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1 **Life Cycle Assessment (LCA) of End-of-Life Dairy Products (EoL-DPs) valorization via**
2 **anaerobic co-digestion with agro-industrial wastes for biogas production**

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19 Declarations of interest: none
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21 **BACKGROUND:** The aim of the present study was to assess the environmental impacts
22 of End-of-Life Dairy Products (EoL-DPs) management via their co-treatment with agro-
23 industrial wastes (AgW) in a centralized biogas facility located in Cyprus using a gate-
24 to-gate LCA approach. Two different scenarios were examined under the framework of
25 this project. In the first one, co-treatment of EoL-DPs with various AgW (in a 20/80,
26 w/w, ratio) was evaluated in a one-stage mesophilic anaerobic digestion (AD) process.
27 In the second scenario, the same amount of EoL-DPs were acidified before
28 methanogenesis with AgW in order to improve biogas production.

29 **RESULTS:** Prior acidification of EoL-DPs showed a better environmental performance
30 compared to the results obtained upon direct co-digestion in a mesophilic digester,
31 having a total impact of 52.44 Pt against 57.13 Pt respectively. Biogas production upon
32 acidification, and therefore energy yield, was higher reaching up to 22.88 m³ CH₄/ton
33 of feed (229.25 kWh/ton of feed), compared to 17.45 m³ CH₄/on of feed (174.85
34 kWh/ton of feed) for the case where no pretreatment was performed.

35 **CONCLUSIONS:** The acidification of EoL-DPs enhanced the environmental performance
36 of the process by reducing its impact by 8.2% (in Pt equivalents). The energy
37 consumption of the biogas plant mixing equipment was identified as the process
38 hotspot. However, further analysis of the environmental performance of the proposed
39 process is required by extending the system's boundaries towards a Cradle-to-Grave
40 approach.

41

42 *Keywords: End-of-Life Dairy Products; Agro-industrial Wastes; Anaerobic Digestion; Life*

43 *Cycle Assessment; Bioenergy.*

44

45 INTRODUCTION

46 Nowadays, general scientific consensus believes that global warming is caused by the
47 emission of anthropogenic greenhouse gases (GHG), mainly derived from fossil fuel
48 combustion ¹. As a result, the demand for renewable energy is rising because of the
49 increasing social awareness of consequences related to non-renewable energy use,
50 e.g. fossil fuel depletion, energy security, and climate change (CC). Renewable energy
51 production in the European Union is targeted to reach 20% and 27% of the total
52 energy production by 2020 and 2030 respectively ^{2,3}. This transition requires insight
53 into environmental alternatives of producing renewable energy, including CC, fossil
54 fuel depletion, and land use changes. Bioenergy is a renewable form of energy
55 produced from biomass, including energy crops, wood, microbial biomass as well as
56 wastes from household, agriculture, cattle, forestry and industrial activities ⁴.
57 Currently, there is a growing interest on the use of biomass for energy purposes in
58 order to satisfy energy requirements all over Europe ⁵. Since biomass accounts for 2/3
59 of the renewable energy produced in Europe, its valorization results in lower
60 dependency on fossil fuels for many European countries, depending on biomass local
61 resources, in order to meet the renewable energy directive objectives ^{6,3}.

62 Biomass can be converted by anaerobic digestion (AD) into biogas, composed
63 of methane (CH₄), carbon dioxide (CO₂) and some trace gases (e.g., hydrogen). It is
64 worth noting that in 2013 total biogas produced in Europe reached 14 billion m³, as in
65 natural gas equivalent, whereas the projection for 2020 is about 28 billion m³ ⁷. Biogas
66 obtained can be exploited in situ to produce electricity or heat or preferably a
67 combination of both through cogeneration in a combined heat and power (CHP) unit.

68 On the other hand, it can be upgraded to the natural gas standards, in the form of
69 biomethane, with a methane content up to 98%. Biomethane can be then forwarded
70 to local natural gas distribution networks in order to be used for electricity and power
71 generation. It can be also used for heating purposes either alone or blended with
72 natural gas. Alternative scenarios include its application as a transportation fuel or a
73 high-tech process energy and raw material for the chemical industry ^{7,3}.

74 Main substrates for AD include agricultural biomass, in the form of animal
75 manures and energy crops (e.g. maize, rye and grass silage), organic residues from
76 processing industries (e.g. glycerin, food waste, beet tails, slaughterhouse wastes etc.),
77 and other organic residues such as roadside grass, forest residues, sewage sludge
78 etc. ⁸. Those feedstocks are characterized by a methane content, in the produced
79 biogas, ranging between 51-72% ⁹. Biogas has the potential to deliver more than 1/3 of
80 natural gas production in Europe and could reach about 15-25% of total bioenergy
81 produced by 2020, compared to 7% in 2007 ³. According to the European Biogas
82 Association, biogas plants in Europe increased by 3%, from 16,834 to 17,376, in 2015
83 and the total amount of electricity produced from biogas is approximately 63.3 TWh,
84 corresponding to the annual consumption of 14.6 million European households ¹⁰.
85 Germany has been in the lead, with 10,846 biogas plants, valorizing mainly agricultural
86 feedstocks (energy crops and agricultural residues), followed by Italy (1,555), France
87 (717), Switzerland (638), Czech Republic (554) and UK (523) ^{10,11}. By the end of 2015,
88 fourteen biogas plants were operating in Cyprus, based on agricultural feedstocks.
89 Their installed electrical capacity was approximately 10 MW_{el}, generating 37.5 GWh of
90 electricity, that represents less than 1% of the total electricity produced per annum ¹².

91 The remaining biomass after AD, so-called digestate, can be further valorized as
92 organic fertilizer for crop cultivation, partly substituting mineral fertilizers ¹³. In
93 general, digestate is considered as an upgraded organic fertilizer since it is rich in
94 nitrogen. When digestates are applied according to best practice guidelines, that have
95 been recently researched and developed (such as better management and storage
96 conditions, i.e. storage facilities that are covered and/or have a high depth to surface
97 area ratio) ¹⁴ they can be considered as an environmentally benign material ¹⁵. Types of
98 digestate that are considered acceptable for use by organic farmers and growers are
99 listed in the EU regulation for organic farming ¹⁶. In addition, in several countries,
100 especially in the UK, independent quality assurance schemes have been developed in
101 order to provide confidence to the market and the society that digestates are safe,
102 consistent and appropriate for use ¹⁷⁻²¹. According to those schemes and regulations,
103 permitted waste input materials include wastes from dairy industry, such as materials
104 unsuitable for consumption or processing (solid and liquid dairy products, milk, food
105 processing wastes, yoghurt and whey) and biological sludge from on-site effluent
106 treatment. Anaerobic digestion, and further composting of the digestate, are currently
107 considered the most important technologies for the transformation of waste biomass
108 to biogas and nutrient recovery and account for up to 95% of biological treatment
109 performed for organic waste ²²⁻²⁴.

110 Uptodate, the majority of biogas plants are configured as single-stage
111 installations. In this way, the microbial consortia that convert the biodegradable organic
112 matter to biogas are present within a single tank and operate under sub-optimal
113 conditions to achieve an overall balance between the sub-processes, i.e. hydrolysis,
114 acidogenesis, acetogenesis, methanogenesis. A variation of the traditional single-stage
115 configuration is the two-stage system in which two reactors are placed in series and
116 optimal trophic conditions are formulated for the distinct anaerobic microbial consortia.
117 Hydrolytic and acidogenic bacteria prevail in the first reactor, whereas methanogenic
118 archaea dominate in the second one. Such configuration may a) produce hydrogen along
119 with volatile fatty acids in the acidogenic stage and increase the methane production in
120 the second (methanogenic) stage ²⁵, and b) avoid the imbalance caused by increased

121 acid production by the faster-growing acidogenic bacteria and the slower organic acid
122 consumption by the more sensitive methanogens, maintaining thus more favorable
123 conditions for the different microbial groups ²⁶, among other advantages. Such a two-
124 stage configuration may lead to increased energy production ²⁵ due to the production
125 of hydrogen and methane blend and reduced key exhaust emissions when burning the
126 blend in an internal combustion engine compared with burning of methane alone ²⁷.
127 Although the two-stage anaerobic digestion systems seem to outmatch the
128 conventional single-stage AD systems in various points it is still unclear if they will lead
129 to real environmental benefits. One way to investigate this is via Life Cycle Assessment
130 (LCA).

131 Several studies have been conducted focusing on the energy balances and
132 emissions of anaerobic digestion of various feedstocks, most notably studies by Styles
133 et al.²⁸, Fusi et al. ²⁹, Lijó et al. ³⁰. However, relatively little environmental assessment
134 work has been carried out for two-stage biogas production processes. Patterson et al.,
135 compared the environmental burdens of a single-stage biogas (methane) production
136 system against a two-stage (hydrogen/methane) production system using two
137 feedstocks with different characteristics and classifications. The systems boundaries
138 included raw biogas upgrade and its utilization as a vehicle fuel. The study showed that
139 the two-stage process using both feedstocks leads to reduction of the fossil fuel (diesel)
140 burdens compared to the single-stage treatment ³¹. Isola et al. assessed the
141 environmental impacts of a portable two-stage AD system fed with a mixture of food
142 waste and cardboard. According to their results the biogas generation rates from the
143 portable AD system were comparable to a conventional full-scale system, while the
144 biogas combustion impacts were more sustainable compared to those associated with
145 conventional fossil fuels ³².

146 Under the framework of LIFE10 ENV/CY/000721 project (Acronym: DAIRIUS) a
147 methodology has been developed in lab and pilot (demonstration) scale, for the
148 integrated management of EoL-DPs in Cyprus. The methodology included the
149 collection and transportation of EoL-DPs in a centralized biogas plant where EoL-DPs
150 were co-treated with agro-industrial wastes (AgW). Valorization scenarios of those

151 residues, that were examined in the present study, regarded their anaerobic co-
152 digestion using a two-stage process realized in Continuous Stirred Tank Reactors
153 (CSTR), where EoL-DPs were acidified in a CSTR reactor, prior to their mixing with AgW
154 in a methanogenic CSTR. In addition, co-digestion of EoL-DPs with AgW, in a single-
155 stage CSTR was also investigated. The two systems were comparatively tested for a
156 period of 9 months under pilot-scale conditions ²⁵ and the environmental performance
157 of the processes which was assessed using a gate-to-gate LCA methodology is
158 presented in this work.

159

160 **EXPERIMENTAL**

161 **Pilot plant configuration**

162 The pilot-scale experimental setup consisted of two conventional CSTR reactors,
163 constructed by stainless steel, with 0.09/0.2 m³ (acidogenic-CSTR) and 1.8/2.0 m³
164 (methanogenic-CSTR), working and total volume respectively. Both reactors were
165 periodically agitated, with a time-scheduled ON/OFF mode. The pilot plant comprised
166 also of two stainless steel stirred feeding tanks with 0.2 m³ total volume, one for the
167 agro-industrial wastes (AgW) mixture and the other one for the EoL-DPs mixture. Both
168 the acidogenic and the methanogenic reactor were operated under controlled
169 mesophilic conditions (37 ± 1 °C). The system had been operating for a total period of
170 350 days in the premises of a full-scale biogas facility (1 MW_{el}) co-digesting AgW in
171 Cyprus. The AgW feedstock used was the same for the full scale and the pilot plant
172 system. In the first operational phase, the system run in a two-stage mode, with the
173 acidogenic reactor fed exclusively with EoL-DPs. After acidification the acidified
174 mixture was mixed with agro-industrial wastes (AgW) and co-digested in the

175 methanogenic bioreactor. In the second operating phase, the system operated without
176 the acidogenic stage, in a single-stage mode. The mixture of raw EoL-DPs and AgW was
177 directly fed and co-digested in the methanogenic bioreactor. Both systems were
178 operated at Hydraulic Retention Time (HRT) of 37 days with the EoL-DPs mixture
179 accounting for ~20% (w/w) of the total feeding stream. Further details on the systems
180 specifications and their operating performance during co-digestion under the different
181 operating scenarios have been previously described and can be found in our recent
182 study ²⁵.

183

184 **LCA methodology**

185 Life cycle assessment (LCA) is an internationally accepted methodology used to provide
186 insight into the environmental consequences of a process ³³. Its aim is to holistically
187 evaluate the environmental consequences of a product system or activity, by
188 quantifying the energy and materials used, the wastes released to the environment,
189 and assessing the environmental impacts of those in terms of energy, materials and
190 wastes. The environmental analysis conducted in this work was carried out according
191 to ISO 14040 guidelines and recommendations ³⁴.

192 This LCA study was focused on the evaluation of the two AD processes tested in
193 the LIFE+ DAIRIUS project, with a view to the optimum energy valorization of EoL-DPs.
194 In such a gate-to-gate LCA, the upstream and downstream processes were not taken
195 into consideration, whereas waste treatment and bioenergy production were the
196 fundamental parts in the assessment boundaries.

197

198 **Goal and scope**

199 The goal of this assessment was to identify, analyze and compare the life cycle
200 environmental impacts from a full-scale anaerobic co-digestion plant (AD) fed with
201 AgW and EoL-DPs in a ratio of 80%-20% (w/w) operating in either a single- or two-
202 stage mode. In the second case, the acidification of the EoL-DPs stream takes place in
203 an acidogenic reactor prior to its mixing with AgW and feeding to the methanogenic
204 reactor. The objective was to identify hotspots affecting the environmental load of a
205 biogas generation plant. The impacts caused by the two scenarios were analyzed,
206 including the ones avoided from the displacement of fossil fuels. Comparison of the
207 two processes was also performed, based on their environmental performance. By
208 determining the environmental load of biogas production from AD, it is possible to
209 identify whether the processes have beneficial or detrimental effects on the
210 environment.

211 If not all of the Life Cycle Assessment (LCA) can be carried out on the full life
212 cycle (from cradle-to-grave), special attention should be given in the analysis of the
213 intermediate stages of a product's life (from cradle-to-gate or from gate-to-gate) ³⁵.
214 For this LCA study, the complete life cycle inventory of industrial scale biogas
215 production with EoL-DPs is unavailable at the early design stage, which makes the
216 partial LCA (from gate-to-gate and nearly gate-to-grave) appropriate and practical for
217 evaluating possible environmental impacts. In this gate-to-gate LCA, the upstream (i.e.
218 the stages of production, collection and transportation of AgW and EoL-DPs to the AD

219 plant) and downstream stages (final use of generated products, such as digestate) of
220 the process developed will not be considered unless otherwise mentioned. The
221 biomass processing and energy production was the fundamental parts in the
222 considered assessment boundaries.

223

224 **Key assumptions**

225 The functional unit must represent the function (common reference unit) of the
226 options compared ³⁶. The main function compared in this study is the bioconversion of
227 waste matter (biomass) into biogas and liquid fertilizer using either a single- or two-
228 stage mode of operation in the anaerobic digestion plant. So, in our case, for all
229 processes and treatment scenarios assessed, 1 ton of raw biomass consisting of 80%
230 (w/w) AgW and 20% (w/w) EoL-DPs, was used as the functional unit. In all scenarios
231 studied in this LCA analysis, the system boundaries were drawn within the biogas plant
232 limits once raw AgW materials and EoL-DPs were delivered to the plant. The data
233 obtained by the pilot plant operation were of vital importance. Based on those data,
234 the realistic energy requirements of such a system and the physicochemical
235 characteristics of the outputs were determined.

236 The present assessment examined the use of generated biogas for electricity
237 and thermal energy production. Electricity was considered to be directed to the grid
238 and consumed at the vicinity of the plant (gate-to-grave approach) ignoring thus any
239 losses in the electricity grid due to distribution, whereas thermal energy was only used
240 to cover the plant's own needs. However, AgW production and transportation to the
241 plant, supply of the feedstock to the plant, transportation of the EoL-DPs to the plant,

242 de-packaging and packages recycling, transportation and distribution of the digestate
243 were not included in this LCA, since the main target of this work was to compare the
244 two waste treatment scenarios. Possible methane emissions from manure storage on
245 the total global warming potential (GWP) of the biogas system were not taken into
246 account due to the fact that feedstock was used directly for feeding in the system. It
247 was also considered that the time needed for the various AgW to be treated via
248 anaerobic digestion is negligible compared to the timescale of environmental impacts.
249 Although the processing of anaerobic effluent (digestate) via centrifugation and the
250 subsequent treatment of the recovered solid fraction of digestate via aerobic
251 composting were considered as part of the system processes, and thus within the
252 system boundaries, the packaging of the produced compost and its distribution to the
253 market or direct spreading as a fertilizer was kept out (gate-to-gate approach).
254 However, it was assumed that the liquid fraction generated from digestate processing,
255 was directly spread in the surrounding area of the biogas plant facility for cultivation
256 purposes, avoiding thus any transportation (gate-to-grave approach). Alternative
257 processing of the liquid digestate fraction, such as aerobic or membrane treatment,
258 was not considered due to the complexity that would have been added to the
259 scenarios compared in this study. The comparison of such alternative practices could
260 be the goal of another LCA and thus is considered to exceed the scope of the present
261 study, which mainly deals with the environmental assessment of the AD configurations
262 tested for the exploitation of the EoL-DPs.

263

264 **System description**

265 Once agro-industrial wastes (i.e. 49% pig manure (PM), 14% liquid cow manure (LCM),
266 9% cheese whey (CW), 5% poultry wastes (PW) and 4% slaughterhouse wastes (SHW))
267 and EoL-DPs (consisting of 93% milk, 5% yogurt, 2% white cheese) were collected, they
268 were transported to the main plant. In the first scenario, the EoL-DPs were acidified,
269 while simultaneous biohydrogen production was taking place (in an acidogenic CSTR
270 reactor under mesophilic pH-controlled conditions at $\text{pH } 5.7 \pm 0.1$) and after mixing with
271 the AgW were fed into the methanogenic mesophilic digester. On the other hand, in
272 the second scenario, the EoL-DPs were mixed with AgW and fed directly into the main
273 mesophilic digester. Recovered biogas from the bioreactor(s), containing carbon
274 dioxide and methane (methanogenic reactor) and hydrogen (in the case of two-stage
275 configuration), was burnt in a Combined Heat and Power (CHP) generator for the
276 production of electrical and thermal energy. The operating hydraulic retention time
277 (HRT), in both methanogenic reactors, was considered to be the same (37 days),
278 simulating the operating conditions of the full-scale plant. The system boundaries of
279 the two bioprocesses are illustrated in Fig. 1 and Fig. 2, for scenario 1 and 2
280 respectively.

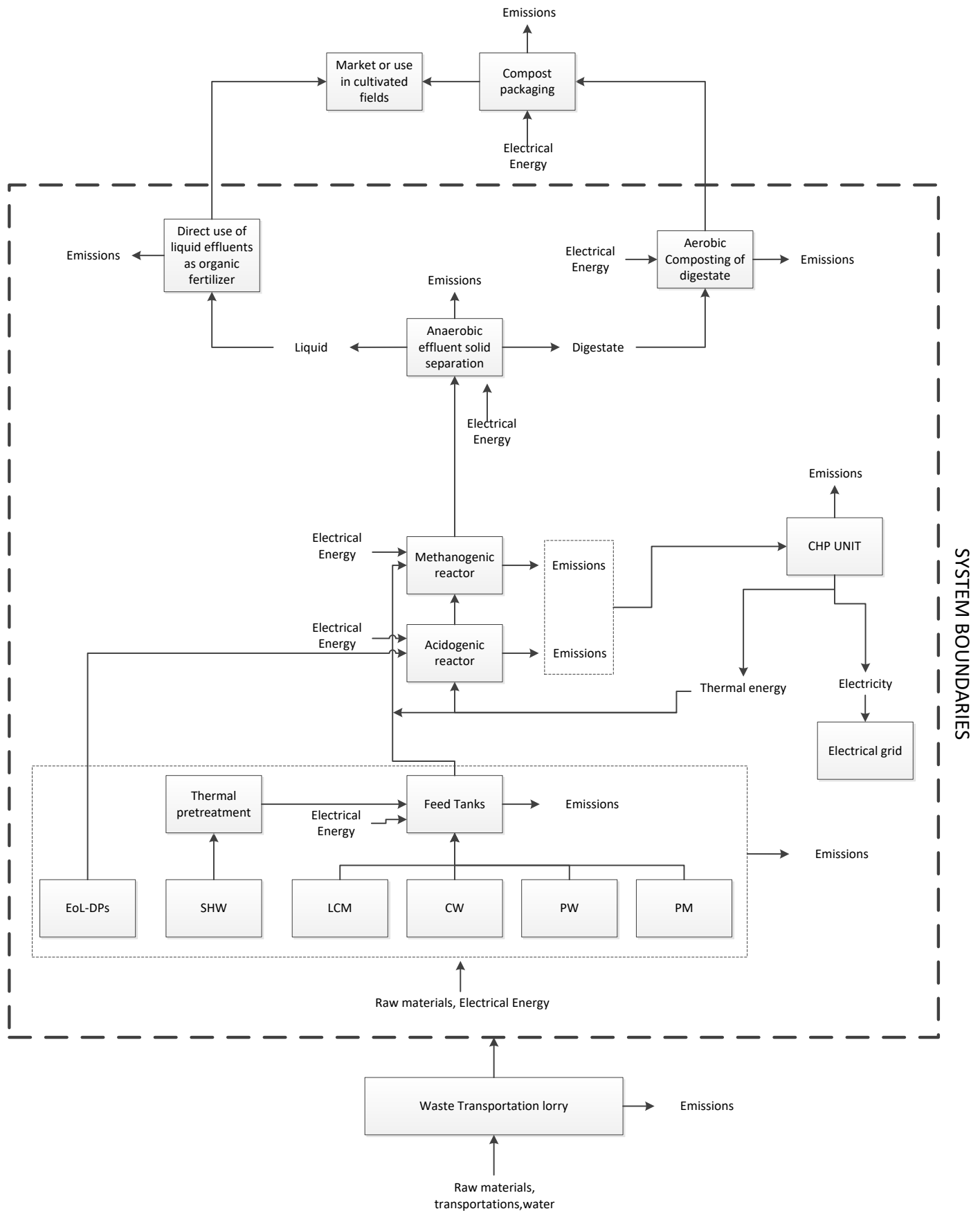
281 The system boundaries for both processes in this gate-to-gate LCA were
282 defined from the physical limits of a typical centralized biogas plant, starting from the
283 raw materials processing inside the facilities of the biogas plant including the energy
284 production, the aerobic composting of produced digestate as well as the direct
285 spreading and use of liquid digestate to adjacent arable land as water for irrigation.
286 Only the inputs (e.g. raw materials, energy) and outputs (e.g. emissions) associated
287 with the processes within the boundary limits were included. The inputs used for the

288 LCI database were the raw materials and energy needs, whereas outputs were the
289 emissions to the biosphere resulting from each process. Upstream activities (e.g.
290 animal breeding in cow farms, milk processing, cheese making, etc), transport and
291 downstream activities (e.g. distribution of the electrical energy to the grid, compost
292 packaging and usage) were not included within the boundaries of this study.

293

294 **Inventory data sources**

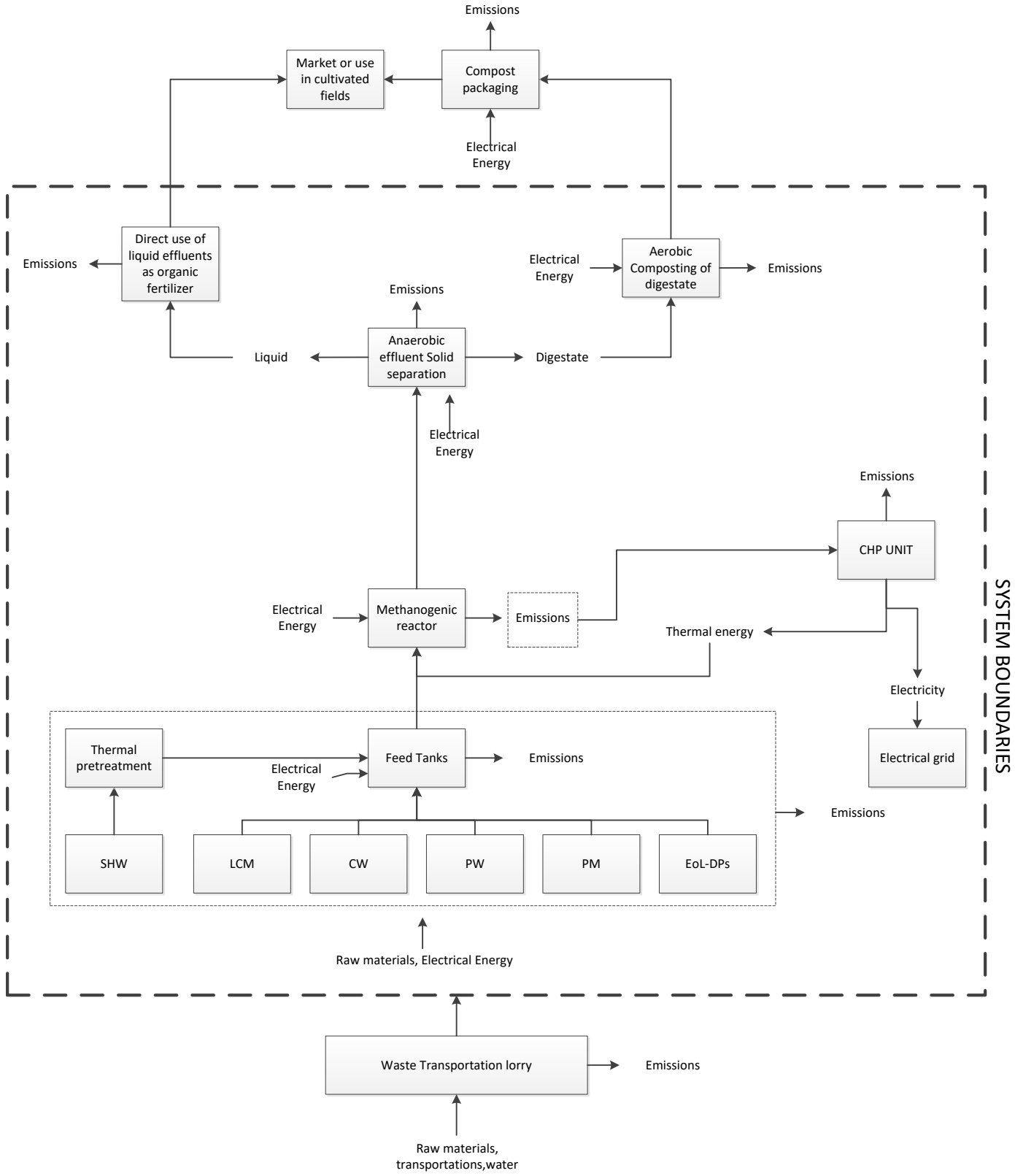
295 Inventory analysis aims to quantify the inputs and outputs within the system
296 boundaries. The result of an inventory is a long list of material and energy requirements,



297
298

299 **Figure 1.** System boundaries for an anaerobic co-digestion plant utilizing AgW and acidified EoL-DPs as
300 feedstocks for biogas production in a two-stage process. Agro-industrial wastes (AgW) include

301 Slaughterhouse Wastes (SHW), Liquid Cow Manure (LCM), Cheese Whey (CW), Poultry Wastes (PW) and
 302 Pig Manure (PM). CHP: Combined Heat and Power.



303
 304

305 **Figure 2.** System boundaries for an anaerobic co-digestion plant utilizing AgW and EoL-DPs as feedstocks
 306 for biogas production in a single-stage process. Agro-industrial wastes (AgW) include Slaughterhouse

307 Wastes (SHW), Liquid Cow Manure (LCM), Cheese Whey (CW), Poultry Wastes (PW) and Pig Manure
308 (PM). CHP: Combined Heat and Power.

309

310 products and co-products as well as waste and outputs into the air, soil and water. This
311 list is referred to as the mass and energy balance or the inventory table. To establish a
312 life cycle inventory (LCI), the first phase is to survey and collect the life cycle data related
313 to the product system, from inputs to outputs. Life-cycle data concerning gaseous
314 emissions from biogas burning were obtained from a library of SimaPro 8.0.2 referring
315 to a 100 kW_{el} (kilowatt electrical power) CHP engine having an electrical efficiency of
316 38% and a thermal efficiency of 46%.

317 LCI data were calculated on the basis of the functional unit of 1 ton of raw
318 material entering the plant, and the energy needs for its treatment. For all processes,
319 the calculation of the energy needs and electricity production was carried out with the
320 hypothesis that all processes are carried out in Cyprus. Cyprus does not currently have
321 any primary energy sources and thus generation of electricity by the Electricity
322 Authority of Cyprus (EAC) is based exclusively on imported fuels, mainly crude oil.
323 Electricity production takes place in three power stations with a total installed capacity
324 of 1478 MW, as presented in SM Table 1.

325 The inputs into the AD process were the electricity use, for transferring wastes
326 between tanks within the facilities of the biogas plant, and stirring of different tanks
327 (i.e. mixing tank, acidogenesis and methanogenesis reactors, buffering and storage
328 tank). The thermal energy required for heating the anaerobic digester(s) at mesophilic
329 conditions (i.e. 37 °C) and also for the pretreatment of SHW (80 °C for 2 hours) was a
330 fraction of the thermal energy recovered by the CHP unit after the combustion of the
331 produced biogas. Thus, external use of heat energy was not considered in the LCA,
332 since it was produced and consumed within the boundaries of the system.

333 The energy yields of the scenarios investigated in this study were based on
334 calculations performed using results obtained from the demonstration pilot plant,
335 which was operated in the framework of LIFE+ DAIRIUS project in Cyprus (see SM
336 Table 2).

337 The energy equivalents used for the determination of the energy yields of the
338 systems after combustion in a typical CHP generator are given in SM Table 3.

339 The energy requirements of the equipment of the system assessed and their
340 operational period, by using a reference unit of 1 ton of treated effluent it is presented
341 in SM Table 4.

342

343 **Impact assessment**

344 Life cycle impact assessment is the phase where the results of the inventory analysis are
345 interpreted in terms of the impacts they have on the environment. The impact
346 assessments of the processes developed during LIFE+ DAIRIUS project were based on
347 the internationally accepted ReCipe v.1.03. ReCiPe comprises a broadest set of endpoint
348 impact categories, including several environmental issues, to assess environmental
349 impact. Moreover, the results were simulated using the three different perspectives,
350 namely individualist (I), hierarchist (H) and egalitarian (E). The latter was finally chosen
351 to evaluate the results, since it takes into account the long term, precautionary
352 environmental impacts, which better serve the scope of this study and thus the
353 following impact categories were identified: Climate change, Human health, Ozone
354 depletion, Human toxicity, Photochemical oxidant formation, Particulate matter

355 formation, Ionizing radiation, Climate change Ecosystems, Terrestrial acidification,
356 Freshwater eutrophication, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine
357 ecotoxicity, Agricultural land occupation, Urban land occupation, Natural land
358 transformation, Metal depletion, Fossil depletion. Weighting of the results are also
359 included in the present study which has been expressed by using the Pt value. Pt is a
360 dimensionless value and each unit is equal to one thousandth of the yearly
361 environmental load of one average European inhabitant.

362

363 **RESULTS**

364 Based on the goal of this study, the hotspots of EoL-DPs and AgW treatments proposed
365 here were identified. Moreover, the overall environmental performance of each
366 treatment scenario per ton of raw organic mixture entering the system, was quantified
367 and presented per impact category.

368

369 **Overview of the results for Scenario 1 (two-stage system)**

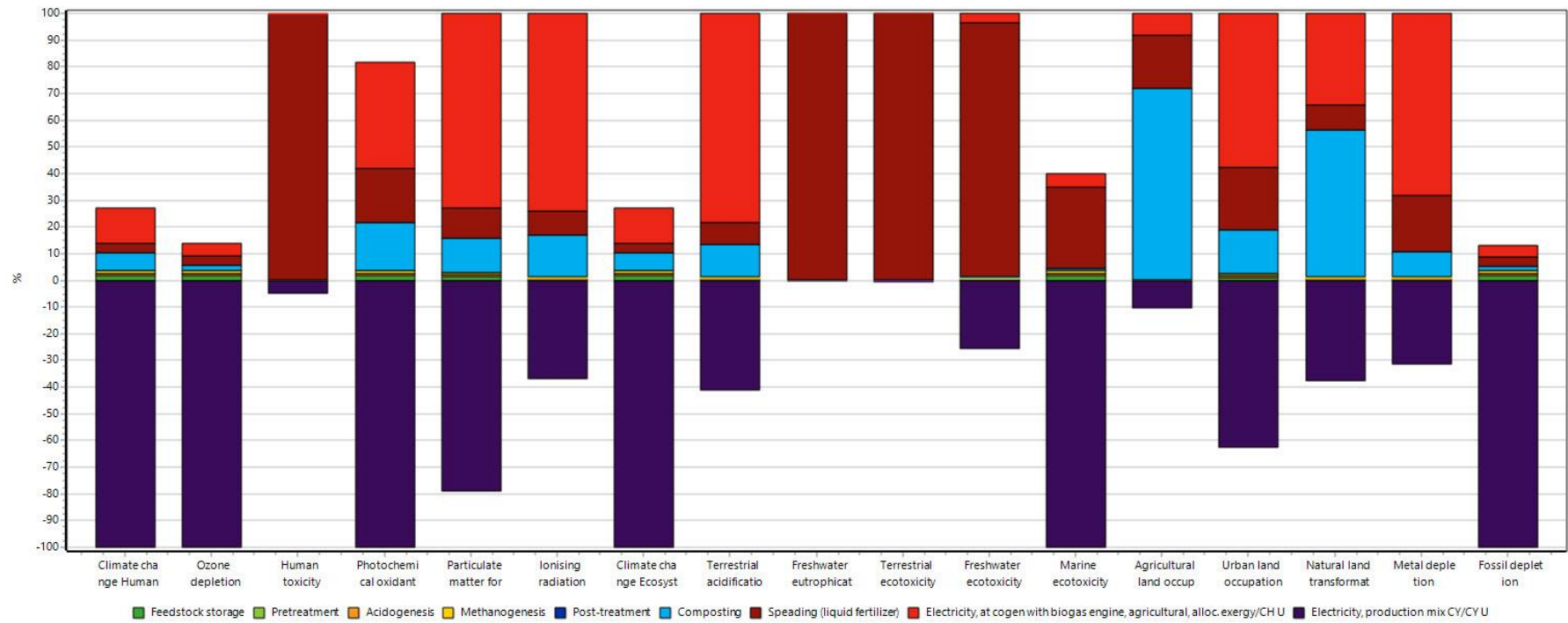
370 The operating scenario of the two-stage process included the acidification of the EoL-
371 DPs in a mesophilic CSTR followed by their co-digestion with the AgW mixture. Under
372 the frame of this operating strategy a 31.1% overall increase in the energy yield of the
373 system was evident (SM Table 2). The main difference in the two operating scenarios
374 was the addition of an acidification step, and thus the supplementation of the LCI with

375 the relative energy inputs and outputs. More information regarding the systems'
376 performance in terms of biofuels production can be found in our recent study ²⁵.

377 The LCIA results of the process for the co-treatment of EoL-DPs with the
378 aforementioned AgW mixture, expressed per ton of raw biomass entering the plant,
379 are presented in Fig. 3 (for details see SM Table 5). As can be seen, the environmental
380 performance of this scenario is generally affected by the composting process, the
381 application of the liquid digested matter to the land as fertilizer and the biogas
382 production stage, as a result of the atmospheric emissions generated during the
383 combustion of biogas in the CHP engine. The pretreatment stage had negligible effect
384 on the environmental performance of the system. The main inputs of the LCIA were
385 the electricity consumption due to the equipment used, while the main outputs were
386 the emissions (CO₂) generated by the CHP engine during the combustion of the biogas
387 and the biogenic emissions from the metabolic activity of the microorganisms during
388 composting. The use of digested liquid (anaerobic effluent) as fertilizer in agricultural
389 soil in the surrounding area of the biogas unit (without taking into account the
390 transportation of this liquid fertilizer) has also been part of this inventory.

391 Normalization is an optional step in LCA that is used for better understanding
392 the relative importance and magnitude of the impact category indicator results³⁷.
393 Results obtained upon normalization are shown in Fig. 4. The most significant impact
394 categories are shown to be human toxicity and terrestrial ecotoxicology of the liquid
395 digested stream after its application as organic fertilizer. The rest of the parameters
396 had negligible effect on the environmental parameters assessed.

397 Based on the pilot plant results, the effect of the additional acidification step
398 on the energy consumption of the unit was negligible. So, the environmental
399 performance of such a plant was not affected as a result of the energy requirements of
400 the equipment used by the acidification stage.

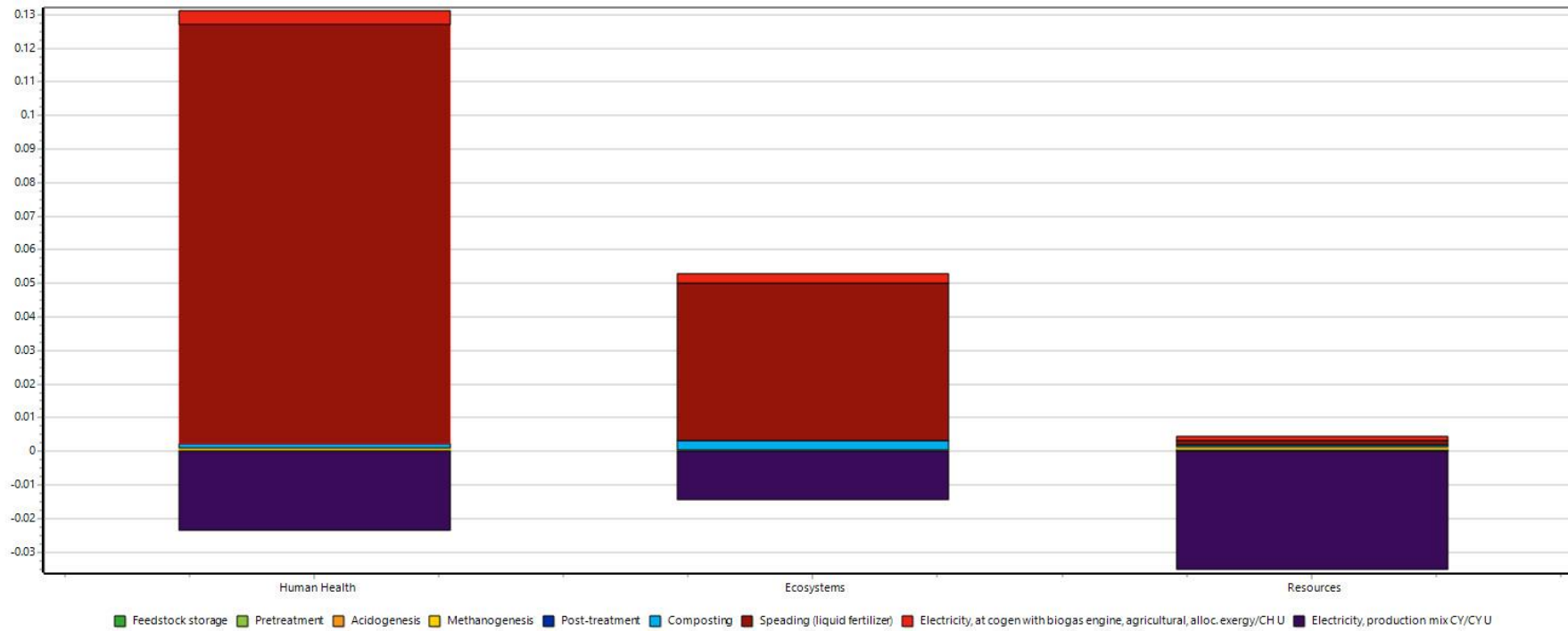


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Figure 3. Characterization data for Scenario 1 (two-stage system operation)



404

405

Figure 4. Normalization results for Scenario 1 (two-stage system operation)

406

407 In Table 1 the weighting of the impacts of Scenario 1 is shown. A total impact of
408 52.44 Pt is presented, while the disposal of the liquid digested stream is responsible for
409 68.82 Pt. In that Table the merits on the environment from the renewable energy
410 produced and the positive effect on fossil depletion are evident.

411

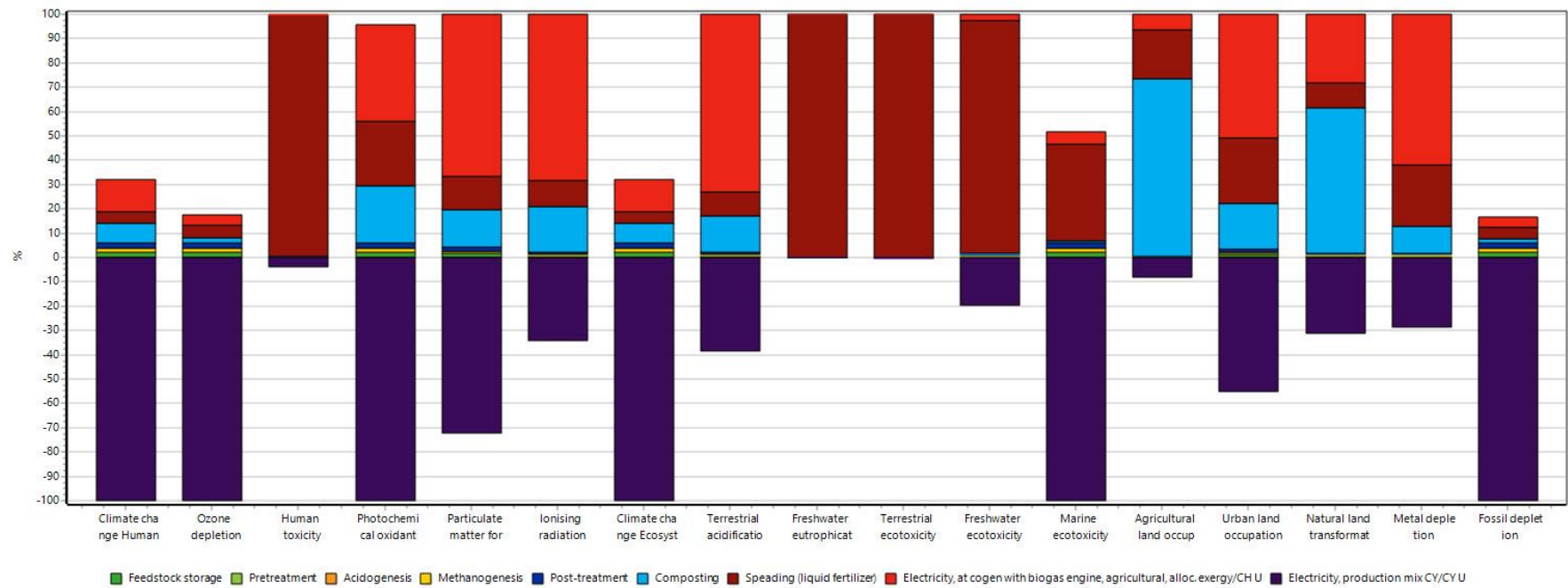
412 **Overview of the results for Scenario 2 (one-stage system)**

413 The LCIA results of the process for the co-treatment of EoL-DPs with the AgW mixture,
414 expressed per ton of raw biomass treated in the plant, are presented in Fig. 5 and SM
415 Table 6. The environmental performance of this scenario is affected by the composting
416 process (which was also the case for Scenario 1), the application of the liquid digested
417 matter to the land as fertilizer and the biogas production stage as a result of the
418 atmospheric emissions generated during biogas combustion in the CHP engine. Once
419 again, the pretreatment stage had negligible effect on the environmental performance
420 of the system. A positive effect is shown because of the energy recovery, both as
421 electricity delivered to the grid and thermal energy for covering the needs of the plant.
422 The main inputs of the LCIA were the electricity consumption of the pilot plant
423 equipment while the main outputs were the emissions (CO₂) generated by the CHP
424 engine during the combustion of the biogas and the biogenic emissions from the
425 metabolic activity of the microorganisms during composting. The use of digested liquid
426 as fertilizer in agricultural soil, and specifically in the surrounding area of the biogas
427 plant (without taking into account the transportation of the liquid fertilizer to the
428 agricultural soil), was also part of this inventory.

429 **Table 1.** Weighting of the impacts for Scenario 1 (two-stage system operation).

Impact category	Unit	Total	Feedstock storage	Pre-treatment	Acidogenesis	Methanogenesis	Post-treatment	Composting	Spreading of liquid anaerobic effluent to land	Electricity, with biogas engine	Electricity, production mix CY/CY U
Human Health	Pt	43.0765	0.1542	0.0074	0.0830	0.1055	0.1542	0.5540	49.9295	1.6260	-9.3775
Ecosystems	Pt	15.4701	0.0944	0.0045	0.0508	0.0646	0.0944	1.1347	18.6385	1.2239	-5.7378
Resources	Pt	-6.1056	0.1155	0.0055	0.0622	0.0790	0.1155	0.1028	0.25158	0.3052	-7.0231
Total	Pt	52.4411	0.3641	0.0174	0.1960	0.2491	0.3641	1.7916	68.8196	3.1552	-22.1384

430



431

432 **Figure 5.** Characterization data for Scenario 2 (one-stage system operation)

433

434

435 Whilst the characterization data show the relative contribution during each
436 stage of the LCA, the characterization step does not show the relative significance of
437 the impacts. Thus, a normalization step was undertaken, the results of which are
438 shown in Fig. 6. The most significant impact categories were shown to be the human
439 toxicity and the terrestrial ecotoxicology of the liquid digested matter after its
440 application as organic fertilizer. The rest of the parameters had negligible effect on the
441 environmental parameters assessed.

442 Fig. 7 illustrates the environmental merits of the process generated by the
443 installation of an acidogenic reactor for the pretreatment of the EoL-DPs based on the
444 weighting results of the processes.

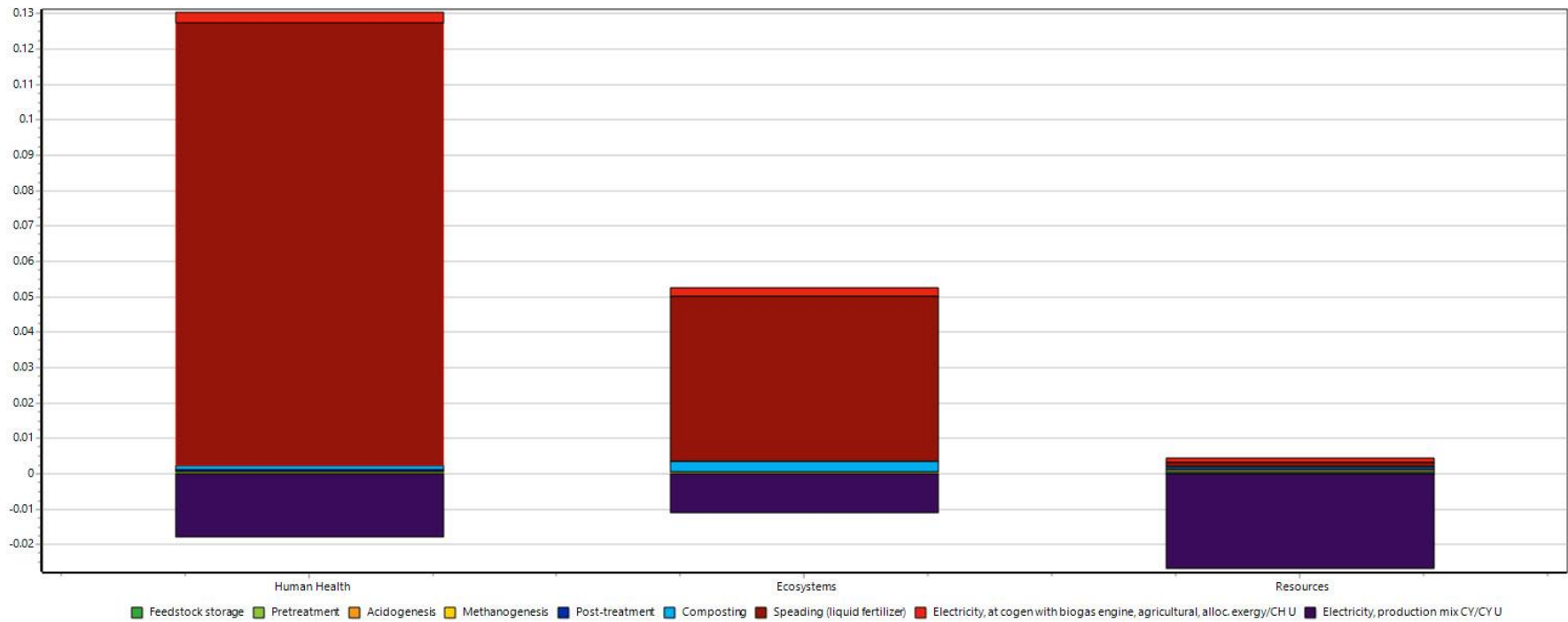
445 The weighting of the impacts for Scenario 2 is presented in SM Table 7 and a
446 total impact of 57.13 Pt is illustrated. The disposal of the liquid digested matter is
447 responsible for the 68.82 Pt. Moreover, as in the case of Scenario 1, the environmental
448 advantages associated with the biogas produced and the positive impact on fossil
449 depletion are also presented.

450

451 **DISCUSSION**

452 In the present study, an analysis was conducted to determine the
453 environmental performance of two integrated waste management processes for the
454 valorization of EoL-DPs for bioenergy production, developed under the framework of
455 LIFE+ DAIRIUS project. The main objective was the identification of the environmental
456 hotspots of each operating scenario of EoL-DPs treatment, in order to provide

457

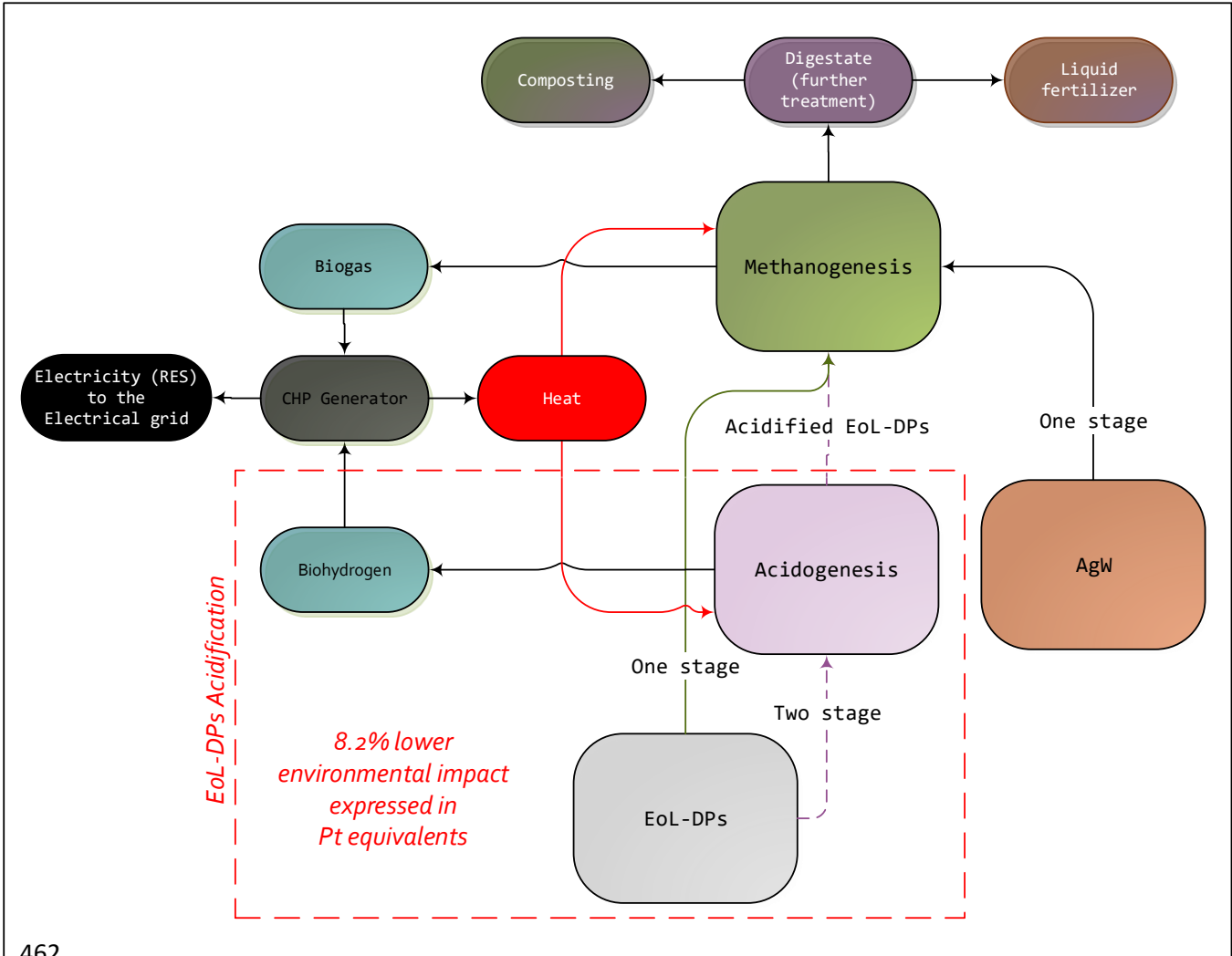


458

459 **Figure 6.** Normalized data for Scenario 2 (one-stage system operation)

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465 **Figure 7.** Graphical representation of the assessment and the environmental effect by

466 the EoL-DPs acidification.

467

468

469 feedback and support the sustainable development of these processes, as well as
470 future ones, in full-scale. The proposed plant was examined as a gate-to-gate
471 assessment.

472 According to the results obtained from this gate-to-gate LCA study it was
473 evident that prior acidification of EoL-DPs, followed by co-digestion with AgW
474 (Scenario 1, two-stage system), showed a better environmental performance
475 compared to the results obtained upon direct co-digestion in a mesophilic digester,
476 having a total impact of 52.44 Pt (Table 1) against 57.13 Pt (SM Table 7) respectively.
477 Biogas production, and therefore energy yield, was higher for Scenario 1, reaching up
478 to 22.88 m³ CH₄/ton of feed (229.25 kWh/ton of feed), compared to Scenario 2 where
479 biogas production was 17.45 m³ CH₄/ton of feed (174.85 kWh/ton of feed). This is the
480 main reason why the environmental performance of Scenario 1 was better than the
481 one of Scenario 2.

482 Weighting of the impacts for each category assessed in this study, including
483 human health, ecosystem and resources, showed that the additional acidogenesis
484 stage in Scenario 1 had a slim contribution on the total negative environmental impact,
485 accounting only for up to 0.26%. Categories with negative impacts on the environment
486 mainly result from the combustion process of the biogas in the CHP generator, which
487 produces gaseous emissions, and the electrical energy demands for its operation.
488 Therefore, air emissions, energy and thermal inputs during processing are the key
489 contributors to the environmental impacts in this LCIA.

490 Our results are in agreement with other LCA studies reported in literature. For
491 example, in a study where the environmental impacts of milk production in a dairy
492 farm located in Northern Italy were assessed, three scenarios were compared
493 regarding manure management, including: a) its storage in an open tank and
494 subsequent use as fertilizer, b) its anaerobic digestion for biogas production and heat
495 generation through biogas combustion and c) a scenario similar to (b) but the digestate
496 was stored in a gas-tight tank ³⁸. It was found that for scenario (a) the GHG emissions
497 were 1.21 kg CO₂ eq.kg⁻¹, whereas for scenario (b) and (c) the GHG emissions were
498 reduced to 0.92 (-23.7%) and 0.77 (-36.5%) kg CO₂ eq.kg⁻¹ respectively. However, for
499 cases (b) and (c) environmental impacts such as acidification, particulate size matter
500 emissions and photochemical ozone formation potential increased due to emissions
501 generated from the CHP engine.

502 In general, liquid effluents are stored for prolonged periods in anaerobic
503 lagoons before the final land application. In our study, the liquid digestate was directly
504 spread to land without extended storage in anaerobic lagoon avoiding thus any
505 negative environmental impacts due to such storage. However, the use of the liquid
506 effluent (digestate) for cultivation purposes greatly contributes to the negative impacts
507 of the plant operation. The environmental impact of the liquid effluent application to
508 land was found to be 68.82 Pt in both cases. In particular, it was found that it had a
509 very significant impact on human health and the ecosystem in both scenarios. In the
510 present gate-to-gate LCA study it was found that the application of the liquid effluent
511 to land contributed for up to 91.81% and 92.98% of the total negative environmental
512 impact for Scenario 1 and 2 respectively. Nevertheless, the anaerobically digested

513 liquid effluent still contains increased amounts of organic compounds (mostly
514 recalcitrant ones) and nutrients which are essential for cultivation purposes and can
515 therefore replace chemical fertilizers. However, in this study, the positive effects due
516 to replacement of chemical fertilizers were not examined in detail because of the type
517 of analysis carried out (gate-to-gate). In this sense, a higher environmental gain would
518 have been achieved in this study by considering further processing of the digestate
519 rather than directly spreading it to land. Several digestate treatment technologies that
520 are able to provide environmental gains may be applied to this end. A recent study has
521 examined in-detail digestate treatment by (a) drying and pelletizing, (b) composting,
522 (c) biological treatment combined with reverse osmosis and drying, (d) ammonia
523 stripping and drying, and compared the results obtained with the ones derived from
524 the case of direct spreading of the digestate on land ³⁹. It was concluded that,
525 compared to spreading, all alternative scenarios were characterized by a significant
526 reduction in air emissions, namely ammonia. Moreover, it was observed that the
527 increase in energy intensity associated with those conversion processes seems to be
528 marginal due to the environmental benefits derived from other environmental
529 dimensions. Another scenario that has been proposed in order to reduce the
530 environmental impact of the spreading of the liquid effluent to land, is the growth of
531 algae, and therefore the production of lipid-rich biomass, since those effluents are rich
532 in nitrogen and phosphorus. A study performed by Coats and colleagues ⁴⁰ has
533 demonstrated that a two-stage AD configuration coupled with algae production results
534 in reduced GHG emissions by 60% compared to a traditional anaerobic lagoon.

535 Biological treatment, including anaerobic digestion and composting, is one of
536 the most frequently used techniques for bio-waste management, currently. Anaerobic
537 digestion is particularly suitable for wet bio-waste and is perceived as a process for
538 energy recovery, producing biogas for energy purposes. Biogas can significantly reduce
539 greenhouse gas emissions (GHG) when injected into the gas distribution grid. In
540 addition, the residue from the process, the digestate, can be composted and used for
541 similar purpose as compost, thus improving overall resource recovery from the waste.
542 In this study, the environmental performance of a two-stage (acidogenesis followed by
543 methanogenesis) compared to a single-stage anaerobic co-digestion process of EoL-
544 DPs with AgW was assessed. Positive impacts were evident because of the
545 replacement of electrical energy in the grid and thermal requirements with electricity
546 and thermal energy produced *in situ* in the plant via biogas combustion. Based on the
547 LIFE+ DAIRIUS pilot plant results, the effect of the acidification stage on the energy
548 requirements of such a plant in this gate-to-gate system is negligible. However, the
549 overall energy efficiency, and as a result the environmental performance of the
550 system, is increased due to the increase of the biogas yield in the two-stage scenario.
551 Therefore, further verification of results is needed on the environmental performance
552 of such a system using inputs from a full-scale two-stage plant. The environmental
553 assessment of such a system should be extended to a Cradle-to-Grave analysis, as part
554 of future work.

555

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560

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