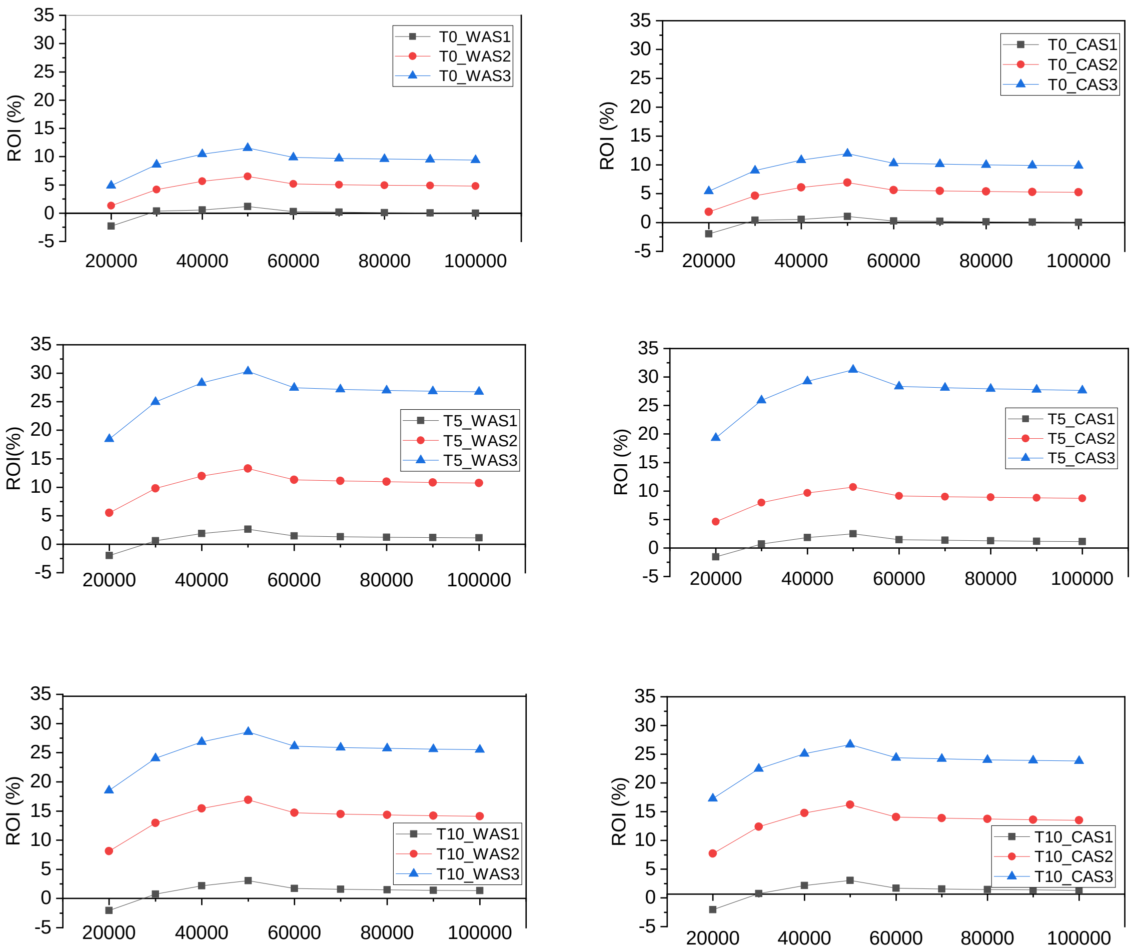
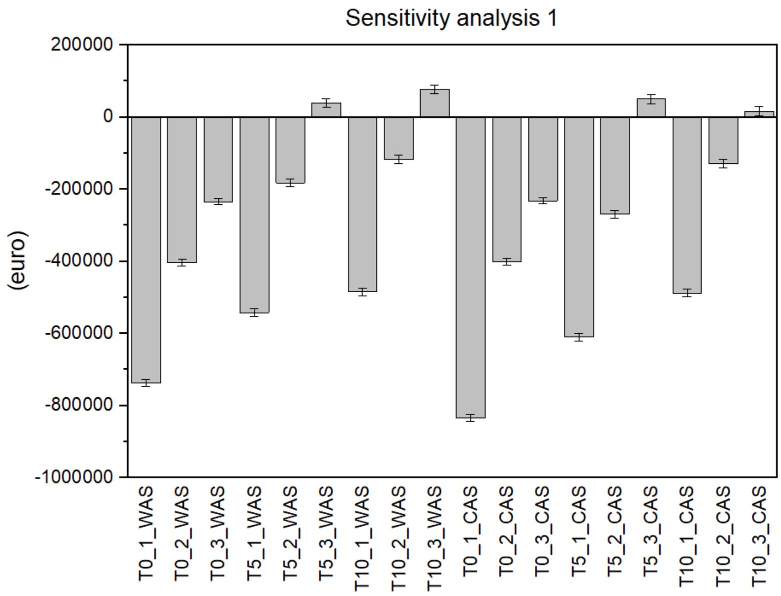


Figure 6: Evaluation of the AD plant size to obtain the maximal benefit CAPEX and OPEX. On x -coordinate is reported the t of OFMSW per year considered.

3.3.4 Economic sensitivity analysis

Two sensitivity analysis were performed. The first economic sensitivity analysis (Figure 7) was carried out as the sensitivity for LCA, by changing the LHV of biogas of the 18 tested AD configuration from -2.5 to+2.5 % of CH_4 (%v/v) content, according to (Wang et al., 2020). The sensitivity analysis was performed considering the net revenues in the first 5 years of amortisation. Even if, the LHV of CH_4 was increased and decreased of ± 2.5 %, the AD configuration economic profitable in the first 5 years of amortisation were T5_3_WAS, T10_3_WAS, T5_3_CAS, T10_3_CAS. These results confirmed the outputs of economic assessment described in sections 3.3.1, 3.3.2 and 3.3.3. In detail, among the profitable configurations: 1) increasing the LHV of +2.5 % the revenues in the first 5 years of amortization was increased in the range from +22.42 % to +42.71 %, respectively for T5_3_WAS and T10_3_CAS.; 2) decreasing the LHV of -2.5 % the revenues in the first 5 years of amortization was decreased from 21.73% to 31.7 % respectively for T5_3_WAS and T10_3_CAS. The second sensitivity analysis (Figure 7) was performed by floating the biogas price of $\pm$20% according to (Li et al., 2020).

Even if, the price of CH_4 was increased and decreased of ±20 %, the AD configuration economic profitable in the first 5 year of amortisation were T5_3_WAS, T10_3_WAS T5_3_CAS, T10_3_CAS. Among the profitable configurations: 1) increasing the price of CH_4 of +20 % the revenues in the first 5 years of amortization were increased in the range from 20.11 % to 41.54 %, respectively for T5_3_WAS and T10_3_CAS; 2) decreasing the price of CH_4 of -20% the revenues in the first 5 years of amortization were decreased from 19.8 % to 29.72 % respectively for T5_3_WAS and T10_3_CAS. To conclude the economic sensitivity analysis, the following state con be asserted: by changing the LHV of CH_4 about $\pm$2.5 % and the price of CH_4 in the range of $\pm$20 %, the AD configuration economically profitable were always: T5_3_WAS, T10_3_WAS T5_3_CAS, T10_3_CAS.



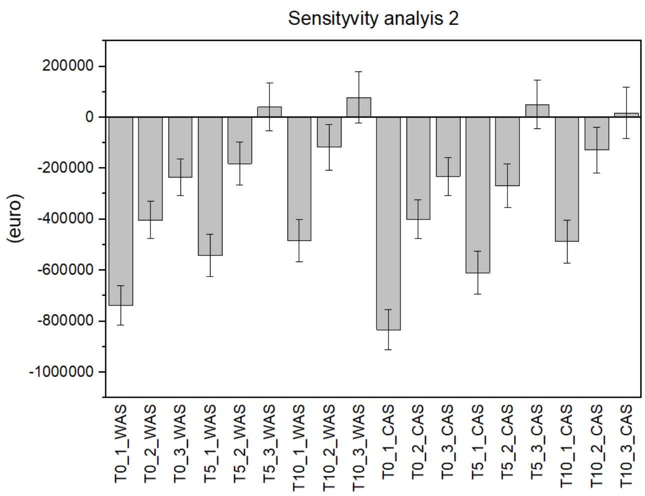


Figure 7: Economic sensitivity analysis. Sensitivity analysis 1 obtained by changing the LHV of CH_4 about $\pm$2.5 %. The second sensitivity analysis was performed changing the price of CH_4 in the range of $\pm$20 %. The sensitivity analysis was carried out on net revenues before 5 years of amortisation.

Conclusions

The aim of the present study was the evaluation of the environmental sustainability through Life Cycle Assessment (LCA) and economic profitability through Life Cycle Costing (LCC) of the 18 AD configurations carried out on OFMSW at three S:I ratio (1:2, 1:1 and 2:1) for three different inoculum incubation times (0, 5 and 10 d). The adopted approach was the eco-efficiency perspective, coming from the combination of technical, environmental (LCA) and economic (LCC) perspectives. From environmental perspective: increasing both the S:I ratio and the inoculum incubation time (5 and 10 days) the environmental impacts decreased, since higher amount of OFMSW was valorised and specific production of biogas with higher methane content was achieved. The lowest values of Climate change were achieved by T10_3_WAS and T10_3_CAS: 28.67 and 27.72 kgCO_2 eq, respectively. LCC was developed to evaluate the economic profitability of the 18 AD configurations tested. The minimum AD plant size for which all the 18 AD configurations were profitable after 5 year of amortisation was 30,000 t/y of OFMSW. Capital and operational costs decreased by increasing the incubation time of the inoculum and the S:I ratio, since a higher specific biogas rate was reached, and smaller AD bio-reactor volume was adopted since HRT decreased. The AD plant size, for which maximal revenues and minimal capital and operational costs were evaluated, was 50,000 t/y OFMSW. To conclude, the AD configurations which reached both the environmental sustainability and economic profitability were: the AD performed both with inoculum WAS and CAS incubated for 5 and 10 d at the highest S:I ratio 2:1: T5_3_WAS, T5_3_CAS, T10_3_WAS and T10_3_CAS.

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Dear Editor,

We kindly ask you to consider the submission of our manuscript entitled *"Life cycle assessment and life cycle costing of advanced anaerobic digestion of organic fraction municipal solid waste"* for publication in the **CHEMOSPHERE**, Elsevier.

The present study evaluated environmental sustainability and economic profitability of optimised anaerobic digestion of organic fraction municipal solid waste (OFMSW) supplied by a real OFMSW treatment plant, to produce methane.
The aim of this study is the evaluation of the environmental sustainability by means of Life Cycle Assessment (LCA) and economic profitability through Life Cycle Costing (LCC) of the 18 AD configurations carried out on Organic Fraction Municipal Solid Waste (OFMSW) at three S:I ratios (1:2, 1:1 and 2:1) for three different inoculum incubation times (0, 5 and 10 d). The adopted approach was the eco-efficiency perspective, coming from the combination of technical, environmental (LCA) and economic (LCC) perspectives. We believe that these results can be of great significance to any readership and make a profound resonance on hot topics such as OFMSW valorisation, through anaerobic digestion and biogas production, considering as fundamental pillar the sustainability. LCA and LCC are performed through SimaPro software. Sensitivity analysis is performed both for environmental and economic assessment to prove the robustness of the results.

I declare that this work is linked to a work presented at THESSALONIKI 2021 8th International Conference on Sustainable Solid Waste Management, and it has been selected for the special issue "Recent Advancements in Anaerobic Digestion" of Chemosphere.

Yours sincerely, on behalf of all the authors,
Francesca Demichelis
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