

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

*Original*

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## Life cycle assessment and life cycle costing of advanced anaerobic digestion of organic fraction municipal solid waste --Manuscript Draft--

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<b>Corresponding Author:</b>	Francesca Demichelis Politecnico di Torino Facoltà di Ingegneria: Politecnico di Torino Torino, 80380000100121140625 ITALY
<b>First Author:</b>	Francesca Demichelis
<b>Order of Authors:</b>	Francesca Demichelis Tonia Tommasi Fabio Alessandro Deorsola Daniele Marchisio Giuseppe Mancini Debora Fino
<b>Abstract:</b>	<p>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<sub>2</sub> 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.</p>
<b>Suggested Reviewers:</b>	Roland Schneider rschneider@atb-potsdam.de David Bolzonella david.bolzonella@univr.it Carminna Ottone carminna.ottone@pucv.cl Nicola Frison nicola.frison@univr.it Charlene Vance charlene.vance@ucd.ie Qilin Wang qilin.wang@uts.edu.au
<b>Opposed Reviewers:</b>	

## 1 Highlights

- 2 • Environmental sustainability and economic profitability of anaerobic digestion (AD)
- 3 • Environmental impact drops by increasing S:I ratio and inoculum incubation time
- 4 • Capex and Opex drop by increasing the inoculum incubation time and the S:I ratio
- 5 • 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.

# Environmental and Economic sustainability



OFMSW



Collection+  
Transport



AD plant

Biogas



Energy

Digestate



**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:

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

- Francesca Demichelis: Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. Email [francesca.demichelis@polito.it](mailto:francesca.demichelis@polito.it)
- Tonia Tommasi: Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. Email [tonia.tommasi@polito.it](mailto:tonia.tommasi@polito.it)
- Fabio Alessandro Deorsola: Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. Email [Fabio.deorsola@polito.it](mailto:Fabio.deorsola@polito.it)
- Daniele Marchisio: Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. Email [danile.marchisio@polito.it](mailto:danile.marchisio@polito.it)
- Giuseppe Mancini: Department of Electric, electronic and informatic engineering, Università degli Studi di Catania, Viale A. Doria 6, 95125, Catania (CT), Italy. Email [gmancini@dica.unict.it](mailto:gmancini@dica.unict.it)
- Debora Fino: Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. Email [Debora.fino@polito.it](mailto:Debora.fino@polito.it)

**Corresponding author:** Francesca Demichelis. Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. **email:** [francesca.demichelis@polito.it](mailto:francesca.demichelis@polito.it)

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

3  
4                   F.Demichelis<sup>1,\*</sup>, T.Tommasi<sup>1</sup>, F.A. Deorsola<sup>1</sup>, D.Marchisio<sup>1</sup>, G. Mancini<sup>2</sup>, D.Fino<sup>1</sup>

5  
6                   <sup>1</sup>Department of Applied Science and Technology (DISAT), Politecnico di Torino, Corso Duca degli  
7     Abruzzi 24, 10129 Torino (TO), Italy

8                   <sup>2</sup> Department of Electric, electronic and informatic engineering, Università degli Studi di Catania,  
9     Viale A. Doria 6, 95125, Catania, Italy

10    **\*Corresponding author:** Francesca Demichelis. Department of Applied Science and Technology (DISAT),  
11    Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino (TO), Italy. **email:**  
12    [francesca.demichelis@polito.it](mailto:francesca.demichelis@polito.it)

13    **Abbreviations**

14    AD anaerobic digestion

15    CAS cow agricultural sludge

16    ESI energy sustainable index

17    LCA life cycle assessment

18    LCC life cycle costing

19    GWP global warming potential

20    MBT mechanical biological treatments

21    MSW municipal solid waste

22    NPV Net Present Value

23    OFMSW Organic fraction municipal solid waste

24    ROI Return On Investment

25    TS Total solids

26    VS Volatile solids

27    WAS Waste activated sludge

28

## 29 **Abstract**

30 The aim of this study is the evaluation of the environmental sustainability by means of Life Cycle Assessment  
31 (LCA) and economic profitability through Life Cycle Costing (LCC) of the 18 AD configurations carried out  
32 on Organic Fraction Municipal Solid Waste (OFMSW) at three S:I ratios (1:2, 1:1 and 2:1) for three different  
33 inoculum incubation times (0, 5 and 10 d). The adopted approach was the eco-efficiency perspective, coming  
34 from the combination of technical, environmental (LCA) and economic (LCC) perspectives. The main findings  
35 of the study were that increasing both the S:I ratio and the inoculum incubation time (5 and 10 days) the  
36 environmental impacts decreased, and economic profitability increased. In detail, the lowest values of Climate  
37 Change were achieved by the AD performed with both inocula WAS and CAS for 10 days at S:I equal to 2:1:  
38 28.67 and 27.72 kg CO<sub>2</sub> eq respectively. The minimum AD plant size for which all the 18 AD configurations  
39 was economically profitable after 5 year of amortisation was 30,000 t/y of OFMSW. Capital and operational  
40 costs decreased by increasing the incubation time of the inoculum and the S:I ratio, since higher specific biogas  
41 rate was reached, and smaller AD bio-reactor volume were adopted because hydraulic retention time  
42 decreased.

43 The AD plant size, for which maximal revenues and minimal capital and operational costs were detected, was  
44 50,000 t/y OFMSW. Among all the AD configurations, the environmental sustainability and economic  
45 profitability were reached by test performed with inocula WAS and CAS incubated for 5 and 10 d at the highest  
46 S:I ratio 2:1.

47

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

50

## 51 **Introduction**

52 In 2019, the production of Municipal Solid Waste (MSW) in Europe ranged from 280 kg per capita in Romania  
53 to 844 kg per capita in Denmark, and in Italy was equal to 500 kg per capita (Eurostat, 2021). In Europe, the  
54 Organic Fraction Municipal Solid Waste (OFMSW) represented an average of 27% of MSW, equal to a  
55 generation of 177 million tonnes (Eurostat, 2021). The traditional OFMSW treatments consist in mechanical

56 biological treatments (MBT), thermo-valorisation, composting and anaerobic digestion (AD). Among them,  
57 anaerobic digestion (AD) is one of the most efficient and environmentally sustainable techniques for organic  
58 waste remediation and valorisation (Ardolino et al., 2018). OFMSW is considered as one of the major  
59 contributors to climate change, human health risk and ecosystem damages. OFMSW is a biodegradable waste  
60 and so it could potentially be employed in renewable energy production processes. AD of OFMSW is a very  
61 attractive option to convert the complex organic matter into a renewable and clean energy source, as biogas.  
62 AD is a biochemical process by which complex organic matter are transformed into simple soluble compounds  
63 in anaerobic environment. The main benefit of AD is the stabilisation of organic matter and pathogens by  
64 converting them into biogas under anaerobic condition. The biogas is a gas mainly made up of methane and  
65 carbon dioxide. In detail, AD is a multistep biological process made up of hydrolysis, acidogenesis,  
66 acetogenesis and methanogenesis. Hydrolysis is the first and rate-limiting step, since it must reduce both  
67 organic matter and high molecular compounds as carbohydrate, proteins and lipids respectively into sugars,  
68 aminoacids and fatty acids. The AD of OFMSW is generally carried out at liquid state condition, which  
69 means total solids (TS) ranged from 0.5 to 10%. In the present study liquid state AD was carried out, in detail  
70 at 6% TS. The AD of organic matter is an environmental sustainable technique since is a carbon neutral  
71 process, but it has disadvantages as long retention time, low removal efficiency organic compounds, strong  
72 sensibility to the variation of pH, alkalinity, temperature, retention time, nitrogen, carbon availabilities and  
73 Carbon Nitrogen (C:N) ratios which affects the AD process stability. To evaluate the environmental  
74 sustainability of AD process, several studies of Life Cycle Assessment (LCA) were carried out on AD  
75 performed with different organic waste as corn silage, dairy manure, food waste (Martinez-Sanchez et al.,  
76 2016) and agricultural waste (Ascher et al., 2020). LCA is a methodology to assess environmental impacts  
77 which covers all the life cycle of product and process. The aim of the present study is the evaluation of the  
78 environmental sustainability through Life Cycle Assessment (LCA) and economic profitability through Life  
79 Cycle Costing (LCC) of the AD configurations tested in (Demichelis et al., under review).

80 The adopted approach was the eco-efficiency perspective, coming from the combination of technical,  
81 environmental (LCA) and economic (LCC) perspectives. In (Demichelis et al., under review) mesophilic AD  
82 was performed on real OFMSW supplied by San Carlo Spa (Fossano, Italy) with two inocula, one coming  
83 from the mesophilic digestate of waste activated sludge (WAS) provided by SMAT (a wastewater treatment

84 plant in the north of Italy), and the second from the mesophilic digestate of cow agricultural sludge (CAS)  
85 supplied by Cascina La Speranza (Candiolo, Italy) at three substrate inoculum ratios (S:I): 1:2, 1:1 and 2:1 for  
86 three inoculum incubation times: 0, 5 and 10 days. Two inocula with different origins were selected to improve  
87 the C:N ratio, in particular animal sludge matter provided enhancement of C:N and buffering capacity. The  
88 main output of the present study was the evaluation of optimal technical feasibility, environmental  
89 sustainability, and economic profitability of AD configurations to scale them at the commercial -industrial  
90 scales.

91

## 92 **2 Materials and methods:**

### 93 **2.1. Environmental sustainability**

94 Life cycle assessment was performed with SimaPro 9.0 software and it was based on ISO 14040 (2006) and  
95 14044 (2006). Ecoinvent 3.0 was employed as database.

96

#### 97 **2.1.1 Goal and scope:**

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

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

102 The functional unit (FU) was 1 t of wet OFMSW. The produced emissions, the consumed material and the  
103 required energy were referred to the FU. The choice of FU equal to 1 t of OFMSW allowed the comparison  
104 with other studies available in the scientific literature (Ascher et al., 2020). The boundary conditions included:  
105 the collection and the transport of OFMSW to the the AD plant, the transport of inoculum to the AD plant, the  
106 AD process and the CHP unit. The OFMSW was collected in the town and then transported to the AD plant.  
107 According to (Demichelis et al., under review) AD was performed in batch feeding at 6%TS on real OFMSW  
108 supplied by San Carlo Spa (Fossano, Italy), with two inocula, one coming from the mesophilic digestate of  
109 waste activated sludge (WAS) provided by SMAT (a wastewater treatment plant in the north of Italy), and the  
110 second from the mesophilic digestate of cow agricultural sludge (CAS) supplied by Cascina La Speranza  
111 (Candiolo, Italy) at three substrate inoculum ratios (S:I): 1:2, 1:1 and 2:1 for three inoculum incubation times:

112 0, 5 and 10 days. Two inocula with different origins were selected to improve the C:N ratio, in particular  
113 animal sludge matter provide enhancement of C:N and buffering capacity. Hence, a total of 18 configurations  
114 of AD of OFMSW were tested. The AD was performed under mesophilic conditions 37°C with constant  
115 mixing at 300 rpm. AD has two outputs: biogas and digestate. The AD configurations adopted the following  
116 code: TX\_Y\_ZZZ, where X can be 0, 5 or 10 days representing the incubation time of the inoculum, Y is the  
117 S:I ratio, in detail 1 for S:I=1:2, 2 for S:I=1:1 and 3 for S:I=2:1 and ZZZ represents the origin of the inoculum  
118 WAS or CAS. Biogas was sent to CHP unit to produce electric energy ( $\eta = 0.45$ ) and heat ( $\eta = 0.55$ ), while  
119 digestate was not valorised, in order to focus the attention only on the benefits coming from biogas-energy  
120 valorisation. The adopted approach was from cradle to gate according to (Wang et al., 2020).

121

### 122 **2.1.2 Life cycle inventory (LCI)**

123 The LCI defined all inputs and outputs involved in the processes. The primary data came from the study of  
124 (Demichelis et al., under review) and in Table 1 these data are scaled up to FU equal to 1 t of OFMSW with a  
125 correction factor 0.8 (Perry, 2008). The LHV of methane was assumed equal to 35.9 MJ/m<sup>3</sup> according to  
126 (González et al., 2020). In Table 1, six AD configurations were yellow coloured since they were energetically  
127 self-sufficient with Energy Sustainable Index higher than 1. The secondary data were taken from Ecoinvent  
128 3.0. and reported in Table 2. According to (Brander et al., 2019) attributional LCA was applied. In detail,  
129 attributional LCA means a modelling approach by which inputs and outputs were attributed to the FU of a  
130 product system linking the unit processes of the system according to a normative rule. Collection and transport  
131 of OFMSW were equal to 20 and 30 km respectively, while the transport of inocula, both for WAS and CAS  
132 was equal to 20 km. Expansion system methodology was applied since electric and heat were re-integrated in  
133 the AD system.

134

### 135 **2.1.3 Life cycle impact assessment (LCIA)**

136 Life cycle impact assessment was performed with the ReCiPe Midpoint (H) method. The AD system was  
137 evaluated both as internal processes with energy productions and as external process including OFMSW  
138 collection, OFMSW and inocula transportations and energy consumption. Both internal and external processes  
139 affected global warming potential (GWP). In the present study, the analysed impact categories were: Climate

140 change (kg CO<sub>2</sub> eq), Ozone depletion (kg CFC-11 eq), Human toxicity, (kg 1,4-DB eq), Cancer effects (CTUh),  
141 Acidification (molc H<sup>+</sup> eq), Terrestrial eutrophication (molc N eq), Marine eutrophication (kg N eq,) and Land  
142 use (kg C deficit). The attention will be focused on Climate Change, because in scientific literature several  
143 studies were available for comparison.

144

#### 145 **2.1.4 Interpretation data e sensitivity analysis**

146 The last step of LCA was the interpretation of the results to evaluate the achievement of the goal. A double  
147 sensitivity analysis was performed to measure and detect possible variation of AD response on environmental  
148 impacts. The first sensitive analysis was performed varying selected parameters as kilometre of transport and  
149 collection of OFMSW, since recent studies prove that biomass yield density (t/ha·y) varied with biomass  
150 supply distance (km) from biorefinery plant location. In detail, the study of (Golecha et al., 2016) stated a  
151 mutual influence and dependency between biomass yield density (t/ha·y) and supply distance (km). The second  
152 sensitivity analysis for LCA section was applied changing the low heating value (LHV) of biogas of the 18  
153 tested AD configurations from -2.5 to+2.5% of CH<sub>4</sub> (% v/v) content, according to (Wang and al., 2020).

	Biogas (NL/kgvs)	CH <sub>4</sub> (%)	CO <sub>2</sub> (%)	Inoculum (t)	OFMSW (t)	H <sub>2</sub> O (m <sup>3</sup> )	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	<b>1.01</b>	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	<b>1.18</b>	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	<b>1.07</b>	4.05	4.95
T10_3_WAS	994.2	69	31	1.1	1	0.65	147.86	117.58	<b>1.26</b>	13.63	16.65

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

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

156

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

157 **Table 2:** Secondary data from Ecoinvent 3.0

158 **2.3 Economic analysis**

159 Economic feasibility was studied by Life Cycle Costing (LCC). LCC is an assessment of all costs related to  
160 the production of a product or service, considering the whole life cycle from production to usage until disposal.  
161 The LCC was carried out in three main modules: data collection, cost estimation and data interpretation. The  
162 target of LCC was the evaluation of the economic cost of the whole life cycle of anaerobic digestion process,  
163 with the aim to reduce and minimise the cost of production. In this study, the result of LCC is the definition of  
164 the economic dimension of the AD process. LCC was performed from the viewpoint of producers. According  
165 to LCA (paragraph 2.1.1), the same goal and scope, system boundary and functional unit were adopted to  
166 perform LCC to obtain an overall consistent analysis.  
167 LCC was calculated considering capital investment, operational costs, profitability of the anaerobic digestion,  
168 Net Present Value (NPV), Return On Investment (ROI) and payback time. The LCC was performed on the  
169 minimum AD plant size for which economic profitability was achieved.

170 **2.3.1 Capital cost evaluation**

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

175 
$$A(\text{euro}) = C_0 \cdot \frac{i \cdot (1+i)^n}{(1+i)^n - 1} \quad (1)$$

176 where  $A$  means the amortization cost,  $C_0$  is the capital investment,  $n$  the number of years of amortisation and  $i$   
177 is the tax of interest.

178

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

179 **Table 3:** List of capital costs.

180

### 181 2.3.2 Operational cost evaluation

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

185

Technique	Operation	Unit	Cost (Euro/unit)	References
Raw material	Collection of OFMSW	Euro/t	0.21	(ISPRA, 2021)
	Inoculum	Euro/m <sup>3</sup>	2.10	(Demichelis et al., 2018)
	Process water	Euro/m <sup>3</sup>	0.13	(Akeberg et al., 2000)
Water and energy consumption	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)

186 **Table 4:** List of operational costs.

187

### 188 2.3.3 Revenue and evaluation of profitability

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

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

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

196 
$$NPV (euro) = \sum_{t=1}^T \frac{C_t}{(1+d)^t} - C_0 \quad (2)$$

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

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

200 
$$ROI (\%) = \frac{\text{Annual net profit}}{\text{Initial total investment}} \cdot 100 \quad (3)$$

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

203

#### 204 **2.3.4 Economic sensitivity analysis**

205 Two sensitivity analysis were performed. The first sensitivity analysis for LCC was performed as sensitivity  
206 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)  
207 content, according to (Wang and al., 2020). The second sensitivity analysis was performed by floating the  $CH_4$   
208 price of  $\pm 20\%$  according to (Li et al., 2020).

209

### 210 **3.Results:**

211

#### 212 **3.1 Environmental sustainability.**

213 Life Cycle Assessment (LCA) was carried out on the 18 AD configurations tested in (Demichelis et al., under  
214 review) and the following impact categories were analysed: Climate change (kgCO<sub>2</sub> eq), Ozone depletion (kg  
215 CFC-11 eq), Human toxicity, Cancer effects (CTUh), Acidification (molc H<sup>+</sup> eq), Terrestrial eutrophication  
216 (molc N eq), Marine eutrophication (kg N eq.) and Land use (kg C deficit). Global warming potential (GWP)  
217 was significantly affected by OFMSW management practices involving significant GHG emissions. The  
218 emissions due to collection and transport of OFMSW, AD of OFMSW and biogas utilisation were summed  
219 up. Conventional OFMSW managements were evaluated to underline the pros coming from to the proposed  
220 AD management. In details, incineration and landfilling achieved 107 kg CO<sub>2</sub> eq and 209 kg CO<sub>2</sub> eq,  
221 respectively, these results agreed with (Cremiato et al., 2018).

222 In the present study, the reduction of GHG emission was due to the use of produced biogas as thermal energy  
223 to heat the bio-digester. This pro was detected in the AD configurations with Energy Sustainable Index (ESI)  
224 major than 1; the AD performed both with inocula WAS and CAS for incubation time of 5 and 10 d at S:I  
225 ratios equal to 1: 1 and 2:1 (Table 1, yellow coloured): T5\_3\_WAS, T5\_3\_CAS, T10\_2\_WAS, T10\_2\_CAS,  
226 T10\_3\_WAS and T10\_3\_CAS. In Figure 1, the GWP reached by the 6 AD configuration with ESI major than  
227 1 was depicted considering the GWP contribute of each phase of AD process. The highest environmental items  
228 were OFMSW and inoculum transport, according to (Golecha et al., 2016).

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

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

	<b>Climate change</b>	<b>Ozone depletion</b>	<b>Human toxicity, cancer effects</b>	<b>Acidification</b>	<b>Terrestrial eutrophication</b>	<b>Marine eutrophication</b>	<b>Land use</b>
<b>Unit</b>	kg CO <sub>2</sub> eq	kg CFC-11 eq	CTUh	molc H+ eq	molc N eq	kg N eq	kg C deficit
<b>T10_3_WAS</b>	28.67	3.9E-03	2.1E-07	0.15	0.20	0.02	50.17
<b>T10_2_WAS</b>	38.19	5.2E-06	2.8E-07	0.19	0.27	0.02	68.67
<b>T10_1_WAS</b>	82.61	1.1E-05	6.4E-07	0.45	0.61	0.05	129.27
<b>T5_3_WAS</b>	37.00	5.2E-06	3.0E-07	0.21	0.29	0.03	59.73
<b>T5_2_WAS</b>	62.36	8.0E-06	4.7E-07	0.34	0.45	0.04	88.75
<b>T5_1_WAS</b>	85.63	1.1E-05	6.2E-07	0.43	0.59	0.05	126.77
<b>T0_3_WAS</b>	50.71	6.4E-06	3.8E-07	0.28	0.37	0.03	68.48
<b>T0_2_WAS</b>	64.37	8.2E-06	4.8E-07	0.35	0.46	0.04	90.42
<b>T0_1_WAS</b>	94.67	1.2E-05	7.1E-07	0.51	0.68	0.06	136.78
<b>T10_3_CAS</b>	27.52	3.7E-06	2.0E-07	0.14	0.19	0.02	47.68
<b>T10_2_CAS</b>	36.33	4.9E-06	2.7E-07	0.18	0.26	0.02	63.96
<b>T10_1_CAS</b>	68.40	9.0E-06	5.1E-07	0.36	0.49	0.04	108.61
<b>T5_3_CAS</b>	30.38	4.1E-06	2.2E-07	0.16	0.22	0.02	50.05
<b>T5_2_CAS</b>	49.23	6.4E-06	3.7E-07	0.26	0.35	0.03	74.67
<b>T5_1_CAS</b>	74.43	9.7E-06	5.6E-07	0.39	0.53	0.05	113.61
<b>T0_3_CAS</b>	47.17	6.0E-06	3.5E-07	0.26	0.34	0.03	64.01

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

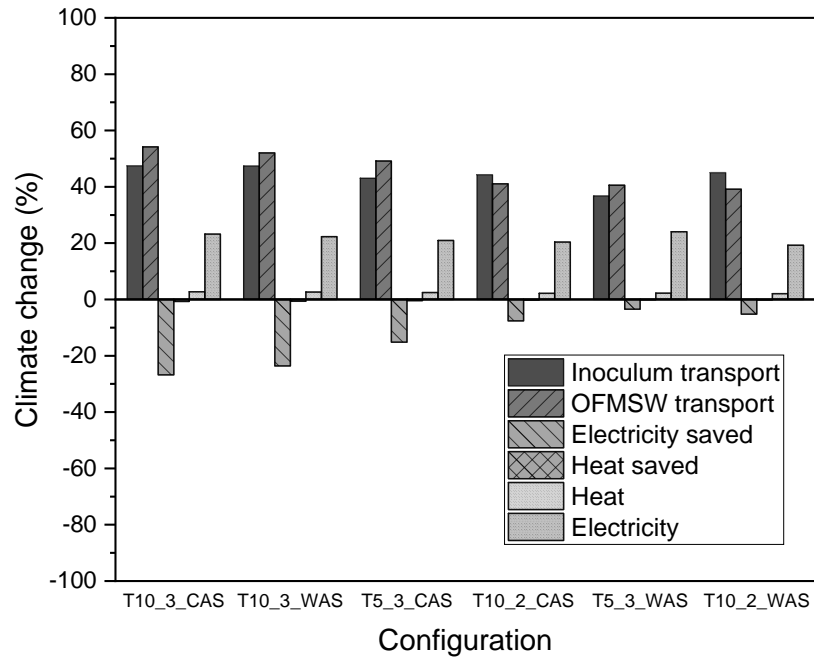
244 **Table 5:** Environmental impacts of the 18 AD configurations

245

246 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 %  $\pm$   
247 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 +  
248 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  
249 the most studied impact category in scientific literature. For the Climate change impact category, the present study considered the contribution of biogenic carbon,  
250 with a factor of biogenic CO<sub>2</sub> equal to 1.

251 In the present study, the highest GWP values were reached by the following configurations: AD performed with inoculum WAS and CAS without incubation (0  
252 day) at S:I ratio equal to 1:2: T0\_1\_WAS reached 94.67 kgCO<sub>2</sub>/t OFMSW and T0\_1\_CAS achieved 92.51 kgCO<sub>2</sub>/t. These results agreed with the study of (Ascher  
253 et al., 2020) who performed the AD of food waste both neglecting and considering the biogenic CO<sub>2</sub> and reached -97.27 and 140.50 kgCO<sub>2</sub> eq per 1 t of food waste  
254 and with the study of (Jin et al., 2015) which reached 96.97 kgCO<sub>2</sub>/t of food waste in mesophilic liquid AD, with S:I ratio equal to 1:2. In Climate change category  
255 (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  
256 increased, increasing the reactor volume and the CO<sub>2</sub> emissions rather than AD configurations with higher S:I (1:1 and 2:1). Moreover, increasing both the S:I ratio  
257 and the incubation time, the specific biogas production and the CH<sub>4</sub> content in the biogas increased, with a consequential decrease of CO<sub>2</sub> emissions and thermal  
258 energy required to heat the bio-digester, 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<sub>2</sub>,  
259 respectively according to (Fei et al., 2021) which reached 29.24 kg CO<sub>2</sub> per 1 t of food waste treated with solid and liquid AD processes. The AD performed both

260 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<sub>2</sub>  
261 per 1 t of food waste treated with solid and liquid AD processes.



262

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

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

266 Usually, dairy waste management consists in stockpiling and land application which caused 307 and 204 kg  
 267 CO<sub>2</sub> eq per ton respectively, according to (Adghim et al., 2020). In the present study, 9 AD configurations  
 268 adopted as inoculum the digestate coming from cow agricultural sludge (CAS) and the reached GWP witnessed  
 269 the positive valorisation of both matrix CAS (as inoculum) and OFMSW (as substrate), which achieved a  
 270 minimum GWP with T10\_3\_CAS (27.52 kg CO<sub>2</sub> eq) and maximum T0\_1\_CAS (92.52 kg CO<sub>2</sub> eq). Moreover,  
 271 the AD performed with inoculum CAS achieved GWP lower than the one using WAS as inoculum, in the  
 272 range of - 4.18 to - 16.51%. This trend was in line with the study of (Cristóbal et al., 2018).

273 Considering the ESI (Table 1) and Climate change values (Table 5 and Figure 1) of all AD configurations with  
 274 ESI major than 1; the decrease of kgCO<sub>2</sub> eq emissions matched with the increase of ESI values. In terms of kg  
 275 CO<sub>2</sub> eq released, the best AD configurations were AD performed with both CAS and WAS inoculum incubated  
 276 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  
 277 for 10 d at S:I ratio equal to 1:1 (T10\_2\_CAS and T10\_2\_WAS), and AD with both CAS and WAS incubated  
 278 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  
 279 ranking reported in (Demichelis et al., under review) performed with ELECTRE II. The AD performed both

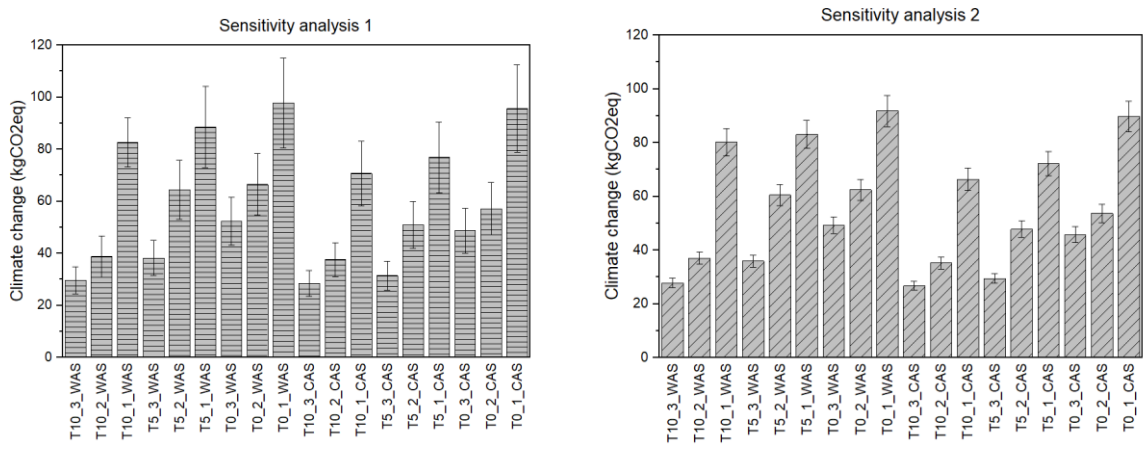
280 with inocula CAS and WAS at the highest S:I ratio (2:1) for the highest inocula incubation time (10 d) reached  
 281 the lowest Human toxicity, Ozone depletion, Cancer effect, Acidification, Terrestrial eutrophication, Marine  
 282 eutrophication, and Land uses values. These values agreed with (Fei et al., 2021). These outputs were due to  
 283 the higher valorisation of OFMSW reached working at higher S:I ratio and the correct disposal of digestate.  
 284 According to (Martinez-Sanchez et al., 2016) the main contribution to the above-mentioned impact categories  
 285 was the application of digestate as fertiliser.

286

### 287 3.2.2 Environmental sensitivity analysis

288 Two sensitivity analysis were performed. The first sensitive analysis was performed varying the following  
 289 parameters: kilometre of transport and collection of OFMSW, since recent studies prove that biomass yield  
 290 density (t/ha·y) varied with biomass supply distance (km) from biorefinery plant location. The transport of  
 291 OFMSW was increased and decreased respectively of plus and minus 10 km. In detail, according to the study  
 292 of (Golecha et al., 2016) a mutual influence and dependency between biomass yield density (t/ha·y) and supply  
 293 distance (km) was detected and the trend of GWP of the 18AD configurations did not change, but increasing  
 294 the transport (km) the GWP increase about 23-18% (Figure 2). The second sensitivity analysis for LCA was  
 295 applied changing the LHV of biogas of the 18 tested AD configuration of  $\pm 2.5\%$  of CH<sub>4</sub> (%v/v) content,  
 296 according to (Wang et al., 2020). Sensitivity analysis, performed by changing the LHV of CH<sub>4</sub>, witnessed that  
 297 GWP values ranged from -1.68. to +5.65 %, but the trend of the tested 18 AD configurations did not change  
 298 (Figure 2). To conclude, the environmental analysis proved that increasing both the S:I ratio and the inoculum  
 299 incubation time the environmental impacts decreased.

300



301 **Figure 2:** Sensitivity analysis. Sensitivity analysis 1 obtained by changing the transports of inoculum and  
 302 OFMSW +10 km and -10 km. Sensitivity analysis 2 obtained by changing the LHV of methane, +2.5 % -2.5  
 303 %.

304

### 305 **3.3 Economic sustainability**

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

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

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

316

#### 317 **3.3.1 Capital cost**

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

324

	HRT (d)	Inoculum (t)	H <sub>2</sub> O (m <sup>3</sup> )	Working.volume reactor(m <sup>3</sup> )	Volume reattor(m <sup>3</sup> )
<b>T0_1_WAS</b>	27	132000	2998.88	14849.9	18562.37
<b>T0_2_WAS</b>	27	66000	14000	9900	12375
<b>T0_3_WAS</b>	28	33000	19500	7700	9625

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

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

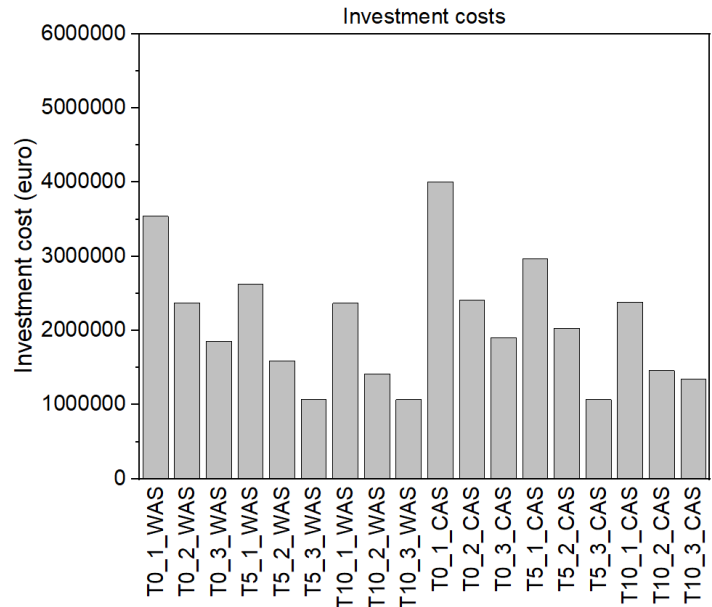
327

328 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  
329 was reported.

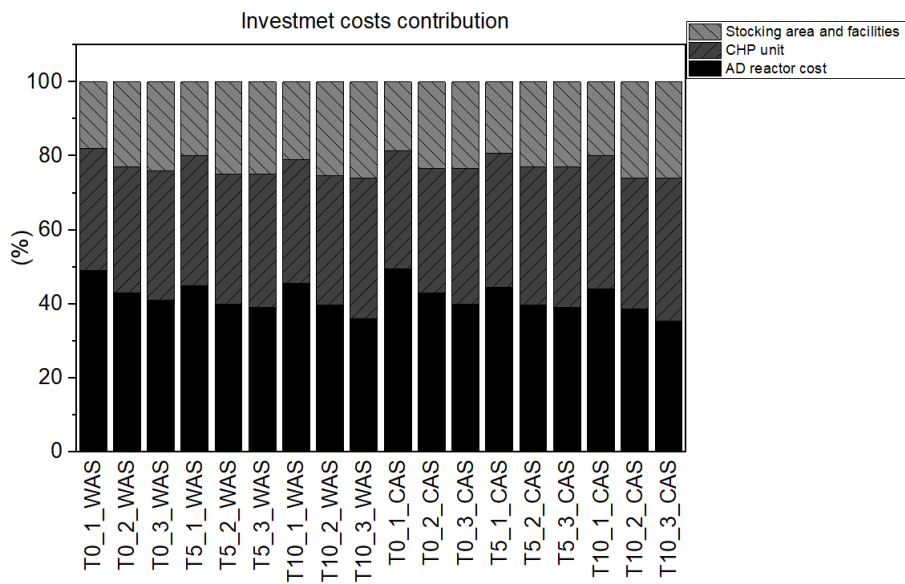
330 30,000 t of OFMSW per year was studied since was the minimum size for which all the 18 AD configuration  
331 were profitable after 5 years of amortisation.

332 The capital costs of the 18 AD configurations are depicted in Figure 3 as total investment costs (euro) and  
333 percentage contribute of each item (%). In detail, increasing the incubation time of the inoculum (5 and 10 d)  
334 and the S:I ratio both with CAS and WAS, the bio-reactor size decreased, because the HRT of the process  
335 decreased, and consequentially its purchase decreased from 49.00 % (T0\_1\_WAS) to 35.33% (T10\_3\_CAS)  
336 of total capital cost. Increasing the S:I ratio (1:1 and 2:1) and the inoculum incubation (5 and 10 d) the CHP  
337 unit cost contribution increased, since higher biogas rate was achieved. The capital costs of AD performed

338 both with WAS and CAS inocula incubated for 10d at S:I ratio equal to 2:1 agreed with the ones reached by  
 339 (Patinvoh et al., 2017) with dry AD.  
 340 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  
 341 like the ones obtained with dry AD (Qian et al., 2015).



342



343

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

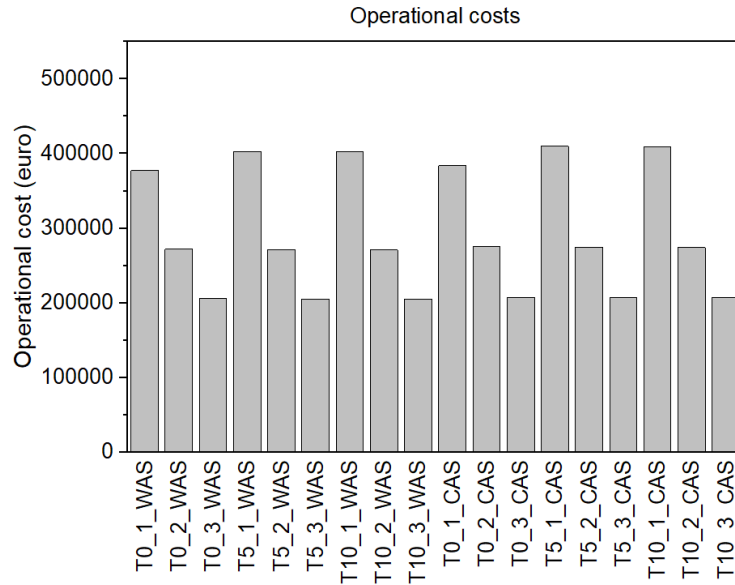
345

346 **3.3.2 Operational costs**

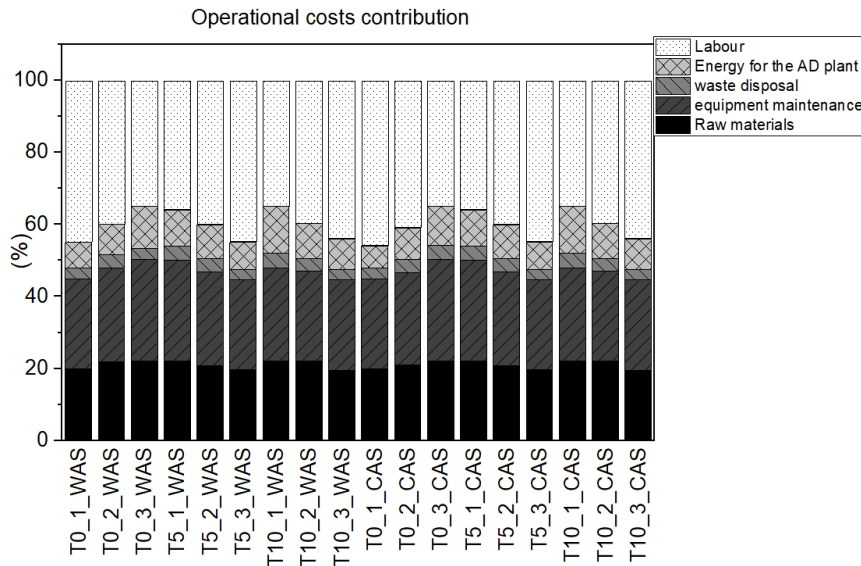
347 Operational costs included the cost of the raw material (i.e. transport of inoculum, the collection and transport  
348 of OFMSW to the AD plant), the equipment maintenance, the disposal of waste and residues, the labours and  
349 the utilities necessary to run the processes as fuel, steam, heat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

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

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



359



360

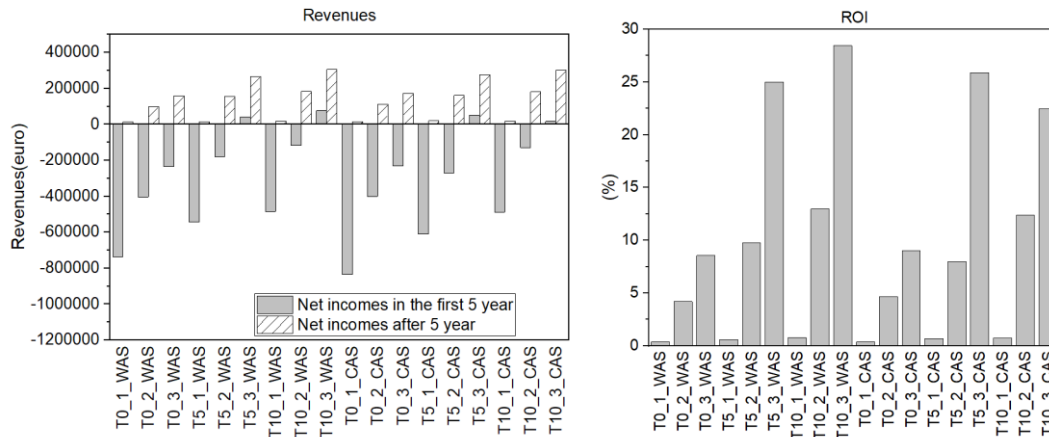
361 **Figure 4:** Operational costs (euro) and percentage contribution (%)

362

363 **3.3.3 Revenues**

364 Figure 5 depicts the incomes of the 18 AD configurations due to the differences between biogas trade and  
 365 capital and operational costs, before and after 5 years of amortization and ROI after 5 years of amortization.  
 366 In the first 5 years of life AD plant the only profitable configurations were AD performed with both inocula  
 367 CAS and WAS incubated for 5 and 10 d at the highest S:I (2:1), respectively: T5\_3\_WAS, T10\_3\_WAS  
 368 T5\_3\_CAS, T10\_3\_CAS. After 5 years of amortization all the 18 AD configurations were profitable and  
 369 among them the most profitable were: T10\_3\_WAS, T10\_3\_CAS. followed by T5\_3\_CAS and T5\_3\_WAS.

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



373

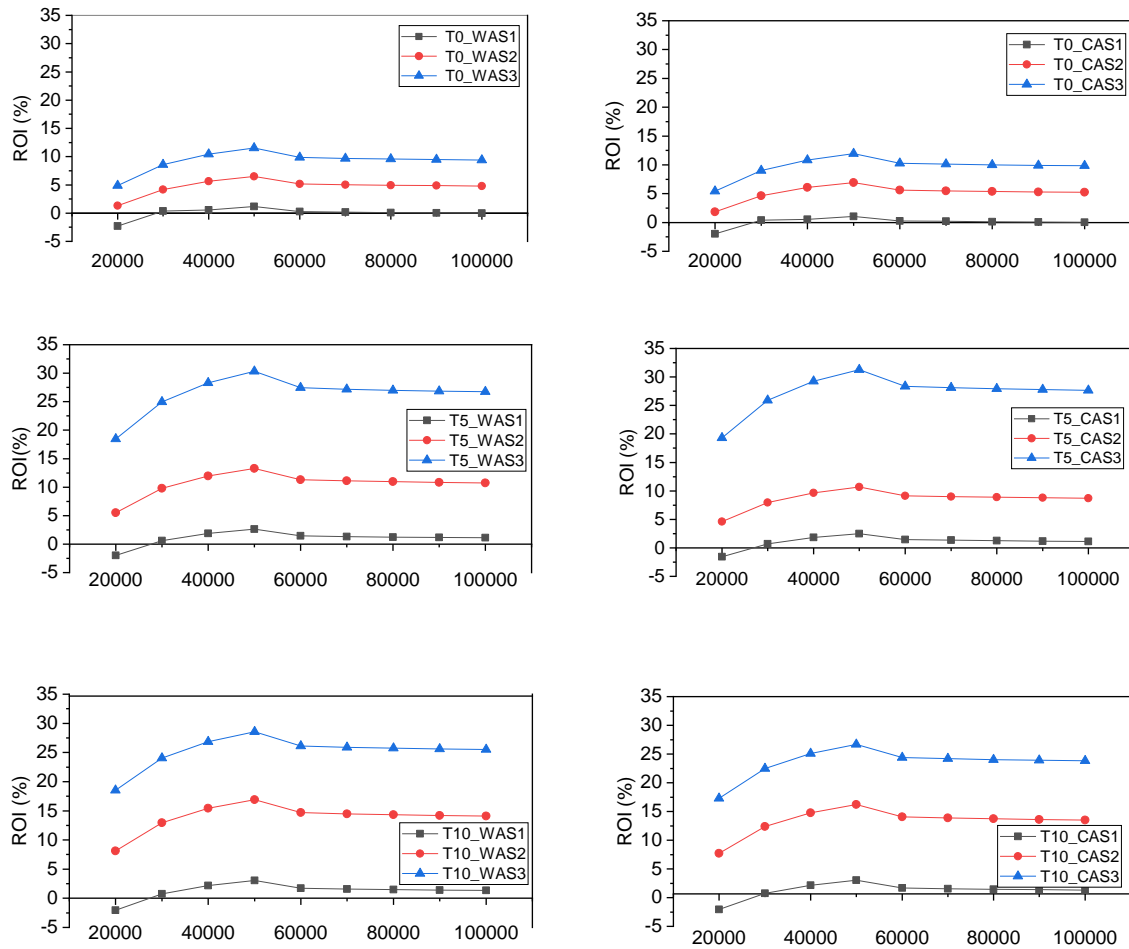
374 **Figure 5:** Revenues (euro) and ROI (%)

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

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

376

377 In particular, only four AD configuration (the AD performed with inocula WAS and CAS incubated for 5 and  
 378 10 d at the highest S:I ratio) had payback time minor of 20 y (the life service of the AD plant), NPV positive  
 379 and ROI higher than 20%. Among them, the T5\_3\_WAS reached best fit NPV, ROI and payback time,  
 380 respectively 2,810,068.86 euro, 28.45% and 11 y. The minimum size for which all the 18 AD configuration  
 381 were profitable after 5 years of amortization was 30,000 t/y of OFMSW. To identify the best fit between  
 382 capital, operational costs and revenues the study of ROI was performed for AD plant size from 20,000 t/y to  
 383 100,000 t/y (Figure 6). The best fit of economic assessment was detected for AD plant size equal to 50,000 t/y  
 384 according to (Demichelis et al., 2018) (Arias et al., 2020).



385

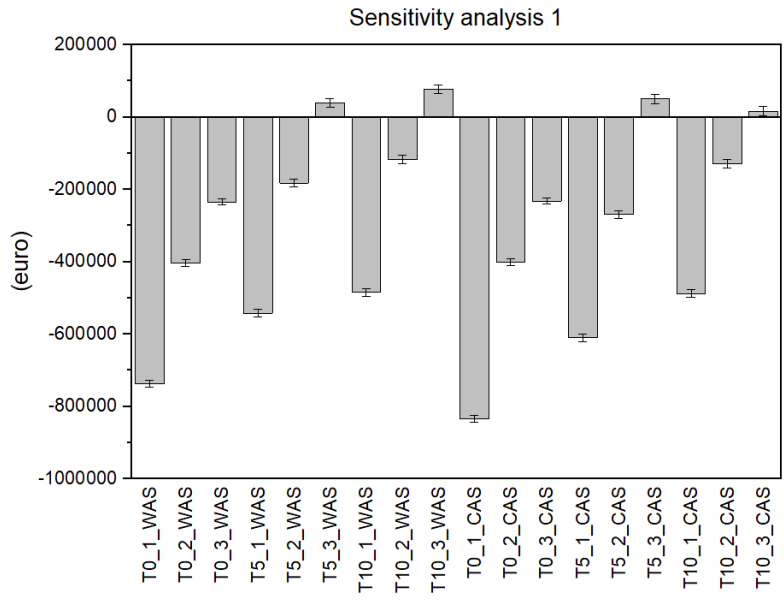
386 **Figure 6:** Evaluation of the AD plant size to obtain the maximal benefit CAPEX and OPEX. On x -coordinate  
 387 is reported the t of OFMSW per year considered.

388

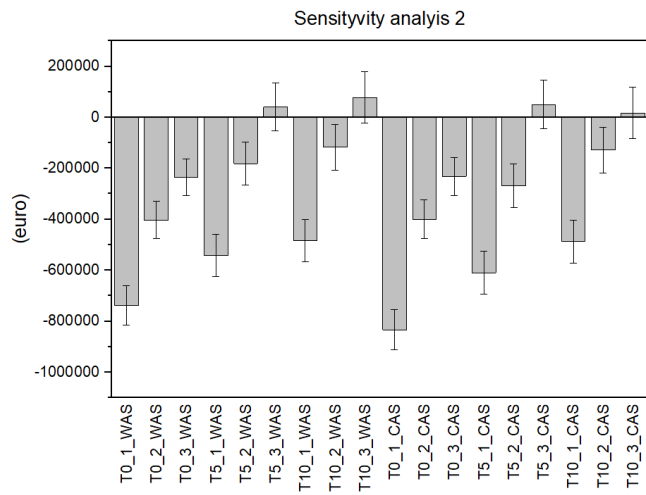
### 389 3.3.4 Economic sensitivity analysis

390 Two sensitivity analysis were performed. The first economic sensitivity analysis (Figure 7) was carried out as  
 391 the sensitivity for LCA, by changing the LHV of biogas of the 18 tested AD configuration from -2.5 to+2.5 %  
 392 of CH<sub>4</sub> (%v/v) content, according to (Wang et al., 2020). The sensitivity analysis was performed considering  
 393 the net revenues in the first 5 years of amortisation. Even if, the LHV of CH<sub>4</sub> was increased and decreased of  
 394 ± 2.5 %, the AD configuration economic profitable in the first 5 years of amortisation were T5\_3\_WAS,  
 395 T10\_3\_WAS, T5\_3\_CAS, T10\_3\_CAS. These results confirmed the outputs of economic assessment  
 396 described in sections 3.3.1, 3.3.2 and 3.3.3. In detail, among the profitable configurations: 1) increasing the  
 397 LHV of +2.5 % the revenues in the first 5 years of amortization was increased in the range from +22.42 % to  
 398 +42.71 %, respectively for T5\_3\_WAS and T10\_3\_CAS.; 2) decreasing the LHV of -2.5 % the revenues in

399 the first 5 years of amortization was decreased from 21.73% to 31.7 % respectively for T5\_3\_WAS and  
400 T10\_3\_CAS. The second sensitivity analysis (Figure 7) was performed by floating the biogas price of  $\pm 20\%$   
401 according to (Li et al., 2020).  
402 Even if, the price of CH<sub>4</sub> was increased and decreased of  $\pm 20\%$ , the AD configuration economic profitable in  
403 the first 5 year of amortisation were T5\_3\_WAS, T10\_3\_WAS T5\_3\_CAS, T10\_3\_CAS. Among the  
404 profitable configurations: 1) increasing the price of CH<sub>4</sub> of +20 % the revenues in the first 5 years of  
405 amortization were increased in the range from 20.11 % to 41.54 %, respectively for T5\_3\_WAS and  
406 T10\_3\_CAS; 2) decreasing the price of CH<sub>4</sub> of -20% the revenues in the first 5 years of amortization were  
407 decreased from 19.8 % to 29.72 % respectively for T5\_3\_WAS and T10\_3\_CAS. To conclude the economic  
408 sensitivity analysis, the following state can be asserted: by changing the LHV of CH<sub>4</sub> about  $\pm 2.5\%$  and the  
409 price of CH<sub>4</sub> in the range of  $\pm 20\%$ , the AD configuration economically profitable were always: T5\_3\_WAS,  
410 T10\_3\_WAS T5\_3\_CAS, T10\_3\_CAS.



411



412

413 **Figure 7:** Economic sensitivity analysis. Sensitivity analysis 1 obtained by changing the LHV of CH<sub>4</sub> about  
 414  $\pm 2.5$  %. The second sensitivity analysis was performed changing the price of CH<sub>4</sub> in the range of  $\pm 20$  %. The  
 415 sensitivity analysis was carried out on net revenues before 5 years of amortisation.

416

417 **Conclusions**

418 The aim of the present study was the evaluation of the environmental sustainability through Life Cycle  
 419 Assessment (LCA) and economic profitability through Life Cycle Costing (LCC) of the 18 AD configurations  
 420 carried out on OFMSW at three S:I ratio (1:2, 1:1 and 2:1) for three different inoculum incubation times (0, 5  
 421 and 10 d). The adopted approach was the eco-efficiency perspective, coming from the combination of

422 technical, environmental (LCA) and economic (LCC) perspectives. From environmental perspective:  
423 increasing both the S:I ratio and the inoculum incubation time (5 and 10 days) the environmental impacts  
424 decreased, since higher amount of OFMSW was valorised and specific production of biogas with higher  
425 methane content was achieved. The lowest values of Climate change were achieved by T10\_3\_WAS and  
426 T10\_3\_CAS: 28.67 and 27.72 kgCO<sub>2</sub> eq, respectively. LCC was developed to evaluate the economic  
427 profitability of the 18 AD configurations tested. The minimum AD plant size for which all the 18 AD  
428 configurations were profitable after 5 year of amortisation was 30,000 t/y of OFMSW. Capital and operational  
429 costs decreased by increasing the incubation time of the inoculum and the S:I ratio, since a higher specific  
430 biogas rate was reached, and smaller AD bio-reactor volume was adopted since HRT decreased. The AD plant  
431 size, for which maximal revenues and minimal capital and operational costs were evaluated, was 50,000 t/y  
432 OFMSW. To conclude, the AD configurations which reached both the environmental sustainability and  
433 economic profitability were: the AD performed both with inoculum WAS and CAS incubated for 5 and 10 d  
434 at the highest S:I ratio 2:1: T5\_3\_WAS, T5\_3\_CAS, T10\_3\_WAS and T10\_3\_CAS.

435

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**Politecnico  
di Torino**

Dipartimento  
di Scienza Applicata  
e Tecnologia

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**Francesca Demichelis,**

Phone: +39 011 090 4671; e-mail: [francesca.demichelis@polito.it](mailto:francesca.demichelis@polito.it)

Department of Applied Science and Technology (DISAT), Politecnico di Torino  
Corso Duca degli Abruzzi 24, 10129 Torino (TO) – Italy

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

Researcher at Politecnico di Torino