

Sustainable management of peel waste in the small-scale orange juice industries: A Colombian case study

Original

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(Article begins on next page)

33 reduced from 0.493 kg in SI to 0.279 kg in SII. The methodology proposed in this case study could
34 be applied to other countries or small and medium scale technologies and could also be useful for the
35 scientific community, enterprises and policy-makers.

36

37

38 **Keywords:** Life Cycle Assessment (LCA); waste management; anaerobic digestion; orange peel
39 waste; waste to energy.

40 ***Glossary of abbreviations and acronyms***

Abbreviation	Definition
AD	Anaerobic Digestion
CC	Climate Change
FEU	Freshwater Eutrophication
GHG	Green House Gas
HHV	Higher Heating Value
ILCD	International Reference Life Cycle Data System
INC	Incineration
IR	Ionized Radiation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
OJ	Orange Juice
OD	Ozone depletion
OPW	Orange Peel Waste
POF	Photochemical Ozone Formation
PM	Particular Matter

SI	Scenario I
SII	Scenario II
SIII	Scenario III
SIV	Scenario IV
WRD	Water Resource Depletion

41

42 **1. INTRODUCTION**

43 The world energy demand increased by almost 150% between 1971 and 2015 and is more than 80%
44 based on fossil fuels (IEA, 2015). Fossil fuels are by far the largest source of Green House Gas (GHG)
45 emissions and their reserves are scarce, variable and unequally distributed (Harsono et al., 2015). All
46 the efforts for the reduction of GHG emissions are currently focused on an energy use transition. In
47 this respect, mitigation policies suggest that waste management could offer an important clean and
48 alternative energy source resulting in overall low carbon economy (European Parliament, 2009).
49 Lignocellulosic waste appears to be a promising feedstock in the scenario of energy supply from
50 renewable sources (Bentsen et al., 2014). Recently, researchers showed an increased interest in the
51 valorization of agro-industrial waste to obtain added-value materials such as essential oils, pectin,
52 biopolymers, animal feed, activated carbons, enzymes, pollutants adsorbents, fuels and energy
53 (Batuecas et al., 2019; Mahato et al., 2018).

54 Orange juice is an important agro-industrial economic sector, which consequently handles a large
55 amount of Orange Peel Waste (OPW). The valorization of OPW presents a very high potential
56 considering its composition in essential oils widely exploited in the chemical industry (Domingos et
57 al., 2019). Furthermore, the exploitation of OPW in Anaerobic Digestion (AD) (Calabrò and Panzera,
58 2018; Paone and Komilis, 2018) and in biorefinery facilities (Martín et al., 2010) are well known
59 processes. In the international citrus market, Colombia is not a relevant player. However, the country
60 has 71.338 ha of planted area with a yield of 539.916-ton year⁻¹. In the specific orange case, it ranks

61 second in national production with 456.301 ton (DANE, 2017). The main consumption is as fresh
62 fruit and in industrial orange juice (OJ). During OJ production, only about half of the orange fresh
63 weight is transformed into juice. The remaining 50% consists of pulp, peel, and seeds (Rezzadori et
64 al., 2012). About 95% of this waste is made of peels (OPW), which are a great disposal issue for this
65 industry since their management requires economic and energy resources, with the risk of air, water
66 and soil contamination.

67 The increase in energy consumption and pollution is a drawback of the Gross Domestic Product
68 growth in the Colombian emerging economy.. Emerging economies have slower sustainable
69 productivity growth than developed economies due to their difficulties in innovation. Technologies
70 in large-scale industrial applications are still challenging, since these solutions involve huge capital
71 investments. On the other hand, these economies are able to utilize the existing technology with a
72 catch-up effect (Li and Lin, 2019). Indeed, small and medium processing scales present a perfect
73 setup for the implantation of new solutions, improving the sustainable productivity and involving
74 lower environmental impact than conventional disposal in landfills (Santos et al., 2015).

75 Plenty of scientific literature on agro-industrial waste management is available since there are
76 numerous ways to recover waste by integrating it into a new productive chain which closes the loop.
77 For instance in cocoa industries in Brazil, the shell waste was used as fuel for boilers, through the
78 incineration (INC) of the shell together with pieces of wood (Fontes et al., 2017). Among the
79 advantages of biofuels use, lower emissions of SO₂ and NO_x are produced than conventional fossil
80 fuels, since their content in sulfur, nitrogen and ashes is lower (Bilgen et al., 2015). Furthermore, the
81 use of agro-industrial waste through biological processes has been widely tested in different industrial
82 facilities (Wandera et al., 2018). The main biological process currently available is AD. Large
83 amounts of waste (OPW as well) can be treated by means of AD techniques, which would increase
84 the profits of an OJ company by integrating the recovered energy in its own productive chain (Zema
85 et al., 2018). Some studies stated that co-combustion with biomass improves the economic and

86 environmental benefits of the plant (Contreras-Lisperguer et al., 2018) in other applications. Despite
87 waste management is becoming a common practice in the industry, the proper evaluation from an
88 environmental point of view is still lacking. In this respect, LCA is a powerful decision-making tool
89 to develop more sustainably efficient processes.

90 In Colombia, several published works dealt with biomass conversion into fuels, such as ethanol and
91 biodiesel (Ministry of Mining and Energy, 2012). However, these studies were mainly based on sugar
92 cane and oil palm wastes in a biorefinery concept, not including in the orange juice industry and OPW
93 valorization. Despite developing the technical basis to valorize the Colombian agro-industrial waste,
94 the potential environmental impacts through LCA studies are poorly understood and require a major
95 effort in this aspect. This work involves the technical, economic and environmental dimensions for
96 energy use through anaerobic digestion and combustion of orange peel residues from an industrial
97 scale. Agro-industrial waste processing alternatives are provided for emerging companies in the Latin
98 American economy with a circular economy perspective.

99 The research work aim is the evaluation of the environmental (LCA) and economic aspects of the
100 most suitable scenarios, taking into account the socioeconomic situation of a small industry in
101 Colombia. The paper begins with a technical evaluation of the alternatives to OPW landfill. Four
102 scenarios were assessed. This research work attempts to provide enough information for decision-
103 making practices in relation the OPW in small and medium OJ industries which could take these case
104 study results as a benchmark. The findings should make an important contribution for Latin American
105 countries in the field of the promotion of zero waste policies and circular economy thinking.

106

107 **2. METHODOLOGY**

108 **2.1 Case study description.**

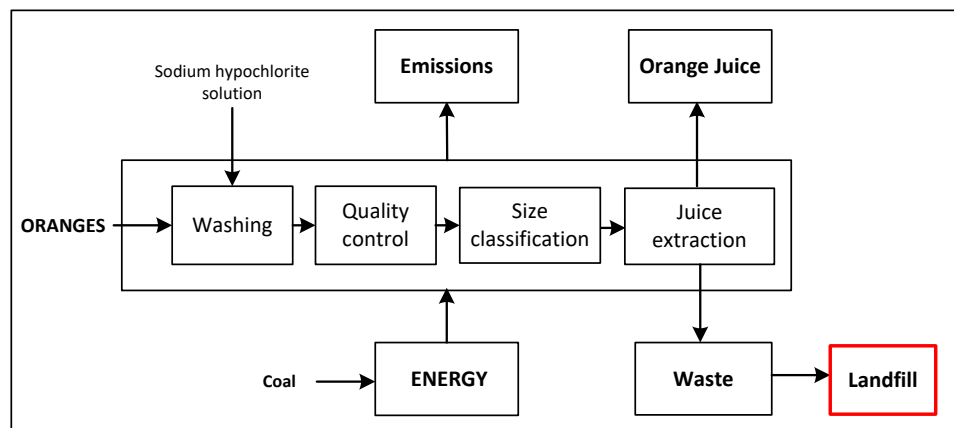
109 The OJ production company considered in this study is FLP Procesados, located near to Manizales-
 110 Colombia.. The company processed 200 tons of oranges per month, which means 16666 kg per day,
 111 considering only three continuously working days per week. The company provided to the authors
 112 data referred to year 2019. Table 1 provides a summary of the utilities and materials used in the
 113 process of OJ production per day. Figure 1 shows the current case study process.

114

115 Table 1. FLP Procesados information. Utilities and materials used in the company per day.

	Flux	Unit
Utilities		
Steam	34421.932	kg
Pressure	109.930	psi
Coal	4054	kg
Materials		
Oranges	16666	kg
Orange juice	8225.050	L
OPW	7953.500	kg
Ash	369	kg

116



117

118 Figure 1. Simplified flowchart diagram of the Scenario I which is the current situation in the
119 case study. Coal is combusted for producing orange juice and OPW is sent to landfill.

120
121 Figure 1 represents the Scenario I (SI) which is the baseline case and constitutes the starting point to
122 design the other scenarios. In Figure 1 it is possible to notice that the OPW is not treated and goes to
123 landfill. Hence, in order to properly manage the OPW, three additional scenarios (II, III, IV) were
124 proposed and compared with SI. In these three scenarios, OPW was treated in its end of life. SII
125 incinerates a mix of dried OPW to replace part of the coal used in the orange juice plant. Scenario III
126 (SIII) produces biogas by means of AD of OPW. The biogas produced is then used as energy for
127 replacing part of the energy consumed by the OJ productive process. Finally, scenario IV traces the
128 previous one, with the additional valorization of the digestate, exploited as fertilizer of the orange
129 crops, closing the loop and adding value to the OJ chain.

130

131 **2.2 LCA Methodology**

132

133 ISO 14040 and 14044 (ISO TC2017 SC5, 2006a, 2006b) defined the LCA methodology with four
134 phases that should be conducted. (i) Goal and scope definition, (ii) Life Cycle Impact Inventory (iii)
135 Life Cycle Assessment and the (iv) Interpretation phase.

136

137 **2.2.1 Goal and scope definition**

138

139 The goal of this study was to determine the environmental performance of three different routes for
140 valorizing the OPW to compare them with the current situation in which OPW is landfilled. In this
141 context, the functional unit selected was 1L of OJ in order to identify how the environmental impacts
142 of its production change if the OPW produced is disposal in landfill or instead it has a waste treatment.

143

144 The system boundaries of this LCA study were cradle to cradle in a circular economy thinking. The
145 Scenario I is the baseline. SI is a typical linear process where the waste is only landfilled without any
146 treatment. Hence, the evaluation of this scenario stand-alone will be in a cradle to gate approach.
147 However, when the other three alternatives scenarios are proposed, the circular thinking has a role to
148 play. Scenario II uses energy produced by the OPW incineration (INC) reducing the coal necessities.
149 Scenario III produces biogas, which is consequently introduced in the system as energy. Additionally,
150 the Scenario IV recovers not only the energy produced by the OPW AD but also an added-value
151 fertilizer from the digestate. Fertilizer from digestate will fertilize the oranges in SIV, closing the loop
152 and getting a circular (cradle to cradle) approach. In the three alternatives to SI, the end of life of
153 OPW is focused in closing the loop. The intention of this assessment was to understand how the fact
154 of include progressively measures of circularity in linearly process will improve the environmental
155 performance of conventional processes.

156

157 **2.2.2 Life Cycle Impact Inventory for different scenarios**

158

159 Life Cycle Inventory (LCI) has been created using the results of the data reported by FLP Procesados
160 company, experimental studies previously published (Cardona A et al., 2004; Zema et al., 2018),
161 experimental data of the authors and the mass and energy balances simulations.

162 The main inputs, such as steam, coal and ashes, production of orange juice and OPW were acquired
163 from the company case study. Biogas production was obtained in lab experiments and scaled up to
164 the industrial size, taking into account the amount of OPW and laboratory results. In all the scenarios,
165 the allocations between OPW and OJ was calculated based on disposal cost (0.049 €/kg) and
166 production cost in the Colombian market context (1.50 €/L equivalent at 60% sold price). The energy
167 recovered in scenarios II, III and IV was used as raw material for a new life cycle.

168

169 **Scenario I (SI)** represents the current situation in the Colombian case study in which orange peel
 170 waste is landfilled after orange juice production . SI includes the coal incineration to generate steam
 171 for running the OJ production (figure 2A). Table 2 presents the LCI for SI and more information can
 172 be found in appendix.

173 Table 2. LCA Inventory of SI. Inputs and outputs are referred to the FU.

Process	Subprocess	Input	Amount	Unit
SI	All stages	Oranges	1.945	kg
		Sodium hypochlorite	0.006	kg
	Washing	Water	0.302	kg
		Steam	Coal	0.493
	production		8.437	MJ
		Output	Amount	Unit
Coal incineration	Steam	OPW	0.967	kg
	production	Coal ash	0.046	kg
		Emissions		
		CO_2	1.193	kg
		SO_2	5.57E-03	kg
	All stages	H_2O	312.132	kg
		N_2	7.200E-03	kg
		O_2	1.130	kg

174

175

176 **Scenario II (SII)** represents the production of 1L of OJ when the OPW landfill is avoided and is
 177 valorized by a waste treatment. LCI of the SII is depicted in Table 3. The waste treatment in SII
 178 consists of OPW followed by its incineration, producing energy auto- consumed by the OJ production
 179 process. In the Table 3 it is possible to notice that the amount of coal needed for 1L OJ is reduced

180 from 0.493 kg in the Scenario I to 0.279 kg in this scenario. Figure 2 B shows the inputs and outputs
 181 of the SII process.

182

183 Table 3. LCA Inventory of SII. Inputs and outputs are referred to the FU.

184

Process	Subprocess	Input	Amount	Unit	
SII	All stages	Oranges	1.945	Kg	
	Washing	Sodium hypochlorite	0.006	Kg	
		Water	0.302	Kg	
	Steam production	Coal	0.279	Kg	
			4.778	MJ	
		OPW	0.273	Kg	
			3.680	MJ	
	Drying	Methane	0.013	m ³	
	Coal+OPW incineration		Output	Amount	Unit
	OJ	OPW	0.967	Kg	
	Energy from SII	4.784	MJ		
Steam production	Coal ash	0.026	Kg		
	OPW ash	9.620E-04	Kg		
All stages	Total emissions				
		CO ₂	1.068	Kg	
		SO ₂	9.690E-02	Kg	
		H ₂ O	404.120	Kg	
		N ₂	5.300E-03	Kg	
		O ₂	1.211	Kg	

185

186 The emissions of CO₂, NO_x, SO₂, H₂O, O₂ and N₂ of each mixture of solid fuels were calculated from
 187 mass balances, biomass combustion and cofiring methodologies (ECOCARBÓN, 1998; Loo and
 188 Koppejan, 2008). The mass and energy balances were based on empirical data from previous studies
 189 conducted in Colombia (Cardona A et al., 2004) and in other countries (Siles et al., 2016). More
 190 information is available in the appendix.

191

192 In **Scenario III (SIII)** waste treatment consists of AD of OPW for production of biogas, which is
 193 then utilized for the energy needs of the OJ plant. Since the energy produced by biogas combustion
 194 is not enough to supply all the OJ plant energy demand, the coal combustion still represents part of
 195 the energy requirements. The SIII setup is represented in Figure 2C. As this scenario is a simulation,
 196 laboratory experiments were conducted in order to confirm the feasibility of producing biogas from
 197 OPW. More information is available in the appendix.

198

Table 4. LCA Inventory of SIII. Inputs and outputs are referred to the FU.

Process	Subprocess	Input	Amount	Unit
Scenario III	All stages	Oranges	1.945	kg
		Sodium hypochlorite	0.006	kg
	Washing	Water	0.302	kg
		Water	0.046	kg
		Sludge	4.867	kg
		Heat	0.495	kWh
		AD	Operation (pumping, transporting)	0.017
		Methane upgrade	0.545	kWh
		Coal	0.331	kg
			5.673	MJ

AD and methane recirculation	Steam production	Methane 97%	0.105	kg
			2.763	Mj
		Output	Amount	Unit
	OJ	OPW	0.967	kg
	Steam production	Coal ash	0.030	kg
	AD	Energy from SIII	3.592	MJ
		Digestate	0.483	kg
	All stages	Total Emissions		
		CO_2	1.545	kg
		SO_2	3.740E-03	kg
		H_2O	219.091	kg

199

200 Assumptions to carry out the AD from OPW. The methane production rate and the energy production
 201 can be seen in appendix.

202 **Scenario IV (SIV)** includes the background of SIII adding, to biogas production, fertilizers recovery
 203 from AD digestate. Figure 2D shows the SIV process. Table 5 shows the LCA inventory of SIV.
 204 SIV represents the total life cycle, thinking in a circular economy way by valorizing every single
 205 waste produced in the process and closing the chain.

206

207

Table 5. LCA Inventory of SIV. Inputs and outputs are referred to the FU.

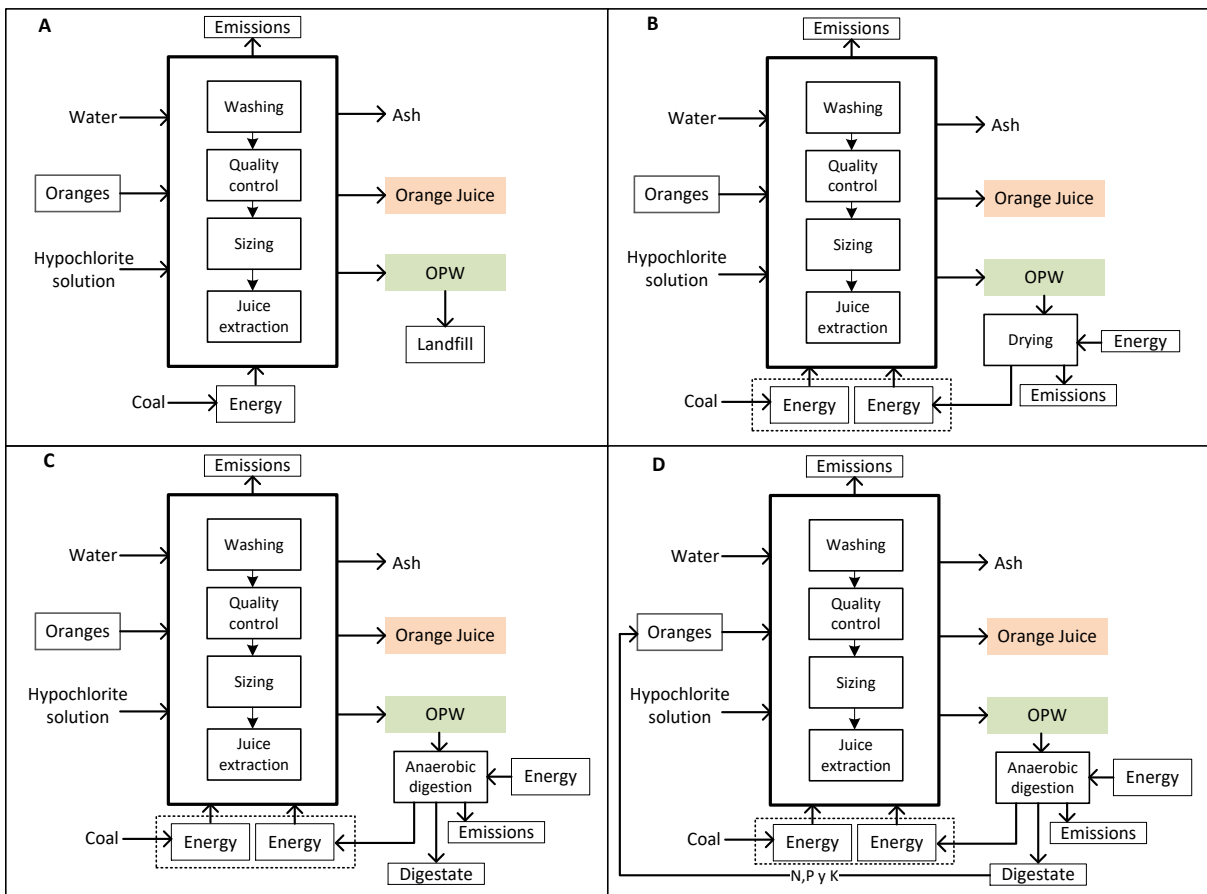
Process	Subprocess	Input	Amount	Unit
Scenario IV	All stages	Oranges	1.945	kg
	Washing	Sodium hypochlorite	0.006	kg
		Water	0.302	kg
		Water	0.046	kg

	Sludge	4.867	kg
	Heat	0.495	kWh
AD	Operation (pumping, trasnporting)	0.017	kWh
	Methane upgrade	0.545	kWh
Fertilizers	Dewatering by pressing	6.769E-03	kWh
	Coal	0.331	kg
		5.673	MJ
Steam production	Methane 97%	0.105	kg
		2.763	Mj
	Output	Amount	Unit
OJ	OPW	0.967	kg
Steam production	Coal ash	0.030	kg
AD	Energy from SIII	3.592	MJ
	Digestate	0.483	kg
	<i>N</i>	1.112E-03	kg
Fertilizers	<i>P</i>	9.670E-05	kg
	<i>K</i>	6.290E-04	kg
	Total Emissions		
All stages	<i>CO</i> ₂	1.545	kg
	<i>SO</i> ₂	3.740E-03	kg
	<i>H</i> ₂ <i>O</i>	219.091	kg
	N in soil	2.446E-04	kg
	<i>NO</i> ₃	2.502E-02	kg
Digestate to fertilizers	<i>N</i> ₂	5.137E-04	kg
	<i>NH</i> ₃	1.668E-05	kg

208

209 In order to remove water from digestate, centrifugation with a 20% efficiency was carried out. This
 210 process had a power consumption of 6.769E-03 kWh. As mentioned previously, the digestate was
 211 used as fertilizer in orange crops (information in appendix). Table 5 shows that 0.331 kg of coal and
 212 0.105 kg methane (from biogas) are necessary to produce 1L of OJ.

213



214

215

216 Figure 2. Foreground of OPW management for all scenarios. (A) SI Coal incineration, (B) SII Coal
 217 + OPW incineration, (C) SIII AD and methane recovery and (D) SIV AD, methane and fertilizers
 218 recovery.

219 **2.2.3 Life Cycle Assessment**

220

221 In the present research work, the LCA was carried out with the International Reference Life Cycle
222 Data System (ILCD) handbook (JRC, 2010) methodology. ILCD method provides guidance for good
223 practices in LCA and is conforms to the ISO 14040 and 14044 (ISO TC2017 SC5, 2006a, 2006b).
224 ILCD method collected a series of methodologies and determined the most relevant impact
225 categories. ILCD method classified its impacts categories by their level of recommendation from I to
226 III. Furthermore, the classification identifies “interim” as those methodologies that are still immature.

227

228 This study follows the ILCD guidelines. ILCD requires midpoint LCA models with level I, level II
229 or level III of recommendation. In order to get the most relevant categories in this study, an
230 uncertainty analysis was performed to detect those ILCD impact categories with a high uncertainty
231 for the model. High uncertainty levels could cause not representatives results. The uncertainty
232 analysis is described below. Hence, the impact categories selected for the present study were based
233 on ILCD recommendations and with low uncertainties. Simapro 8.3 software and Ecoinvent 3 were
234 used for calculating these potential environmental impacts.

235

236 **2.2.4 Interpretation phase**

237

238 In the last phase of every LCA, an interpretation of the results should be conducted. In the present
239 study, the interpretation of the results will be detailed in the following sections.

240

241 **3. RESULTS**

242

243 **3.1 LCA RESULTS**

244

245 The LCA results for all scenarios considered in the present research work are shown in Figure 3.
246 Climate change (CC), ozone depletion (OD) particulate matter (PM), photochemical ozone formation
247 (POF), acidification (AC), freshwater eutrophication (FEU) and water resource depletion (WRD)
248 were the impact categories analyzed. As showed in Figure 2, the impact analysis considered in this
249 work is focused on the waste management of OPW from OJ production including raw materials,
250 energy needs and disposal.

251

252 Table 6 represents the numerical results of the environmental impacts in every scenario. Figure 3
253 presented graphical results of the comparative LCA for the four assessed scenarios. Both in Table 6
254 and Figure 3 it is possible to notice that SI obtained the highest environmental impacts in 6 of the 7
255 assessed categories. In SI, OPW is not disposed of correctly and presents certain drawbacks associated
256 with the use of coal. SII achieved the lowest environmental impacts in five categories (CC, OD, PM,
257 POF and FEU). These results revealed that incineration could improve the overall sustainability of
258 the process avoiding the landfilling.

259

260 Regarding those scenarios which includes AD, SIII and SIV reduced the carbon footprint (CC) and
261 POF around 40% compared to SI, due to the reduction in coal use. Likewise, SIII and SIV reduced
262 their impacts in OD, PM and AD around 30% in comparison to SI. With respect to FEU category,
263 SIII and SIV, reduced more than 160% their environmental impact compared with the baseline case
264 study (SI).

265

266 In WRD, the scenarios with biogas production (SIII and SIV) obtained worse environmental behavior
267 than the ones with a minor (SII) or null (SI) waste management approach. SI revealed the smallest
268 value of WRD, 35.5% and 38.6% lower than SIII and SIV, respectively. WRD in SI obtained $8.018E-$
269 $02 \text{ m}^3 \text{ H}_2\text{O eq}$ which was very similar to SII (only 4.1% lower). In this regard, it is important to

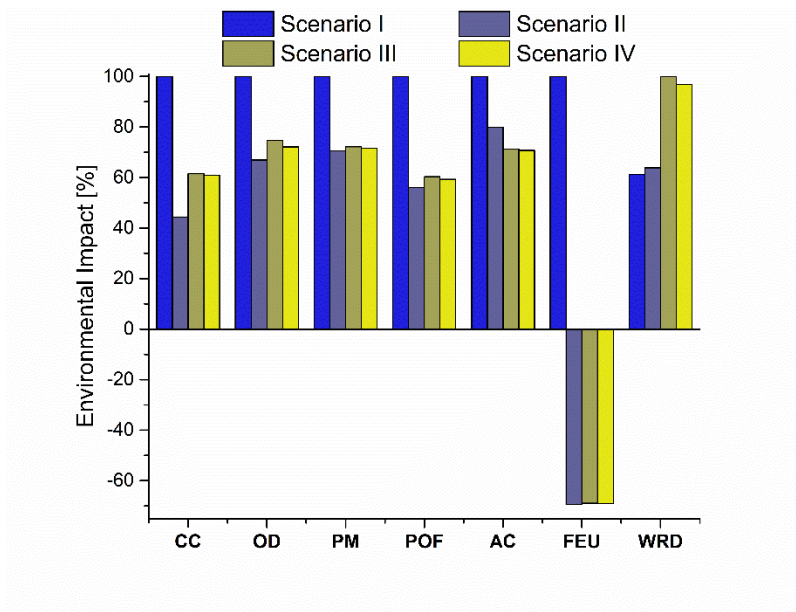
270 highlight that SI is the simplest scenario since SII, SIII and SIV added water-consuming processes to
271 the value chain.

272 Regarding water issues, it should be pointed out that the introduction of other processes increased
273 water footprint. In spite of the bad results in WRD, these processes reduced other environmental
274 impacts. The addition of a waste treatment to the baseline case (SI) reduced the environmental impacts
275 in 6 to 7 categories in SII, SIII and SIV (see Figure 3 or Table 6).

276

277 SII presented the best environmental results in terms on Freshwater Eutrophication due to the
278 avoidance of landfilling. SII presented a decrease of 16.40% and 17,10 % in CC in contrast to the AD
279 scenarios, SIII and SIV, respectively. In accordance with the present results, previous studies (Tonini
280 et al., 2012) demonstrated that a scenario which includes co-firing, such as SII, allowed an
281 improvement in CC. Both AD scenarios (SIII and SIV) showed little difference in the impact
282 categories analyzed. Furthermore, SIV showed always better environmental behavior than SII,
283 confirming the good properties of anaerobic digestate valorization.

284



285

286

Figure 3. Comparative LCA results in all scenarios.

287

288

Table 6. Characterization of impact scores for scenarios I Coal incineration, II Coal + OPW

289

incineration, III AD and methane recovery and IV Anaerobic Digestion, methane and fertilizers

290

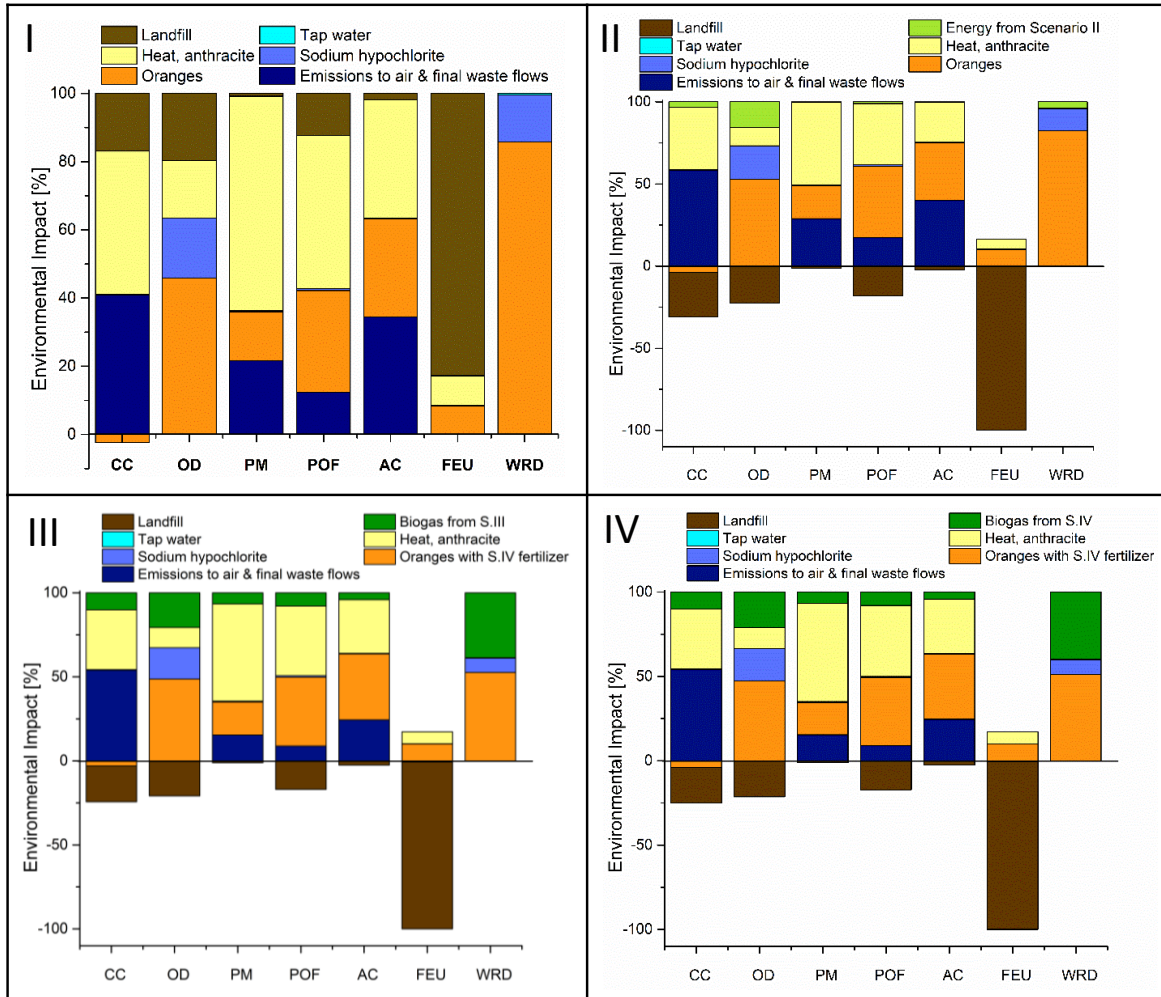
recovery.

291

Impact category	Unit	SCENARIO			
		I	II	III	IV
CC	kg CO ₂ eq	2.78	1.23	1.71	1.69
OD	kg CFC-11 eq	1.42E-08	9.53E-09	1.06E-08	1.01E-08
PM	kg PM _{2.5} eq	1.53E-03	1.08E-03	1.10E-03	1.09E-03
POF	kg NMVOC eq	3.55E-03	1.99E-03	2.14E-03	2.08E-03
AC	molc H ⁺ eq	2.06E-02	1.65E-02	1.47E-02	1.45E-02
FEU	kg P eq	5.23E-04	-3.65E-04	-3.60E-04	-3.65E-04
WRD	m ³ water eq	7.70E-02	8.01E-02	1.25E-01	1.14E-01

292

293



294

295 Figure 4. Contribution of life cycle stages to total impact scores (scaled to 100%) in all scenarios: I
 296 Coal incineration, II Coal + OPW incineration, III AD and methane recovery and IV AD, methane
 297 and fertilizers recovery. Climate change (CC), ozone depletion (OD) particulate matter (PM),
 298 photochemical ozone formation (POF), acidification (AC), freshwater eutrophication (FEU) and
 299 water resource depletion (WRD).

300

301 Figure 4 shows the contribution of each item in each scenario to the environmental impacts. In the
 302 upper left part of Figure 4, the environmental impacts of SI with their contributions are showed.

303 In SI, 41.98% of CC is due to the coal as fuel in the boiler for steam production. In addition, emissions
 304 generated by the combustion of coal (such as CO₂ and SO₂) scored 40.86% of the total CC impact.

305 The final disposal in landfill contributed to 16.93% of CC. Moreover, a positive contribution
306 (negative value in CC, see Figure 4 I) is observed in CC category. This aspect is due to the biogenic
307 CO₂ capture in oranges. Regarding the OD in Scenario I, 45.87% of the impact is related to the orange
308 production and 17.57% to the use of sodium hypochlorite in washing stage. In a lowest proportion,
309 the use of coal and landfill contribute 16.85% and 19.65%, respectively. Regarding PM, POF, and
310 AC, the largest contributions were due to the use of coal, followed by the oranges production and the
311 emissions and final waste flows. In the FEU category, 82.75% of the impact is due to the landfill. In
312 SI, the use of water in orange crops contributed 85.8% of WRD.

313

314 The contribution of each impact category in SII is shown in the upper right part of Figure 4. In CC,
315 OD, POF and FEU categories, positive contributions were observed due to the landfilling avoidance.
316 Moreover, the energy recovered in the process through the use of OPW as fuel provides a reduction
317 in CC from 2.781 kg of CO₂ eq in SI to 1.235 kg of CO₂ eq in SII. In this CC category, the greatest
318 contribution is caused by the emissions generated during the OPW drying stage i.e. the combustion
319 of coal-OPW mixture and the use of coal as fuel. These results reflect those of Dong et al., 2018 who
320 also found that direct emissions have great influence in the environmental impacts during an
321 incineration process of waste to energy,. Only 3.31% of CC in SII is ascribable to the energy
322 recovered. PM, POF and AC categories presented tendencies similar to SI, but with environmental
323 impacts lower than those of SI due to the landfilling avoidance. Likewise, FEU category presented a
324 vast positive (negative value) contribution for the use of OPW in a new cycle, i.e. OPW recovery,
325 avoiding the landfill. Additionally, in this category a reduction of 3% was observed for the
326 substitution of coal by INC process. In the case of WRD, the greatest impact was provoked by the
327 cultivation of oranges and the use of sodium hypochlorite.

328

329 In environmental impacts of SIII, an increase of 0.475 kg CO₂ eq was observed for CC regarding the
330 value obtained in SII. The most influential factors in this category were emissions and waste

331 generation, followed by the coal as in SI. The energy recovery from the biogas contributed by 10.15%
332 on CC impact. Moreover, biogas production scored 20.65%, 6.63%, 7.86%, 4.10% and 38.70% in the
333 OD, PM, POF, AC and WRD categories, respectively. For WRD, SIII presented the highest value
334 with 1.140E-01 m³ water eq, as showed in Table 6, due to the large amounts of water used during the
335 anaerobic digestion.

336

337 Regarding SIV, the CC impact reduced from -3.029% in SIII to -3.796% in SIV, since the recovery
338 of the digestate allows the production of a fertilizer used in the orange crops . Consequently, this
339 reduction in CC impact was provoked by an increase in the biogenic CO₂ in SIV compared to SIII.
340 The “closing-the-loop” approach revealed important benefits in OD category as well, with 97% SIV
341 of the impact obtained in SIII. For PM, POF, AC, FEU and WRD, reductions of 0.559%, 0.863%,
342 0.411%, 0.202% and 1.47%, respectively, were also obtained in SIV compared to SIII. These findings
343 were also reported by Bühle et al., (2012) who described reductions in climate change, even taking
344 into account a transport of 5 km for the application of digestate-derived fertilizers.

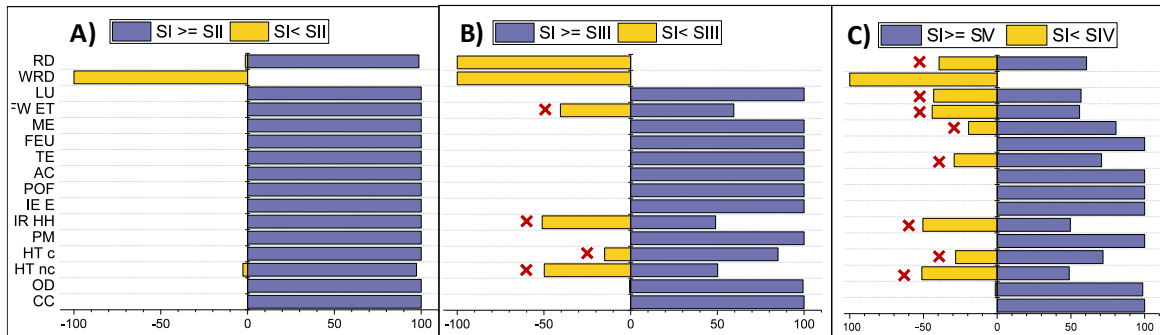
345

346 **3.1.1 Uncertainty analysis**

347

348 Primary data of this case study were introduced in the software as unique values. However, the data
349 items used in this LCA study were taken from the Ecoinvent database with lognormal distribution
350 around the medium value characterized by its standard deviation. When these items are combined,
351 their variability could affect the uncertainty of the LCA model downstream. Hence, in order to
352 determine the most relevant impact categories, the authors decided to carry out an uncertainty analysis
353 with the Montecarlo distribution. Calculations were conducted with 1000 iterations and a confidence
354 interval of 95%. All the impact categories implemented by the ILCD are reported in Figure 5. Due to
355 the uncertainties and their development, some of these categories are classified as interim. As
356 previously discussed, the developers of ILCD method classified the impact categories by

357 recommendation levels. Ionizing Radiation E (IR E) is classified as interim. Hence, the authors
 358 consider that interim methods should be excluded, that is why IR E was not taken into account in this
 359 study.



360
 361 Figure 5. Uncertainty analysis results conducted with the Montecarlo distribution. A) Scenario I
 362 compared with Scenario III. B) Scenario I compared with Scenario III. C) Scenario I compared with
 363 Scenario IV.

364 Figure 5 represents the uncertainty analysis when the baseline scenario (SI) is compared with the
 365 others. When SI is compared with SII (Figure 5 A), the results revealed that the potential
 366 environmental impacts of SII are very likely higher than those from SI (in 15 of the 16 evaluated
 367 categories) without uncertainty. On the other hand, SI will get higher values with a negligible
 368 uncertainty in the WRD case. The uncertainty of some impact categories in SI-SIII comparison
 369 (Figure 5B) highlights that the results in which SIII<SI could not be representative since they showed
 370 uncertainty values higher than 10% (HT c category), around 40% (FW EU category) and around 50%
 371 (HT nc and IR HH categories). Similarly, when the baseline scenario (SI) was compared with SIV
 372 (see Figure 5 C), high values of uncertainty were found in Mineral, fossil and renewable resource
 373 depletion (RD), Land Use (LU), Freshwater ecotoxicity (FW ET), Marine eutrophication (ME),
 374 Terrestrial eutrophication (TE), Ionizing radiation HH (IR HH), Human toxicity (HT), cancer (c) and
 375 non-cancer (nc) effects. In Figure 5 the red crosses represent those categories excluded due to their
 376 high uncertainty.

377

378 **3.2 Techno-economic results**

379

380 Figure 2 shows four scenarios for OPW management: the baseline coal incineration (SI), coal+OPW
381 incineration (SII), biogas production (SIII), and biogas and fertilizer production (SIII and SIV). A
382 simulation using SuperPro Designer ® v 10 (Intelligent Inc.) was used to calculate the mass and
383 energy balance of each scenario, based on the primary data provided by FLP Procesados. Batch
384 operation with a constant feed rate of 16,666 kg of oranges, equivalent to 8325 L OJ / batch is
385 considered for all scenarios.

386 In scenario II, the solid OPW (77.38% of water) stream from the cold press juice extraction is
387 conveyed to the drying step. Combustion of natural gas provides the heat to dry the material to a water
388 content of about 20% before being sent to the coal/OPW fired steam plant. Feeding the coal burner
389 with the solid fuel mixture allows as much as 43% of dried OPW. On the other hand, OPW stream
390 is submitted to the anaerobic digestion (AD) step in scenarios III and IV. In order to know the amount
391 of potentially produced biogas in SIII and SIV, AD experiments were performed as described in
392 section 2.2.2. As showed in the LCA analysis, Scenario II is better than Scenario I in terms of
393 environmental results. The same occurs in six of the seven categories when comparing SII and SIII
394 or SIV (see Figure 3). When comparing capital investment, the anaerobic digestion scenarios (SIII
395 and SIV) require from 2 to 90 million of €, while the drier and feed system conditioning of the coal
396 boiler involved in SII are simpler, faster and cheaper. The cost study approach was carried out for SI
397 and SII (see appendix).

398

399 **4. DISCUSSION**

400

401 Results from the comparative LCA revealed that the coal incineration (SI) produced the highest
402 environmental impacts in all the environmental impact categories assessed. In SII, a potentially

403 polluting organic waste can be converted into a valuable source of benefits from self-exploitation of
404 energy. INC and AD scenarios achieved savings mainly for: (1) coal substitution, (2) biofuel
405 production, (3) avoidance of OPW disposal in landfills and (4) fertilizers recirculation provided by
406 the digestate. The findings of the present work corroborate the results of a recent study by Maier et
407 al., (2019), which exposed positive effects of fossil resources substituting practices. For this reason,
408 establishing the aforesaid bioenergy alternatives appeared to be beneficial for the environment.

409

410 Some LCA studies have been reported with the use of citrus or fruit waste on biomethane, digestate,
411 ethanol and limonene alternatives. Regarding Climate Change category, Pourbafrani et al., (2013)
412 reported 205.9 g CO₂eq/kWh and Joglekar et al., (2019) 0.375 kg CO₂ eq/kg of citrus waste. In the
413 present study, 1714 g CO₂eq /kWh and 1.77 kg CO₂ eq/kg of OPW in SIII (biogas obtained of AD
414 of OPW), and 1691 g CO₂eq/kWh and 1.74 kg CO₂ eq/kg of OPW in SIV (fertilizers recovery from
415 AD digestate). Hence, the lower CC results reported in literature may be due to the differences in the
416 systems process for production of ethanol (cited reference) and methane (this study).

417 Salemdeeb et al., (2018) found that the lowest environmental impacts were produced by composting,
418 followed by anaerobic digestion and incineration. In contrast, in this study the lowest environmental
419 impacts were observed in SII-incineration followed by SIII-biogas production and SIV-biogas and
420 fertilizers-SIV. These differences are attributable to the different characteristics of the raw materials,
421 system limits and conditions of the geographical location. However, SIV allowed to close the circle
422 owing to the biogas and fertilizer production, and its incorporation into a new cycle in the system.

423 Prior studies noted the importance of the use of fruit waste in methane production by anaerobic
424 digestion to improve the environmental behaviour of productive chains compared to their baseline
425 scenarios. A reduction of 77% in greenhouse emissions was found by Pourbafrani et al., (2013) with
426 the substitution natural gas with biomethane from AD process for electricity generation, and the
427 displacemente synthetic fertilizer by the digestate. Furthermore, reduction in all impacts categories

428 was described by Ariyanto et al., (2017), showing that biogas plant had lower impact than disposal in
429 landfill. According with the literature, results of the present study revealed a reduction in all
430 environmental impacts, except for water resource depletion when waste is managed avoiding the
431 landfill. Therefore, OPW is a potential feedstock to produce multiple products in biorefineries, with
432 significant reductions in their environmental impacts.

433 The present study showed a reduction in the environmental impacts when the energy is produced
434 either from direct co-combustion of OPW and coal, or AD of OPW. In accordance with the results
435 presented in this work, previous studies (Zema et al., 2018) demonstrated that the energy produced
436 by AD of OPW at industrial level is a sustainable practice. Furthermore, Zuwala and Sciazko, (2010)
437 showed that emission rates during the co-combustion of biomass and coal reduced the emissions of
438 CO₂ and SO₂. The results of the present study are consistent with those of Ardolino and Arena, (2019),
439 who indicated that biomethane produced from AD with biowaste as raw material is a clean and
440 renewable source, which offers substantial reductions in GHG emissions and resources consumption.
441

442 It is known that the higher the amount of OPW is contained in the INC mixture, the higher the
443 reduction in the environmental impact categories is expected. This is mainly due to the lower levels
444 of sulfur and nitrogen in biomass than coal. According to Santos et al., (2015) dried OPW showed
445 moderate levels of carbon (44–62%), high levels of oxygen (30–47%), lower levels of hydrogen (3–
446 6%), nitrogen (1 –2.6%), sulfur (0.4–0.8%) and ashes with a maximum of 7.8% compared to
447 conventional fuels. For this reason, positive environmental impacts are obtained when the highest
448 possible OPW content is incorporated into solid fuel mixtures. In order to get the best environmental
449 behavior for OPW INC mixtures, the maximum percentage of OPW (43%) was chosen for the coal-
450 OPW mixture in SII of this study.

451

452 OPW incineration is in line with earlier observations which showed that Colombian sugarcane
453 industry exploits a proportion of 10% coal and 90% bagasse in its boilers, optimizing the reduction
454 in environmental impacts for the generation of 114MW in 2009, 260 MW in 2015 and 360 MW for
455 2017 (Becerra Quiroz et al., 2017).

456

457 LCA studies of biowaste to energy have been reported previously. According to Maier et al., (2019),
458 it is possible to obtain important reductions in environmental categories avoiding fossil fuel
459 incineration. They got the following reductions: acidification (+1% to -71%), eutrophication (-2% to
460 -85%), fossil resource depletion (-2% to -84%), respiratory effects (0% to -96%), and photochemical
461 ozone formation (+3% to -59%). Consistently with the literature, this research found significant
462 reductions in CC, OD, PM POF AC and FEU when the fossil fuel is replaced by bioenergy sources.
463 These advantages were achieved by INC and AD adoption. For the OPW specific case, Negro et al.,
464 (2017) already highlighted that OPW management is a relevant issue to solve since conventional
465 disposal is neither economically nor environmentally attractive. In accordance with the Colombian
466 socioeconomic situation, the present study results suggested that INC is better option than AD in a
467 small-medium scale orange juice production factory.

468

469 SIV results broadly supports the work of other studies in this area linking AD digestate with fertilizer.
470 Basosi, R., Cellura, M., Longo, S., & Parisi, (2018) presented the digestate obtained from AD as a
471 product that can replace the marginal N, P, and K fertilizers. The main weakness is that replacements
472 are performed without any consideration about the real soil needs. Hence, soil analysis of the case
473 study location was taken into account, showing contents of N 2.83 g/kg (low), P 12.89 ppm (low) and
474 K 0.24 cmol/kg (medium). These low levels can be possibly due to low fertilization and nutrients
475 leaching. For this reason, the application of these elements shall become convenient.

476

477 Preliminary economic aspects in the AD scenarios (SIII and SIV) revealed that this option is
478 economically not recommended for a small juice producer because of large investments in facilities
479 (around M€ 3.12). These results seem to be consistent with other works. Mel et al., (2015) reported
480 that the capital investments to produce 22483.20 m³ day⁻¹ of biogas is €7.11 million and payback time
481 is 8.2 years. Important cost factors such as the size of the plant, its technical complexity, the capital
482 cost, the regulatory compliance and biogas purification make this scenario unlikely in the near future
483 for small to medium-sized juice processing Colombian companies. In contrast, economic adjustments
484 of the dryers and boiler of FLP company are lower than AD scenarios.

485 For all above-mentioned reasons, SII was chosen as the best-case scenario for the OPW management,
486 aimed at optimizing the environmental, energetic performances and waste disposal of the company
487 case study. It has been defined based on the following criteria: (1) Environmental profile of each
488 scenario; (2) Potential/existing technical and economical limitations related to sophisticated
489 equipment, advanced technology and trained personnel in near future.

490 Despite these promising results, questions remain. Further research should be undertaken to
491 investigate the more economic alternatives for AD of OPW.

492 **5. CONCLUSIONS**

493

494 The aim of the present paper was to propose, assess and compare alternative scenarios to the current
495 techno-economic and environmental situation of OPW management in a Latin American case study..

496 The initial finding that emerged from this study is that avoiding landfill in OJ industries obtained
497 economic and environmental benefits.

498

499 The following conclusions can be drawn from the present study. In SII, positive contributions were
500 observed due to the avoided landfill. The energy recovered using OPW as fuel provides a reduction

501 in CC of 1.235 kg of CO_2 eq in SII with respect to SI. PM, POF and AC categories presented similar
502 tendencies due to the avoided landfill.

503

504 Those scenarios with anaerobic digestion as a solution to avoid landfill SIII and SIV are
505 environmentally friendly options compared to Scenario I, but they incur higher costs than Scenario
506 II. In anaerobic digestion scenario SIV, the CC impact is reduced, since the recovery of the digestate
507 produce fertilizer and this is reused for the orange crops. This additional stage produces a reduction
508 from -3.029% of CC impact in SIII to -3.796% in SIV. Important benefits were found as well in the
509 OD category which had 97% SIV of the impact obtained in SIII. For PM, POF, AC, FEU and WRD,
510 reductions of 0.559%, 0.863%, 0.411%, 0.202% and 1.47%, respectively, were also obtained in SIV
511 compared to SIII.

512

513 With minor modifications of the solid fuel feed system, SII was the best scenario. It achieves savings
514 of coal substitution at the steam production stage from 0.493 kg in SI to 0.279 kg, thanks to the use
515 of dried OPW biofuel, and avoids waste disposal in landfills. SII also offers economic advantage in
516 comparison with AD SII and SIV.. In developing countries, it is clear that the low-cost option of the
517 solid fuel feed system would be suitable for other industries that use coal fired steam facilities and
518 want to switch to greener sustainable energy technologies in developing countries.

519

520 Despite its local nature, this study offers a comprehensive assessment of OPW in Latin American
521 economies. For this specific case study, a more economic AD process could produce findings that
522 account for the overall sustainability of the process. This study suggests that appropriate management
523 of OPW allows to avoid landfill gaining economic and environmental benefits. These results can be
524 used to develop targeted interventions aimed at OPW management in other countries or even with
525 other kinds of waste with AD potential.

526

527 Future work should include experimental campaign for mixtures combustion of OPW and coal in a
528 steam boiler, from pilot plant to industrial scale. These tests will provide more accurate results on
529 emissions and energy efficiency of the fuel. It is further recommended to evaluate the extraction of
530 essential oils, which inhibits the biogas production and can also provide additional economic benefits.

531

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533

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542

543 **Appendix A.**

544 Supplementary data associated with this article can be found in attached doc.

545

546 **REFERENCES**

547 Ardolino, F., Arena, U., 2019. Biowaste-to-Biomethane: An LCA study on biogas and syngas roads.

548 Waste Manag. <https://doi.org/10.1016/j.wasman.2019.02.030>

549 Ariyanto, T., Cahyono, R.B., Vente, A., Mattheij, S., Millati, R., Sarto, Mohammad J, T., Syamsiah,

550 S., 2017. Utilization of fruit waste as biogas plant feed and its superiority compared to landfill.

551 Int. J. Technol. 8, 1385–1392. <https://doi.org/10.14716/ijtech.v8i8.739>

552 Basosi, R., Cellura, M., Longo, S., & Parisi, M.L., 2018. Life Cycle Assessment of Energy Systems
553 and Sustainable Energy Technologies: The Italian Experience. [https://doi.org/10.1007/978-3-](https://doi.org/10.1007/978-3-319-93740-3)
554 [319-93740-3](https://doi.org/10.1007/978-3-319-93740-3)

555 Batuecas, E., Tommasi, T., Battista, F., Negro, V., Sonetti, G., Viotti, P., Fino, D., Mancini, G., 2019.
556 Life Cycle Assessment of waste disposal from olive oil production: Anaerobic digestion and
557 conventional disposal on soil. *J. Environ. Manage.* 237, 94–102.
558 <https://doi.org/10.1016/j.jenvman.2019.02.021>

559 Becerra Quiroz, A.P., Buitrago Coca, A.L., Pinto Baquero, P., 2017. Sostenibilidad del
560 aprovechamiento del bagazo de caña de azúcar en el Valle del Cauca, Colombia. *Ing. Solidar.*
561 12, 133–149. <https://doi.org/10.16925/in.v12i20.1548>

562 Bentsen, N.S., Felby, C., Thorsen, B.J., 2014. Agricultural residue production and potentials for
563 energy and materials services. *Prog. Energy Combust. Sci.* 40, 59–73.
564 <https://doi.org/10.1016/J.PECS.2013.09.003>

565 Bilgen, S., Keleş, S., Sarıkaya, İ., Kaygusuz, K., 2015. A perspective for potential and technology of
566 bioenergy in Turkey: Present case and future view. *Renew. Sustain. Energy Rev.* 48, 228–239.
567 <https://doi.org/10.1016/J.RSER.2015.03.096>

568 Bühle, L., Hensgen, F., Donnison, I., Heinsoo, K., Wachendorf, M., 2012. Life cycle assessment of
569 the integrated generation of solid fuel and biogas from biomass (IFBB) in comparison to
570 different energy recovery, animal-based and non-refining management systems. *Bioresour.*
571 *Technol.* 111, 230–239. <https://doi.org/10.1016/j.biortech.2012.02.072>

572 Calabrò, P.S., Panzera, M.F., 2018. Anaerobic digestion of ensiled orange peel waste: Preliminary
573 batch results. *Therm. Sci. Eng. Prog.* 6, 355–360.
574 <https://doi.org/https://doi.org/10.1016/j.tsep.2017.12.011>

575 Cardona A, C.A., Sánchez T, J.Ó., Ramírez A, J.A., Alzate R, L.E., 2004. Biodegradation of organic
576 solid wastes from market places. *Rev. Colomb. Biotecnol.* VI, 78–89.
577 <https://doi.org/10.15446/rev.colomb.biote>

578 Contreras-Lisperguer, R., Batuecas, E., Mayo, C., Díaz, R., Pérez, F.J., Springer, C., 2018.
579 Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica. *J.*
580 *Clean. Prod.* 200, 390–401. <https://doi.org/10.1016/j.jclepro.2018.07.322>

581 DANE, E., 2017. Boletín Técnico Encuesta Nacional Agropecuaria (ENA) 2017 Encuesta Nacional
582 Agropecuaria.

583 Domingos, I., Ferreira, J., Cruz-Lopes, L., Esteves, B., 2019. Polyurethane foams from liquefied
584 orange peel wastes. *Food Bioprod. Process.* 115, 223–229.
585 <https://doi.org/https://doi.org/10.1016/j.fbp.2019.04.002>

586 Dong, J., Tang, Y., Nzihou, A., Chi, Y., Weiss-Hortala, E., Ni, M., 2018. Life cycle assessment of
587 pyrolysis, gasification and incineration waste-to-energy technologies: Theoretical analysis and
588 case study of commercial plants. *Sci. Total Environ.* 626, 744–753.
589 <https://doi.org/10.1016/j.scitotenv.2018.01.151>

590 ECOCARBÓN, 1998. Calderas a Carbón, Gomez C, A. ed. UNIVERSIDAD PONTIFICIA
591 BOLIVARIANA, Medellín.

592 European Parliament, 2009. Directive 2009/28/EC of the European Parliament and of the Council of
593 23 April 2009. *Off. J. Eur. Union* 140, 16–62.
594 https://doi.org/10.3000/17252555.L_2009.140.eng

595 Fontes, C.M.A., Silva, R.B., Lima, P.R.L., 2017. Characterization and Effect of Using Bottom and
596 Fly Ashes from Co-combustion of Cocoa Waste as Mineral Addition in Concrete. *Waste and*
597 *Biomass Valorization* 1–11. <https://doi.org/10.1007/s12649-017-0031-x>

598 Harsono, S.S., Salahuddin, Fauzi, M., Purwono, G.S., Soemarno, D., Kissinger, 2015. Second
599 Generation Bioethanol from Arabica Coffee Waste Processing at Smallholder Plantation in Ijen
600 Plateau Region of East Java. *Procedia Chem.* 14, 408–413.
601 <https://doi.org/10.1016/J.PROCHE.2015.03.055>

602 IEA, 2015. CO2 Emissions from Fuel Combustion Highlights. 2015. IEA Paris, Fr.

603 ISO TC2017 SC5, 2006a. ISO 14040:2006 Environmental management -- Life cycle assessment --
604 Principles and framework.

605 ISO TC2017 SC5, 2006b. ISO 14044:2006 Environmental management -- Life cycle assessment --
606 Requirements and guidelines.

607 Joglekar, S.N., Pathak, P.D., Mandavgane, S.A., 2019. Process of fruit peel waste biorefinery : a case
608 study of citrus waste biorefinery , its environmental impacts and recommendations.
609 <https://doi.org/10.1007/s11356-019-04196-0>

610 JRC, E.C., 2010. European Commission-Joint Research Centre-Institute for Environment and
611 Sustainability: International Reference Life Cycle Data System (ILCD) Handbook-General
612 guide for Life Cycle Assessment-Detailed guidance, March 2010.

613 Li, J., Lin, B., 2019. The sustainability of remarkable growth in emerging economies. *Resour.*
614 *Conserv. Recycl.* 145, 349–358. <https://doi.org/10.1016/j.resconrec.2019.01.036>

615 Loo, S. van, Koppejan, J., 2008. *The Handbook of Biomass Combustion and Co-firing*, First. ed.
616 Earthscan, London.

617 Mahato, N., Sharma, K., Sinha, M., Cho, M.H., 2018. Citrus waste derived nutra-/pharmaceuticals
618 for health benefits: Current trends and future perspectives. *J. Funct. Foods* 40, 307–316.
619 <https://doi.org/10.1016/j.jff.2017.11.015>

620 Maier, J.M., Sowlati, T., Salazar, J., 2019. Life cycle assessment of forest-based biomass for

621 bioenergy: A case study in British Columbia, Canada. *Resour. Conserv. Recycl.* 146, 598–609.
622 <https://doi.org/10.1016/j.resconrec.2019.02.035>

623 Martín, M.A., Siles, J.A., Chica, A.F., Martín, A., 2010. Biomethanization of orange peel waste.
624 *Bioresour. Technol.* 101, 8993–8999. <https://doi.org/10.1016/j.biortech.2010.06.133>

625 Mel, M., Yong, A.S.H., Avicenna, Ihsan, S.I., Setyobudi, R.H., 2015. Simulation Study for Economic
626 Analysis of Biogas Production from Agricultural Biomass. *Energy Procedia* 65, 204–214.
627 <https://doi.org/10.1016/j.egypro.2015.01.026>

628 Ministry of Mining and Energy, 2012. Assessment of biofuels chain production life cycle in
629 Colombia. Medellín.

630 Negro, V., Ruggeri, B., Fino, D., Tonini, D., 2017. Life cycle assessment of orange peel waste
631 management. *Resour. Conserv. Recycl.* 127, 148–158.
632 <https://doi.org/10.1016/j.resconrec.2017.08.014>

633 Paone, E., Komilis, D., 2018. Strategies for the sustainable management of orange peel waste through
634 anaerobic digestion. *Environ. Manage.* 212, 462–468.
635 <https://doi.org/10.1016/j.jenvman.2018.02.039>

636 Pourbafrani, M., McKechnie, J., L MacLean, H., Saville, B.A., 2013. Life cycle greenhouse gas
637 impacts of ethanol, biomethane and limonene production from citrus waste. *Environ. Res. Lett.*
638 8, 12. <https://doi.org/10.1088/1748-9326/8/1/015007>

639 Rezzadori, K., Benedetti, S., Amante, E.R., 2012. Proposals for the residues recovery: Orange waste
640 as raw material for new products. *Food Bioprod. Process.* 90, 606–614.
641 <https://doi.org/10.1016/j.fbp.2012.06.002>

642 Salemdeeb, R., Bin, M., Christian, D., Abir, R., Tabbaa, A., 2018. An environmental evaluation of
643 food waste downstream management options : a hybrid LCA approach. *Int. J. Recycl. Org.*

644 Waste Agric. 7, 217–229. <https://doi.org/10.1007/s40093-018-0208-8>

645 Santos, C.M., Dweck, J., Viotto, R.S., Rosa, A.H., de Morais, L.C., 2015. Application of orange peel
646 waste in the production of solid biofuels and biosorbents. *Bioresour. Technol.* 196, 469–479.
647 <https://doi.org/10.1016/j.biortech.2015.07.114>

648 Siles, J.A., Vargas, F., Gutiérrez, M.C., Chica, A.F., Martín, M.A., 2016. Integral valorisation of
649 waste orange peel using combustion, biomethanisation and co-composting technologies.
650 *Bioresour. Technol.* <https://doi.org/10.1016/j.biortech.2016.03.056>

651 Tonini, D., Hamelin, L., Wenzel, H., Astrup, T., 2012. Bioenergy production from perennial energy
652 crops: a consequential LCA of 12 bioenergy scenarios including land use changes. *Environ. Sci.*
653 *Technol.* 46, 13521–13530. <https://doi.org/10.1021/es3024435>

654 Wandera, S.M., Qiao, W., Algapani, D.E., Bi, S., Yin, D., Qi, X., Liu, Y., Dach, J., Dong, R., 2018.
655 Searching for possibilities to improve the performance of full scale agricultural biogas plants.
656 *Renew. Energy* 116, 720–727. <https://doi.org/10.1016/J.RENENE.2017.09.087>

657 Zema, D.A., Fòlino, A., Zappia, G., Calabrò, P.S., Tamburino, V., Zimbone, S.M., 2018. Anaerobic
658 digestion of orange peel in a semi-continuous pilot plant: An environmentally sound way of
659 citrus waste management in agro-ecosystems. *Sci. Total Environ.* 630, 401–408.
660 <https://doi.org/10.1016/j.scitotenv.2018.02.168>

661 Zuwala, J., Sciazko, M., 2010. Full-scale co-firing trial tests of sawdust and bio-waste in pulverized
662 coal-fired 230t/h steam boiler. *Biomass and Bioenergy.*
663 <https://doi.org/10.1016/j.biombioe.2010.03.003>

664