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

D.L. Ortiz[a,γ], E. Batuecas[b,γ], C.E. Orrego[c*], L. Joana Rodríguez[a], E. Camelin[d], D. Fino[d]

[a] Department of Industrial Engineering, Universidad Nacional of Colombia, Manizales, 170004, Colombia
[b] Department of Thermal and Fluid Engineering, Universidad Carlos III de Madrid, Av. de la Universidad, 30, 28911 Leganés, Madrid, Spain
[c] Department of Physics and Chemistry, Universidad Nacional de Colombia, Manizales, 170004, Colombia.
[d] Department of Applied Science and Technology, Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino 10129, Italy

[γ] These authors contribute equally.
[*] Corresponding author: ceorregoa@unal.edu.co

Abstract

Appropriate waste management in emerging economies like Colombia should be an asset for the overall sustainability. In the Orange Peel Waste case, incineration and Anaerobic Digestion are challenging solutions for the orange juice agro-industrial sector. The development of these kinds of solutions present an opportunity to avoid the landfill, which is the conventional practice. However, alternatives should be assessed in order to determine their feasibility. This paper aims to assess if incineration and Anaerobic Digestion are potential alternatives to landfill from a techno-economic and environmental perspective. To this aim, a comparative Life Cycle Assessment was carried out in four scenarios. The first scenario represents orange juice production with coal as the energy supply and a traditional landfill waste management approach. In the second scenario, the peels are incinerated to avoid landfill and reduce the need for coal. The third scenario represents the valorization of the peels by means of Anaerobic Digestion which produces biogas for the energy requirements of the industrial process. In the fourth scenario, apart from the energy from biogas, the digestate becomes a fertilizer for use in the orange crops. The results revealed that scenario III and IV are environmentally friendly options compared to Scenario I, but they incur higher costs than Scenario II. Therefore, Scenario II is more suitable for the Colombian socioeconomic reality since Scenario II is not only techno-environmentally achievable, but also economically feasible. Coal substitution should be

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

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

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

1. INTRODUCTION

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

Orange juice is an important agro-industrial economic sector, which consequently handles a large amount of Orange Peel Waste (OPW). The valorization of OPW presents a very high potential considering its composition in essential oils widely exploited in the chemical industry (Domingos et al., 2019). Furthermore, the exploitation of OPW in Anaerobic Digestion (AD) (Calabrò and Panzera, 2018; Paone and Komilis, 2018) and in biorefinery facilities (Martín et al., 2010) are well known processes. In the international citrus market, Colombia is not a relevant player. However, the country has 71.338 ha of planted area with a yield of 539.916-ton year^{-1}. In the specific orange case, it ranks second in national production with 456.301 ton (DANE, 2017). The main consumption is as fresh fruit and in industrial orange juice (OJ). During OJ production, only about half of the orange fresh weight is transformed into juice. The remaining 50% consists of pulp, peel, and seeds (Rezzadori et al., 2012). About 95% of this waste is made of peels (OPW), which are a great disposal issue for this industry since their management requires economic and energy resources, with the risk of air, water and soil contamination.

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

Plenty of scientific literature on agro-industrial waste management is available since there are numerous ways to recover waste by integrating it into a new productive chain which closes the loop. For instance in cocoa industries in Brazil, the shell waste was used as fuel for boilers, through the incineration (INC) of the shell together with pieces of wood (Fontes et al., 2017). Among the advantages of biofuels use, lower emissions of SO_2 and NO_X are produced than conventional fossil fuels, since their content in sulfur, nitrogen and ashes is lower (Bilgen et al., 2015). Furthermore, the use of agro-industrial waste through biological processes has been widely tested in different industrial facilities (Wandera et al., 2018). The main biological process currently available is AD. Large amounts of waste (OPW as well) can be treated by means of AD techniques, which would increase the profits of an OJ company by integrating the recovered energy in its own productive chain (Zema et al., 2018). Some studies stated that co-combustion with biomass improves the economic and environmental benefits of the plant (Contreras-Lisperguer et al., 2018) in other applications. Despite waste management is becoming a common practice in the industry, the proper evaluation from an environmental point of view is still lacking. In this respect, LCA is a powerful decision-making tool to develop more sustainably efficient processes.

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

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

2. METHODOLOGY

2.1 Case study description.

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

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

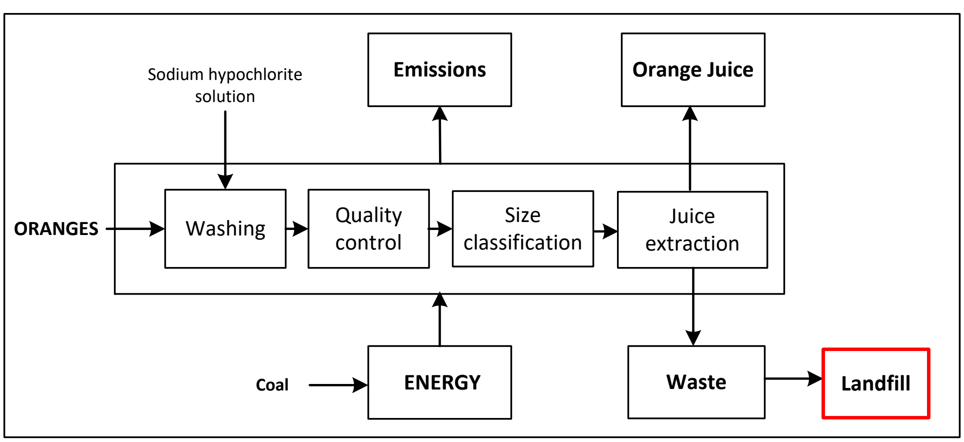

Figure 1. Simplified flowchart diagram of the Scenario I which is the current situation in the case study. Coal is combusted for producing orange juice and OPW is sent to landfill.

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

2.2 LCA Methodology

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

2.2.1 Goal and scope definition

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

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

2.2.2 Life Cycle Impact Inventory for different scenarios

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

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

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

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
Coal incineration	Washing	Sodium hypoclorite	0.006	kg
		Water	0.302	kg
	Steam production	Coal	0.493	kg
			8.437	MJ
		Output	**Amount**	**Unit**
	Steam production	OPW	0.967	kg
		Coal ash	0.046	kg
	All stages	Emissions		
		CO_2	1.193	kg
		SO_2	5.57E-03	kg
		H_20	312.132	kg
		N_2	7.200E-03	kg
		O_2	1.130	kg

Scenario II (SII) represents the production of 1L of OJ when the OPW landfill is avoided and is valorized by a waste treatment. LCI of the SII is depicted in Table 3. The waste treatment in SII consists of OPW followed by its incineration, producing energy auto- consumed by the OJ production process. In the Table 3 it is possible to notice that the amount of coal needed for 1L OJ is reduced from 0.493 kg in the Scenario I to 0.279 kg in this scenario. Figure 2 B shows the inputs and outputs of the SII process.

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

Process	**Subprocess**	**Input**	**Amount**	**Unit**
SII	All stages	Oranges	1.945	Kg
Coal+OPW incineration	Washing	Sodium hypoclorite	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
		Output	**Amount**	**Unit**
	OJ	OPW	0.967	Kg
	Steam production	Energy from SII	4.784	MJ
		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_20	404.120	Kg
		N_2	5.300E-03	Kg
		O_2	1.211	Kg

The emissions of CO_2, NO_x, SO_2, H_2O, O_2 and N_2 of each mixture of solid fuels were calculated from mass balances, biomass combustion and cofiring methodologies (ECOCARBÓN, 1998; Loo and Koppejan, 2008). The mass and energy balances were based on empirical data from previous studies conducted in Colombia (Cardona A et al., 2004) and in other countries (Siles et al., 2016). More information is available in the appendix.

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

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
	Washing	Sodium hypoclorite	0.006	kg
		Water	0.302	kg
	AD	Water	0.046	kg
		Sludge	4.867	kg
		Heat	0.495	kWh
		Operation (pumping, trasnporting)	0.017	kWh
		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_20	219.091	kg

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

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

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 hypoclorite	0.006	kg
		Water	0.302	kg
		Water	0.046	kg

	AD	Sludge	4.867	kg
		Heat	0.495	kWh
		Operation (pumping, trasnporting)	0.017	kWh
		Methane upgrade	0.545	kWh
	Fertilizers	Dewatering by pressing	6.769E-03	kWh
	Steam production	Coal	0.331	kg
			5.673	MJ
		Methane 97%	0.105	kg
			2.763	Mj
		Output	**Amount**	**Unit**
	OJ	OPW	0.967	kg
AD and methane recirculation	Steam production	Coal ash	0.030	kg
	AD	Energy from SIII	3.592	MJ
		Digestate	0.483	kg
	Fertlizers	N	1.112E-03	kg
		P	9.670E-05	kg
		K	6.290E-04	kg
	All stages	Total Emissions		
		CO_2	1.545	kg
		SO_2	3.740E-03	kg
		H_20	219.091	kg
	Digestate to fertilizers	N in soil	2.446E-04	kg
		NO_3	2.502E-02	kg
		N_2	5.137E-04	kg
		NH_3	1.668E-05	kg

	N	6.672E-05	kg

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

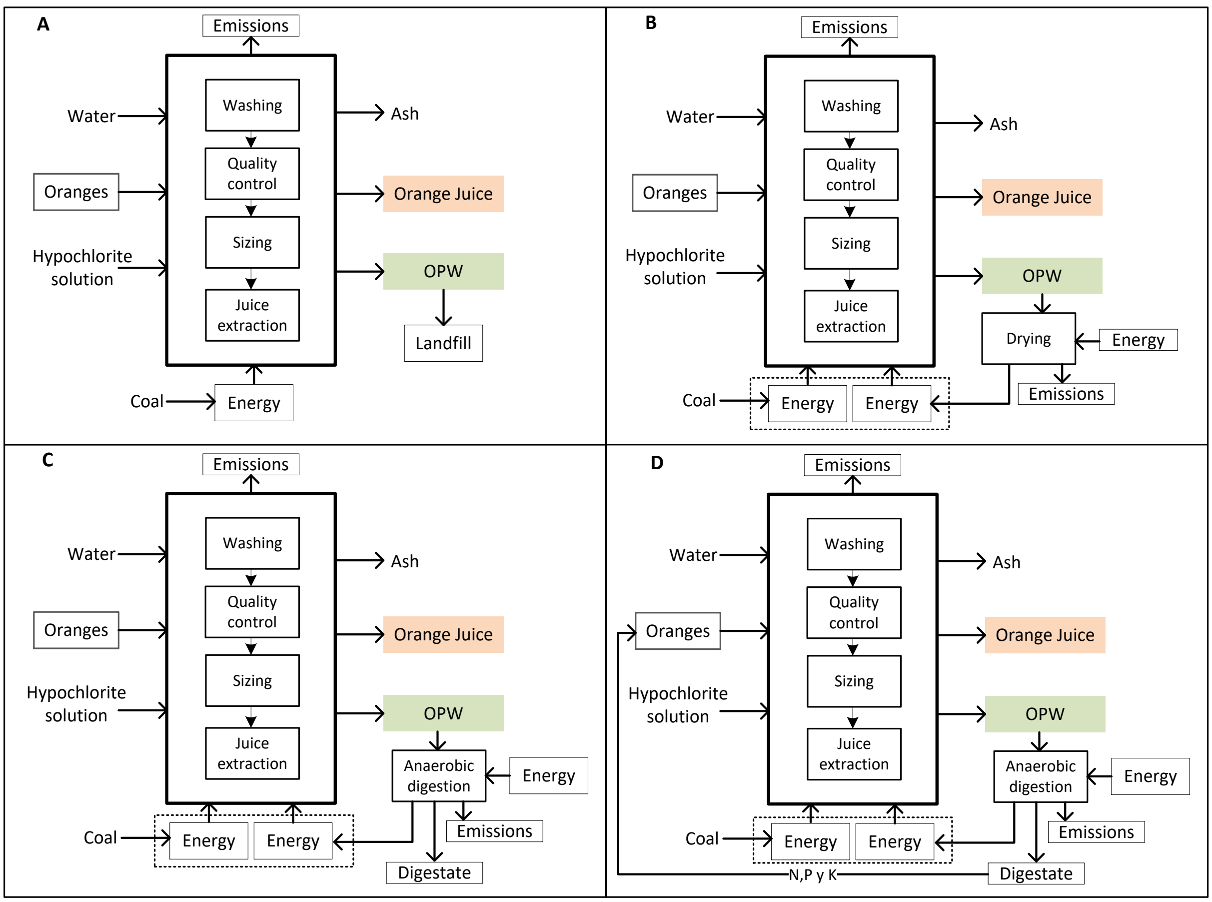

Figure 2. Foreground of OPW management for all scenarios. (A) SI Coal incineration, (B) SII Coal + OPW incineration, (C) SIII AD and methane recovery and (D) SIV AD, methane and fertilizers recovery.

2.2.3 Life Cycle Assessment

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

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

2.2.4 Interpretation phase

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

3. RESULTS

3.1 LCA RESULTS

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

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

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

In WRD, the scenarios with biogas production (SIII and SIV) obtained worse environmental behavior than the ones with a minor (SII) or null (SI) waste management approach. SI revealed the smallest value of WRD, 35.5% and 38.6% lower than SIII and SIV, respectively. WRD in SI obtained 8.018E-02 m^3 H_2O eq which was very similar to SII (only 4.1% lower). In this regard, it is important to highlight that SI is the simplest scenario since SII, SIII and SIV added water-consuming processes to the value chain.

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

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

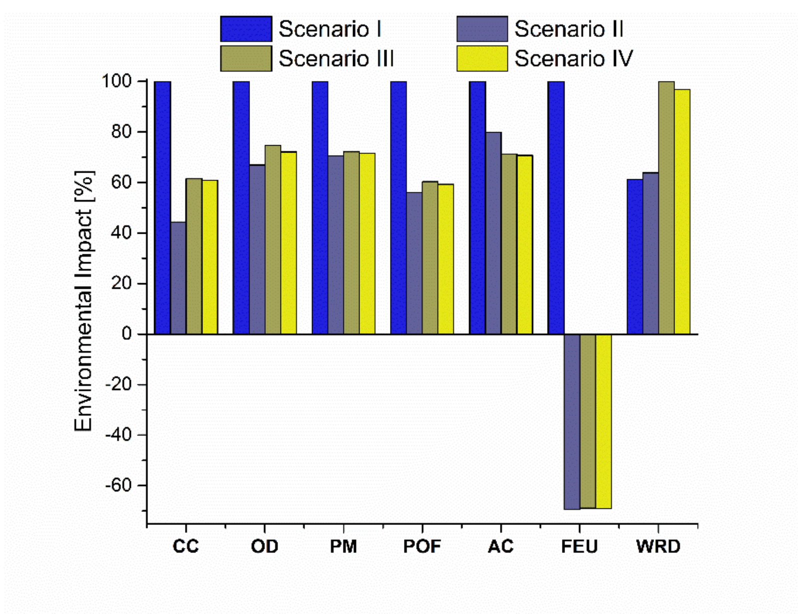

Figure 3. Comparative LCA results in all scenarios.

Table 6. Characterization of impact scores for scenarios I Coal incineration, II Coal + OPW incineration, III AD and methane recovery and IV Anaerobic Digestion, methane and fertilizers recovery.

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 PM2.5 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

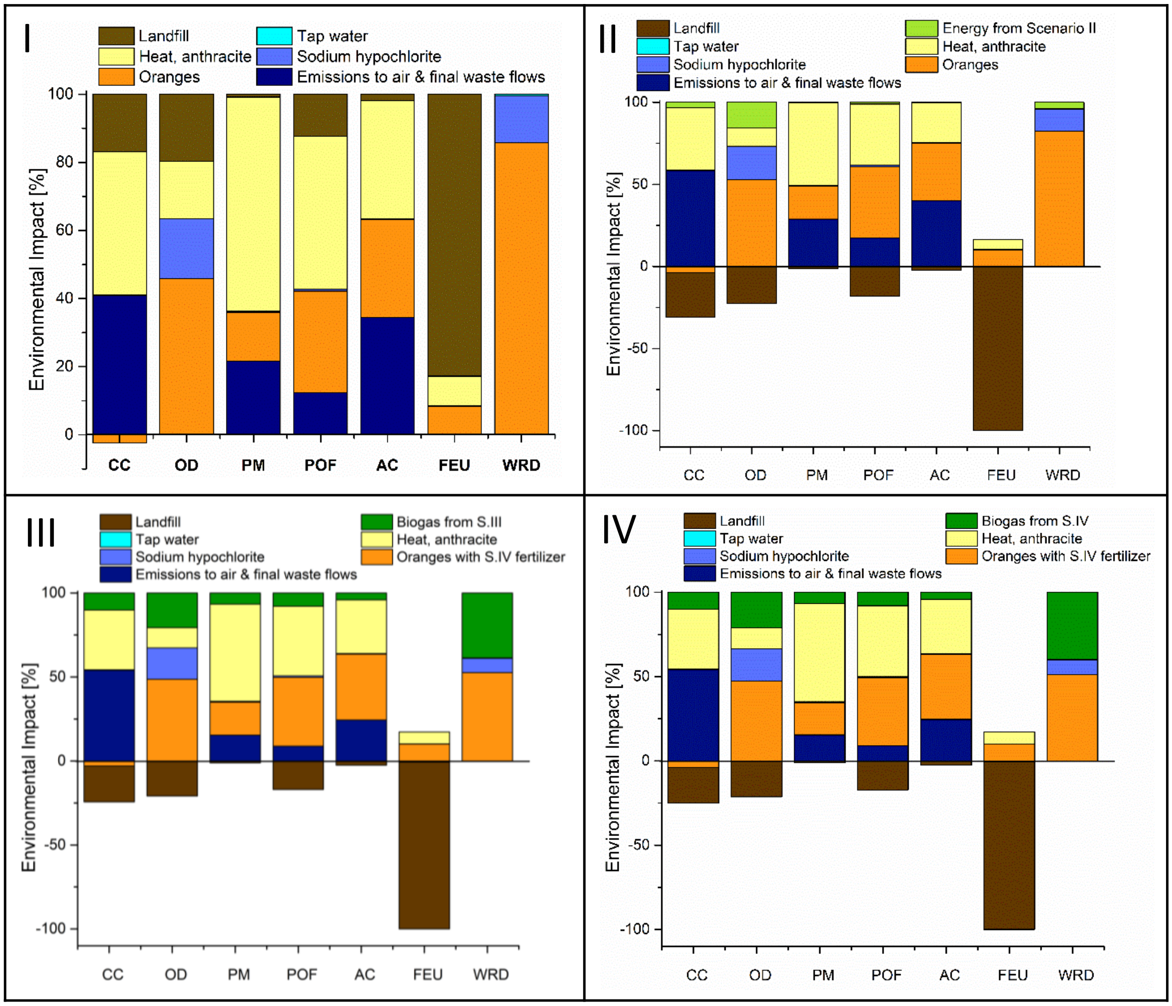

Figure 4. Contribution of life cycle stages to total impact scores (scaled to 100%) in all scenarios: I Coal incineration, II Coal + OPW incineration, III AD and methane recovery and IV AD, methane and fertilizers recovery. Climate change (CC), ozone depletion (OD) particulate matter (PM), photochemical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

Figure 4 shows the contribution of each item in each scenario to the environmental impacts. In the upper left part of Figure 4, the environmental impacts of SI with their contributions are showed. In SI, 41.98% of CC is due to the coal as fuel in the boiler for steam production. In addition, emissions generated by the combustion of coal (such as CO_2 and SO_2) scored 40.86% of the total CC impact.

The final disposal in landfill contributed to 16.93% of CC. Moreover, a positive contribution (negative value in CC, see Figure 4 I) is observed in CC category. This aspect is due to the biogenic CO_2 capture in oranges. Regarding the OD in Scenario I, 45.87% of the impact is related to the orange production and 17.57% to the use of sodium hypochlorite in washing stage. In a lowest proportion, the use of coal and landfill contribute 16.85% and 19.65%, respectively. Regarding PM, POF, and AC, the largest contributions were due to the use of coal, followed by the oranges production and the emissions and final waste flows. In the FEU category, 82.75% of the impact is due to the landfill. In SI, the use of water in orange crops contributed 85.8% of WRD.

The contribution of each impact category in SII is shown in the upper right part of Figure 4. In CC, OD, POF and FEU categories, positive contributions were observed due to the landfilling avoidance. Moreover, the energy recovered in the process through the use of OPW as fuel provides a reduction in CC from 2.781 kg of CO_2 eq in SI to 1.235 kg of CO_2 eq in SII. In this CC category, the greatest contribution is caused by the emissions generated during the OPW drying stage i.e. the combustion of coal-OPW mixture and the use of coal as fuel. These results reflect those of Dong et al., 2018 who also found that direct emissions have great influence in the environmental impacts during an incineration process of waste to energy,. Only 3.31% of CC in SII is ascribable to the energy recovered. PM, POF and AC categories presented tendencies similar to SI, but with environmental impacts lower than those of SI due to the landfilling avoidance. Likewise, FEU category presented a vast positive (negative value) contribution for the use of OPW in a new cycle, i.e. OPW recovery, avoiding the landfill. Additionally, in this category a reduction of 3% was observed for the substitution of coal by INC process. In the case of WRD, the greatest impact was provoked by the cultivation of oranges and the use of sodium hypochlorite.

In environmental impacts of SIII, an increase of 0.475 kg CO_2 eq was observed for CC regarding the value obtained in SII. The most influential factors in this category were emissions and waste generation, followed by the coal as in SI. The energy recovery from the biogas contributed by 10.15% on CC impact. Moreover, biogas production scored 20.65%, 6.63%, 7.86%, 4.10% and 38.70% in the OD, PM, POF, AC and WRD categories, respectively. For WRD, SIII presented the highest value with 1.140E-01 m3 water eq, as showed in Table 6, due to the large amounts of water used during the anaerobic digestion.

Regarding SIV, the CC impact reduced from -3.029% in SIII to -3.796% in SIV, since the recovery of the digestate allows the production of a fertilizer used in the orange crops . Consequently, this reduction in CC impact was provoked by an increase in the biogenic CO_2 in SIV compared to SIII. The “closing-the-loop” approach revealed important benefits in OD category as well, with 97% SIV of the impact obtained in SIII. For PM, POF, AC, FEU and WRD, reductions of 0.559%, 0.863%, 0.411%, 0.202% and 1.47%, respectively, were also obtained in SIV compared to SIII. These findings were also reported by Bühle et al., (2012) who described reductions in climate change, even taking into account a transport of 5 km for the application of digestate-derived fertilizers.

3.1.1 Uncertainty analysis

Primary data of this case study were introduced in the software as unique values. However, the data items used in this LCA study were taken from the Ecoinvent database with lognormal distribution around the medium value characterized by its standard deviation. When these items are combined, their variability could affect the uncertainty of the LCA model downstream. Hence, in order to determine the most relevant impact categories, the authors decided to carry out an uncertainty analysis with the Montecarlo distribution. Calculations were conducted with 1000 iterations and a confidence interval of 95%. All the impact categories implemented by the ILCD are reported in Figure 5. Due to the uncertainties and their development, some of these categories are classified as interim. As previously discussed, the developers of ILCD method classified the impact categories by recommendation levels. Ionizing Radiation E (IR E) is classified as interim. Hence, the authors consider that interim methods should be excluded, that is why IR E was not taken into account in this study.

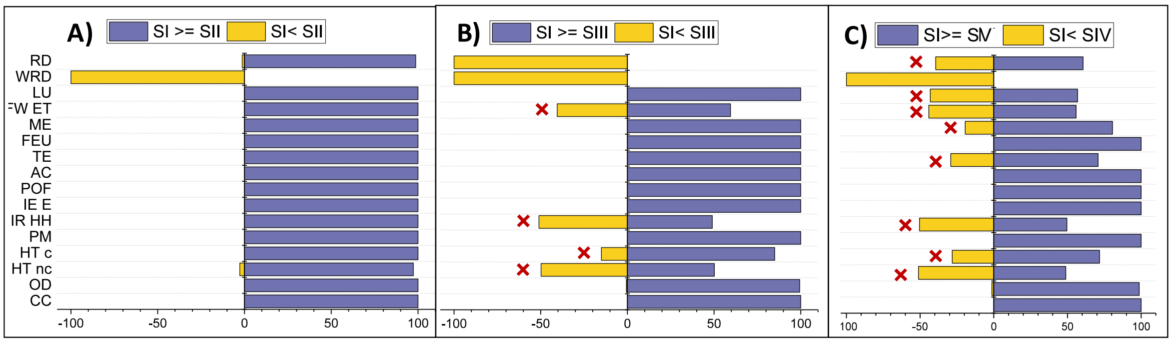

Figure 5. Uncertainty analysis results conducted with the Montecarlo distribution. A) Scenario I compared with Scenario III. B) Scenario I compared with Scenario III. C) Scenario I compared with Scenario IV.

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

3.2 Techno-economic results

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

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

4. DISCUSSION

Results from the comparative LCA revealed that the coal incineration (SI) produced the highest environmental impacts in all the environmental impact categories assessed. In SII, a potentially polluting organic waste can be converted into a valuable source of benefits from self-exploitation of energy. INC and AD scenarios achieved savings mainly for: (1) coal substitution, (2) biofuel production, (3) avoidance of OPW disposal in landfills and (4) fertilizers recirculation provided by the digestate. The findings of the present work corroborate the results of a recent study by Maier et al., (2019), which exposed positive effects of fossil resources substituting practices. For this reason, establishing the aforesaid bioenergy alternatives appeared to be beneficial for the environment.

Some LCA studies have been reported with the use of citrus or fruit waste on biomethane, digestate, ethanol and limonene alternatives. Regarding Climate Change category, Pourbafrani et al., (2013) reported 205.9 g CO_2eq/kWh and Joglekar et al., (2019) 0.375 kg CO_2 eq/kg of citrus waste. In the present study, 1714 g CO_2eq /kWh and 1.77 kg CO_2 eq/kg of OPW in SIII (biogas obtained of AD of OPW), and 1691 g CO_2eq/kWh and 1.74 kg CO_2 eq/kg of OPW in SIV (fertilizers recovery from AD digestate). Hence, the lower CC results reported in literature may be due to the differences in the systems process for production of ethanol (cited reference) and methane (this study).

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

Prior studies noted the importance of the use of fruit waste in methane production by anaerobic digestion to improve the environmental behaviour of productive chains compared to their baseline scenarios. A reduction of 77% in greenhouse emissions was found by Pourbafrani et al., (2013) with the substitution natural gas with biomethane fromAD process for electricity generation, and the displacemente synthetic fertilizer by the digestate. Furthermore, reduction in all impacts categories was described by Ariyanto et al., (2017), showing that biogas plant had lower impact than disposal in landfill. According with the literature, results of the present study revealed a reduction in all environmental impacts, except for water resource depletion when waste is managed avoiding the landfill. Therefore, OPW is a potential feedstock to produce multiple products in biorefineries, with significant reductions in their environmental impacts.

The present study showed a reduction in the environmental impacts when the energy is produced either from direct co-combustion of OPW and coal, or AD of OPW. In accordance with the results presented in this work, previous studies (Zema et al., 2018) demonstrated that the energy produced by AD of OPW at industrial level is a sustainable practice. Furthermore, Zuwala and Sciazko, (2010) showed that emission rates during the co-combustion of biomass and coal reduced the emissions of CO_2 and SO_2. The results of the present study are consistent with those of Ardolino and Arena, (2019), who indicated that biomethane produced from AD with biowaste as raw material is a clean and renewable source, which offers substantial reductions in GHG emissions and resources consumption.

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

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

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

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

Preliminary economic aspects in the AD scenarios (SIII and SIV) revealed that this option is economically not recommended for a small juice producer because of large investments in facilities (around M€ 3.12). These results seem to be consistent with other works. Mel et al., (2015) reported that the capital investments to produce 22483.20 m^3 day^{-1} of biogas is €7.11 million and payback time is 8.2 years. Important cost factors such as the size of the plant, its technical complexity, the capital cost, the regulatory compliance and biogas purification make this scenario unlikely in the near future for small to medium-sized juice processing Colombian companies. In contrast, economic adjustments of the dryers and boiler of FLP company are lower than AD scenarios.

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

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

5. CONCLUSIONS

The aim of the present paper was to propose, assess and compare alternative scenarios to the current techno-economic and environmental situation of OPW management in a Latin American case study.. The initial finding that emerged from this study is that avoiding landfill in OJ industries obtained economic and environmental benefits.

The following conclusions can be drawn from the present study. In SII, positive contributions were observed due to the avoided landfill. The energy recovered using OPW as fuel provides a reduction in CC of 1.235 kg of CO_2 eq in SII with respect to SI. PM, POF and AC categories presented similar tendencies due to the avoided landfill.

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

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

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

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

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Appendix A.

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

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