Low-cost anaerobic digester to promote the circular bioeconomy in the non-centrifugal cane sugar sector: a life cycle assessment

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Abstract

This study aimed to assess the potential environmental benefits of implementing low-cost digesters to valorize agro-industrial waste in the non-centrifugal cane sugar (NCS) sector. Two scenarios were considered: i) the current scenario in which organic waste and wastewater were burned outdoor and discharged into a water body, respectively; ii) the anaerobic digestion (AD) scenario, in which low-cost biodigesters were used for organic waste and wastewater treatment on-site. Results showed that low-cost digesters were a sustainable alternative to mitigate environmental impacts, especially those associated with water source pollution. Indeed, in the AD scenario, the environmental impact categories of Freshwater Eutrophication and Marine Eutrophication showed a decrease of 87.6% and 99.4%, respectively, compared to the current scenario. Thus, by treating organic waste and wastewater on-site while producing bioproducts (*i.e.* biofuel and biofertilizer), low-cost digesters could contribute to boosting the circular bioeconomy in the NCS production sector.

Keywords

Anaerobic digestion; Biogas; Life cycle assessment; Sustainability; Sugarcane waste

1. Introduction

The promotion of affordable, clean, and sustainable modern energy is one of the sustainable development goals (SDGs), which have been endorsed by more than 190 countries (United Nations, 2015). On the other hand, agro-industrial activities and their impact on the environment are drastically increasing due to population growth. Thus, there is a need to move towards a more sustainable agriculture and food industry. In this context, reusing agro-industrial waste appears to be a promising strategy to supply modern and renewable energy (De Corato *et al*., 2018). In the case of Colombia, it was observed that agro-industrial biomass represents the main renewable energy source that might provide up to 15-28% of the national energy mix (Gutiérrez *et al*., 2020; Escalante *et al*., 2011). More than 80% of agricultural production (planted in 66% of the national agricultural land area) consists of only 13 crops, including sugarcane that accounts for 49% of the national food production (MADR, 2017).

Among all the sugarcane uses in Colombia, the production of non-centrifugal cane sugar (NCS) stands out, since it represents 48% of the total sugarcane planted area (Asocaña, 2020). Colombia is the second-highest NCS-producer country in the world after India (Rodríguez *et al*., 2018). The weather conditions for NCS production in Colombia are optimal, so it is produced in different regions of the country throughout the whole year. Also, the NCS plays an important role rooted in the culture of Colombian families, since it is an autochthonous product, mainly consumed by the low-income population groups. NCS has been traditionally consumed as a sweetener in most sugarcane growing regions of the world, where it is known by different names, the most common ones being jaggery (South Asia), panela (Latin America), muscovado (Philippines), and kokuto (Japan) (Jaffé, 2015). The production of NCS requires large amounts of fertilizers for sugarcane cultivation, which are typically synthetic fertilizers (López, 2015). Moreover, NCS processing traditionally requires external energy sources such as firewood, which is also used for cooking workers' food in the same factory.

Besides, the NCS production generates organic waste (*i.e.* agricultural crop residues-ACR and sugarcane scum-SCS) and wastewater, which usually are burnt outdoor or discharged into water bodies causing odors, greenhouse gas (GHG) emissions, and, water and soil pollution (Guerrero and Escobar, 2015). If these wastes were properly managed, they could contribute to increasing the sustainability of the process. Recent studies have shown that these wastes can be valorized through anaerobic digestion (AD) (Mendieta *et al.*, 2020a), generating a clean fuel (biogas) and a biofertilizer (digestate) that might contribute to the circular bioeconomy of the NCS sector. In this context, the plastic tubular digester is a suitable technology due to its low-cost and ease of implementation and handling. Moreover, it does not require specialized skills for construction and maintenance.

Despite the technical feasibility and economic benefits of the integration of AD in the NCS sector have been already proven (Mendieta *et al.*, 2020b), the assessment of its environmental benefits is still lacking. The life cycle assessment (LCA) is a systematic tool for identifying, quantifying, and assessing environmental impacts through the whole life cycle of a product, process, or activity (ISO/TC 207/SC 5, 2006a). It includes energy and material uses and releases to the environment from cradle to grave (*e.g*. raw materials extraction, production, use, and final disposal). Several studies that carried out an LCA to evaluate the environmental impacts of agro-industrial waste (*e.g*. from orange juice and olive oil production) management, proved that AD is an environmentally friendly solution for their valorization concerning the conventional strategies (*e.g*. landfilling, disposal to soil) (Batuecas *et al*., 2019; Ortiz *et al*., 2020). In addition, small-scale digesters implemented in rural households and small-scale farms of different Asian, African, and Latin American countries, have been proved to provide several environmental benefits. It was mainly due to the reduction of air emissions generated by the combustion of traditional fuels for cooking (*e.g*. GLP, firewood) and the reduction of synthetic fertilizer use (Vu *et al*., 2015; Lansche and Müller, 2017; Garfí *et al*., 2019; Pérez *et al*., 2014). Nevertheless, to the best of the authors' knowledge, there is no study assessing the potential environmental benefits of implementing low-cost digesters to valorize agro-industrial waste in the NCS sector.

This study aimed to assess, for the first time, the environmental impacts of the implementation of low-cost digesters in a NCS processing unit by using the LCA methodology. Two scenarios were considered: i) the current scenario in which organic waste (*i.e*. agricultural crop residues and sugarcane scum) and wastewater are burned outdoor and discharged into a water body, respectively; ii) the AD scenario, in which low-cost biodigesters are used for organic waste and wastewater treatment on-site promoting the circular bioeconomy by recovering energy and nutrients. Given the lack of literature on LCA applied to NCS production, this research is proposed as a first general approach to quantify the environmental burdens of the process, promoting future efforts in favor of this agro-industry.

2. Materials and Methods

2.1. Case study description

The NCS processing plant considered in this study is located in Colombia (6°29'14.43"N 72°58'20.16"W). It processes around 2,400 tons of sugarcane annually, producing 259 tons of NCS, and generating 72 tons of SCS and 661 tons of ACRs. Fig. 1A shows the flow diagram of NCS production. It consists of two main phases: cultivation and harvesting, and NCS processing. In total 30 hectares are cultivated using chemical fertilizers (N-P-K). Sugarcane is harvested up to twice a month, obtaining sugarcane stalks which are transported by mules or horses to the NCS processing unit. ACRs are generated with a harvesting potential of 50%. However, around 62% of ACRs are burned in the open field, releasing harmful gases into the atmosphere. The remaining amount of the ACRs goes through an agricultural chopper and is then reused as animal feed.

NCS processing consists of the following steps: milling, clarification, evaporation, concentration, and packaging. The process begins with the extraction of sugarcane juice in roller mills, which are manually fed. Subsequently, the juice is transported to the evaporation system (clarification, evaporation, and concentration). In the clarification stage, the increase in juice temperature together with the addition of vegetable flocculating agents allows the removal of impurities from the juice. In the evaporation and concentration stages, the heat supplied is used in the phase-change of the water (from liquid to vapor), and sugar concentration increases (Rodríguez *et al.*, 2018). Because NCS is hygroscopic, it is properly packaged for preservation and marketing. The thermal energy used is produced by a furnace through the combustion of cane bagasse and firewood. Moreover, the following inputs are also required: electricity for the machinery, natural binder, lime, vegetable oil, and packing materials. Around 24% of SCS generated after the clarification is concentrated by evaporation and is then reused as animal feed, while the rest is discharged into a water body. The wastewater generated from the NCS processing (washing of equipment, utensils, and machinery) is also discharged into the water bodies.

Human labor is essential in the NCS production sector. Since the process is carried out 24 hours a day, and at least 6 days a week, workers live on-site. Firewood cookstoves are usually used to cook their food. However, they are responsible for air pollution in confined and unventilated kitchen spaces by realizing harmful emissions (*e.g.* particulate matter, sulfur oxides). Moreover, household wastewater generated from workers' daily activities (*e.g.* bathrooms, kitchen, laundry) is discharged into the environment.

In this study, the integration of AD technology in the NCS processing unit is proposed (Fig. 1B). Particularly, low-cost geomembrane tubular biodigesters have been designed to treat 30% of the collected ACRs and 76% of the SCS produced (Mendieta *et al.*, 2020b). The remaining ACRs, which are not treated with AD technology, are burned in the open field. Additionally, the wastewater generated in the process is reused for the dilution of these substrates. The AD system was designed so that the clean fuel (biogas) produced can completely replace the firewood used to cook workers' food. Moreover, a biofertilizer (digestate) is obtained that would decrease the requirements of synthetic fertilizers (Mendieta *et al*., 2020b). Table 1 shows the main design and operational characteristics of the biodigesters. This design was for the same NCS processing unit of the present study, in which the amounts of waste were counted, and utilizing experimental tests, the potential for biogas production in a low-cost tubular digester configuration was determined.

2.2. Life cycle assessment methodology

The general framework for conducting an LCA is described by the ISO 14040 and 14044 standards (ISO/TC 207/SC 5, 2006a, 2006b). The methodology consists of four phases: i) goal and scope definition, ii) life cycle inventory analysis (iii) life cycle impact assessment, and iv) results interpretation. The following subsections describe the specific content of each phase.

2.2.1. Goal and scope definition

The goal of the LCA was to assess the environmental impacts of the integration of NCS production with AD technology. Two scenarios were considered: i) The current scenario in which organic waste (*i.e.* agricultural crop residues and sugarcane scum) and wastewater are burned outdoor and discharged into a water body, respectively (scenario A); ii) The AD scenario, in which low-cost digesters are used for organic waste and wastewater treatment on-site promoting the circular bioeconomy by recovering energy and nutrients (scenario B).

The functional unit selected for the study was 1 t of NCS since the main function of the system is to produce NCS. The system boundaries of this LCA study are depicted in Fig. 1. They included: synthetic fertilizer production and transport; direct emissions to air and water due to synthetic fertilizer and digestate (biofertilizer) application to soil; air emissions due to ACR burning in the open field; firewood production and transport; air emissions due to firewood and bagasse combustion in the furnace and the cookstove; electricity consumption; production and transport of chemicals (natural binder, lime, vegetable oil); rainwater consumption; emissions to water due to wastewater and SCS discharge; packaging material production; materials for digesters construction and maintenance; and air emissions due to biogas combustion and biogas losses. For the transportation of firewood, chemicals, and other materials to the NCS processing plant, an average distance of 20 km was considered. Allocation according to physical causality was used in this study. Thus, the potential environmental impacts were totally allocated to the final product (NCS), neglecting the by-products (*e.g*. SCS or ACRs reused as animal feed) (ISO/TC 207/SC 5, 2006a, 2006b).

2.2.2. Life cycle inventory analysis

Inventory data for the investigated scenarios are summarized in Table 2. The amount of synthetic fertilizers has been calculated considering the nutrients requirements for sugarcane cultivation per hectare. In the current scenario (scenario A) it was 100 kg of urea, 80 kg of superphosphate, and 80 kg of potassium chloride (de Medeiros Silva *et al*., 2020). In the AD scenario (scenario B), the amount of synthetic fertilizer is lower, since digestate can partially replace it. The amount of synthetic fertilizer replaced by the digestate was determined considering its nutrients composition (Mokomele *et al*., 2019; Mendieta *et al*., 2020b).

Data regarding electricity, chemicals, firewood (for the furnace), water consumption, as well as packaging materials needed for the production of NCS, were collected on-site and provided by the producer. The electricity consumption for the agricultural chopper was estimated considering the equipment specifications. In the AD scenario (scenario B), this energy requirement increased because the digesters feedstock (ACRs) require a particle size reduction pretreatment, which can be performed by the same equipment. This electricity consumption was calculated based on Mendieta *et al*. (2020b). The consumption of firewood and biogas in the cookstoves was estimated according to Ramírez and Taborda (2014) and Mendieta *et al*. (2020b). A detailed engineering design of the low-cost geomembrane tubular biodigesters was carried out in order to estimate the type and amount of materials needed (Mendieta *et al*., 2020b). The lifespan of construction materials was chosen according to manufacturers' specifications (*i.e*. 5, 15, and 20 years for PVC pipes and fittings, geomembrane, and masonry, respectively). The construction and dismantling of infrastructures and equipment at the NCS production facility were not considered. Indeed, due to their long lifespan, their potential environmental impacts can be neglected.

Direct air emissions from synthetic fertilizer and digestate application on agricultural land were taken from the literature (Caldeira-Pires *et al*., 2018). Emission rates for estimating nitrate leaching and phosphorus runoff from synthetic fertilizer and digestate application in the field were taken from Renouf *et al*. (2010). Direct air emissions from ACRs open burning and the combustion in the furnace were estimated based on previous studies (Pereira *et al*., 2015; Sfez *et al*., 2017). Direct water emissions from the juice pre-cleaning stage and the residual SCS discharge were taken from García *et al*. (2007).

Wastewater characteristics were estimated according to the literature (Yang *et al*., 2021). Direct indoor emissions from the combustion of firewood (scenario A) and biogas (scenario B) in cookstoves were estimated considering the emissions rates reported by Sfez *et al*., (2017). Fugitive CH_4 emissions from leaks were considered as low as 5% of biogas production since the low-cost digesters were supposed to be well-maintained (Bruun *et al*., 2014; Garfí et al., 2019). Background data (*i.e*., data of construction materials and fertilizer production and transportation) were obtained from the *Ecoinvent 3* database (Moreno-Ruiz *et al*., 2014; Weidema *et al*., 2013).

2.2.3. Life cycle impact assessment

Potential environmental impacts were calculated using the software SimaPro 8 (Pre-sustainability, 2020) and the ReCipe midpoint method (hierarchist approach) (Goedkoop *et al*., 2009). This analytical tool is in accordance with ISO 14040 standards. The characterization phase was performed considering the following impact categories: Climate Change, Ozone Depletion, Terrestrial Acidification, Freshwater Eutrophication, Marine

Eutrophication, Photochemical Oxidant Formation, Particulate Matter Formation, Metal Depletion, and Fossil Depletion. Normalization was carried out to compare all the environmental impacts at the same scale. This provides information on the relative significance of the indicator results, allowing a fair comparison among the impacts estimated for each scenario (ISO/TC 207/SC 5, 2006a). In this study, the European normalization factors (Europe ReCiPe H) were used (Goedkoop *et al.*, 2009).

2.3. Sensitivity analysis

A sensitivity analysis was carried out to evaluate the influence that the distance (20 km) assumed for firewood transportation had on the environmental impacts of the two scenarios considered. In particular, the distance was increased to 50 and 80 km, and the results were recalculated while keeping the other parameters constant (Clavreul *et al.*, 2012). The sensitivity index was calculated (SI, Eq. 1) according to Hamby (1994):

$$SI = (D_{\mathrm{final}} - D_{\mathrm{default}}) / D_{\mathrm{default}} \qquad (1)$$

where, D represents the output value of each environmental indicator (*e.g.* Climate change, Terrestrial acidification), when the input value of the transport distance increases to 50 and 80 km ("final" subscript), and when it corresponds to the base scenario (20 km) ("default" subscript).

3. Results

3.1. Life cycle impact assessment

The potential environmental impacts associated with each scenario are shown in Fig. 2 and Table 3. Comparing the two scenarios, a similar environmental performance can be observed, except in two impact categories: Freshwater Eutrophication and Marine Eutrophication. In the other impact categories (Climate change, Ozone depletion, Terrestrial acidification, Photochemical oxidant formation, Particulate matter formation, Metal depletion, and Fossil depletion), the environmental impact showed a decrease of up to 5% in the AD scenario (scenario B) compared to the current scenario (scenario A). It was because the implementation of the low-cost biodigesters reduced the indoor air emissions due to the use of firewood in the cookstove and the consumption of synthetic fertilizers. The small reduction of the environmental impacts in these categories is mainly due to the fact that the largest contribution to the overall impact is caused by the cultivation and NCS processing steps, which are almost the same in both scenarios. In particular, the largest contribution to Climate change, Ozone depletion, Terrestrial acidification, Metal depletion was attributed to sugarcane cultivation and harvesting, being up to 52.5%, 65.5%, 73.9 %, and 82.6% of the overall impact with similar values in both scenarios, respectively. This was due to the production, transportation, and use of synthetic fertilizers for sugarcane cultivation. Similarly, previous studies showed that more than half of the impact on Climate Change was due to processes located outside the small-scale farms, where synthetic fertilizer is produced (Sfez *et al*., 2017). For the same impact categories, the second-largest contribution was associated with NCS processing (*i.e.* up to 42.8%, 34.9%, 22.1%, and 17.8% of the overall impact in both scenarios, respectively). Moreover, the NCS processing contributed the most in the impact categories of Photochemical oxidant formation and Particulate matter formation; for scenario A it was 54.9% and 71.1%, respectively, while for scenario B it was 56.9% and 74.9%, respectively. It was mainly attributed to air emissions generated by the furnace. Similarly, the contribution to the overall impact in the Fossil depletion impact category was equally attributed to both NCS processing (around 52.8% in both scenarios) and sugarcane cultivation (up to 47.2% in both scenarios). It was due to the consumption of synthetic fertilizer, chemicals, and plastic materials for packaging and digester implementation.

In both scenarios, the environmental impact caused by the use of cookstove is less than 3% in all the impact categories. Similarly, the construction of the low-cost biodigesters had a negligible impact (<3% of the overall impact) in all impact categories, which was in accordance with previous studies (Garfí *et al.*, 2019).

As mentioned above, the main effect achieved with the integration of low-cost digesters in the NCS production sector was the reduction of the environmental impacts, especially those associated with water bodies pollution. In the AD scenario (scenario B) the environmental impact categories of Freshwater Eutrophication and Marine Eutrophication showed a decrease of 87.6% and 99.4%, respectively, compared to the current scenario (scenario A). This means that the implementation of the low-cost biodigesters can almost eliminate the environmental impacts associated with the discharge of industrial and domestic wastewater generated by NCS processing (*i.e.* washing) and household activities (*e.g.* toilet flushing). Likewise, Ortiz *et al.* (2020) reported a 160% decrease for the Freshwater eutrophication impact category for the treatment of orange peel waste through AD, compared to the baseline scenario in which waste is landfilled.

The results of this study showed that low-cost digesters are responsible for other environmental benefits as well when implemented in small-scale agro-industries. Indeed, low-cost digesters are environmentally friendly technology that, not only produce clean fuel and a biofertilizer but also can treat waste and wastewater on-site and in a sustainable way avoiding their uncontrolled disposal or discharge into the environment (Lansing *et al.*, 2017). By treating organic waste and wastewater on-site while producing bioproducts, low-cost digesters contribute to boosting the circular bioeconomy in the NCS production sector.

To sum up, the production of biogas for cooking and biofertilizer for the cultivation of sugarcane, through AD technology, helps to reduce environmental impacts in the NCS sector. Although the use of digestate as a biofertilizer contributes to partially reducing environmental impacts, the production, transportation, and application of synthetic fertilizers still have a large contribution to the overall impacts (from 14.8 to 98.8% depending on the impact categories). Due to the high dilution of the substrates (ACR+SCS) with the wastewater, the digestate was only able to provide 3% of the fertilizer needs for sugarcane cultivation. In this sense, to improve the environmental performance of the low-cost biodigesters, it must be designed and operated to produce a better quality digestate (higher nutrient content).

3.2. Normalization

The normalized results showed that Freshwater Eutrophication and Marine Eutrophication are the most significant impact categories for both scenarios (Fig. 3). In these impact categories, the AD scenario (scenario B) is more environmentally friendly than the current scenario (Scenario A). As mentioned above, low-cost digesters are appropriate technologies that can treat waste and wastewater on-site and in a sustainable way avoiding their uncontrolled disposal or discharge into the environment. By treating organic waste and wastewater on-site while producing bioproducts, low-cost digesters contribute to boosting the circular bioeconomy in the NCS production sector.

3.3. Sensitivity analysis

The results of the sensitivity analysis (Table 4) showed that the Ozone depletion impact category was the most affected by the firewood transportation distance (sensitivity index up to 7.30% for both scenarios). Furthermore, the other environmental categories presented a variability of less than 5% concerning the baseline scenario in which a typical distance of 20 km was considered.

On the whole, the results obtained in this study showed to be robust since they were not significantly influenced by the firewood transportation distance.

4. Conclusions

The implementation of the low-cost biodigesters contributed to reducing the environmental impacts associated with the production of organic waste and wastewater generated from the NCS agro-industry. It can almost eliminate the environmental impacts associated with the discharge of wastewater generated by NCS processing (*i.e.* washing) and household activities (*e.g.* toilet flushing). Indeed, the impact categories of Freshwater Eutrophication and Marine Eutrophication showed a decrease of up to 99%, compared to the current scenario. Closing the loop by valorizing the organic residues on-site and recovering energy from biogas and nutrients from digestate contributes to boosting the circular bioeconomy in the NCS sector.

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Table 1. Characteristics of the low-cost tubular geomembrane biodigesters for the treatment of waste generated in a NCS processing unit (Mendieta *et al*., 2020b).

Parameter	**Value**	**Unit**
Digesters quantity	3	-
Volume for each digester	106.0	m^3
Liquid fraction in the digester	75	%
Feeding flow	2.29	$m^3\ d^{-1}$
Temperature	23	°C
Hydraulic retention time	33	days
Organic loading rate	0.55	$kg\ VS\ m^{-3}\ d^{-1}$
Methane content in biogas	50.4	%
Specific biogas production	0.132	$m^3\ kg^{-1}VS$
Biogas production rate	0.065	$m^3\ m^{-3}_{digester}\ d^{-1}$
Volatile solids removal	72.1	%

Table 2. Summary of the inventory (inputs and outputs) for the two scenarios considered: NCS production with current waste and wastewater management solutions (scenario A); NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B). Values are referred to the functional unit (1 t of NCS).

	Scenario A	**Scenario B**	**Unit**
Inputs			
Synthetic fertilizer production and transport			
N (as urea)	1.16E-02	1.13E-02	t
P (as P_2O_5)	1.64E-02	1.58E-02	t
K (as K_2O)	9.26E-03	9.06E-03	t
Transport (N-P-K)	7.45E-01	7.23E-01	t km
NCS processing			
Electricity (for cane milling)	6.95E+01	6.95E+01	kWh
Firewood (for the furnace)	2.16E-01	2.16E-01	t
Natural binder	1.10E-02	1.10E-02	t
Lime	9.26E-04	9.26E-04	t
Vegetable oil	1.85E-04	1.85E-04	t
Heat-shrinkable polyolefin	1.50E-03	1.50E-03	t
Corrugated cardboard box	1.78E-02	1.78E-02	t
Electricity (for packaging machinery)	6.18E+00	6.18E+00	kWh
Water (washing)	1.54E+00	1.54E+00	m^3
Transport (firewood, chemicals, and other materials)	4.95E+00	4.95E+00	t km
Agricultural chopper			
Electricity	3.63E-01	4.76E-01	kWh
Cooking food for workers			
Firewood (for the cook stove)	2.05E-02	-	t
Transport (firewood)	4.11E-01	-	t km
Household activities			

Rainwater	1.03E+00	1.03E+00	m^3
Construction materials for the AD system			
Geomembrane (Polyethylene)	-	1.49E-04	t
Plastic pipes and fittings	-	5.84E-05	t
Bricks	-	1.38E-03	t
Cement	-	5.72E-05	t
Sand	-	3.41E-04	t
Transport (materials)	-	2.59E-03	t km
Outputs			
Direct air emissions from synthetic fertilizer and digestate application in the field			
NH_3	1.39E-03	1.39E-03	t
NO_X	3.47E-04	3.47E-04	t
NO_3	2.43E-03	2.43E-03	t
N_2O	2.32E-04	2.32E-04	t
Direct water emissions from synthetic fertilizer application in the field			
Nitrate via leaching	7.53E-04	7.53E-04	t
Phosphorous via runoff	2.10E-03	2.10E-03	t
Direct air emissions from ACR open burning			
CO_2 (biogenic)	9.25E-01	7.48E-01	t
CO (biogenic)	6.12E-04	4.95E-04	t
NO_X	6.09E-04	4.93E-04	t
N_2O	3.36E-05	2.72E-05	t
SO_X	3.27E-05	2.64E-05	t
CH_4 (biogenic)	2.52E-04	2.04E-04	t
NMVOC	4.26E-05	3.44E-05	t
PM_{10}	6.90E-04	5.58E-04	t
$PM_{2.5}$	3.45E-04	2.79E-04	t
Direct air emissions from firewood combustion in the furnace			

CO_2 (biogenic)	3.33E+00	3.33E+00	t
CO (biogenic)	1.12E-02	1.12E-02	t
NO_X	2.02E-03	2.02E-03	t
N_2O	1.31E-04	1.31E-04	t
SO_X	2.90E-04	2.90E-04	t
CH_4 (biogenic)	3.24E-03	3.24E-03	t
NMVOC	2.19E-03	2.19E-03	t
PM_{10}	4.53E-03	4.53E-03	t
$PM_{2.5}$	1.81E-03	1.81E-03	t
Direct water emissions from juice pre-cleaning stage	6.55E+00	6.55E+00	MWh
Total nitrogen	2.05E-04	2.05E-04	t
Direct water emissions from residual SCS discharge			
Total nitrogen	1.14E-03	-	t
Total phosphorous	2.11E-04	-	t
Direct water emissions from wastewater (NCS processing)			
Total nitrogen	7.49E-02	-	t
Total phosphorous	9.13E-03	-	t
Direct air emissions from biogas losses			
CH_4 (biogenic)	-	6.97E-04	t
Direct air emissions from cookstove using firewood (scenario A) or biogas (scenario B)			
CO_2 (biogenic)	3.19E-02	3.99E-02	t
CO (biogenic)	8.79E-04	5.25E-05	t
CH_4 (biogenic)	2.30E-04	2.77E-05	t
NMVOC	1.95E-04	1.66E-05	t
NO_X	4.11E-06	2.49E-05	t
N_2O	2.05E-06	2.49E-06	t
$PM_{2.5}$	6.57E-05	0.00E+00	t
PM_{10}	2.18E-04	1.38E-05	t
SO_2	1.75E-05	1.38E-06	t

Direct water emissions from wastewater (household activities)			
Total nitrogen	4.98E-02	-	t
Total phosphorous	6.07E-03	-	t

(ACR: agricultural crop residues; SCS: sugarcane scum; NCS: non-centrifugal cane sugar)

Table 3. Total potential environmental impacts for the two scenarios considered: NCS production with current waste and wastewater management solutions (scenario A); NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B).

Environmental impact category	**Unit**	**Scenario A**	**Scenario B**	**Decrease in environmental impact (%)**
Climate change	kg CO_2 eq	4.38E+02	4.35E+02	0.54
Ozone depletion	kg CFC-11 eq	1.75E-05	1.72E-05	1.87
Terrestrial acidification	kg SO_2 eq	8.04E+00	7.94E+00	1.26
Freshwater eutrophication	kg P eq	1.76E+01	2.18E+00	87.61
Marine eutrophication	kg N eq	1.27E+02	8.14E-01	99.36
Photochemical oxidant formation	kg NMVOC	9.17E+00	8.83E+00	3.66
Particulate matter formation	kg PM_{10} eq	9.90E+00	9.40E+00	5.08
Metal depletion	kg Fe eq	1.56E+01	1.52E+01	2.43
Fossil depletion	kg oil eq	6.00E+01	5.95E+01	0.91

Table 4. Results of the sensitivity analysis on the potential environmental impacts for the two scenarios considered: NCS production with current waste and wastewater management solutions (scenario A); NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B).

	Sensitivity index (%)			
Environmental impact category	**Scenario A**		**Scenario B**	
	50 km	**80 km**	**50 km**	**80 km**
Climate change	0.83	1.66	0.76	1.53
Ozone depletion	3.66	7.31	3.40	6.80
Terrestrial acidification	0.17	0.34	0.16	0.32
Freshwater eutrophication	0.00	0.00	0.02	0.03
Marine eutrophication	0.00	0.00	0.07	0.15
Photochemical oxidant formation	0.19	0.38	0.18	0.36
Particulate matter formation	0.07	0.14	0.07	0.13
Metal depletion	1.24	2.48	1.16	2.32
Fossil depletion	2.13	4.25	1.96	3.92

Fig. 1. Flow diagrams and system boundaries of the alternatives: i) NCS production with current waste and wastewater management solutions (scenario A), ii) NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B). (ACR: agricultural crop residues; SCS: sugarcane scum; NCS: non-centrifugal cane sugar).

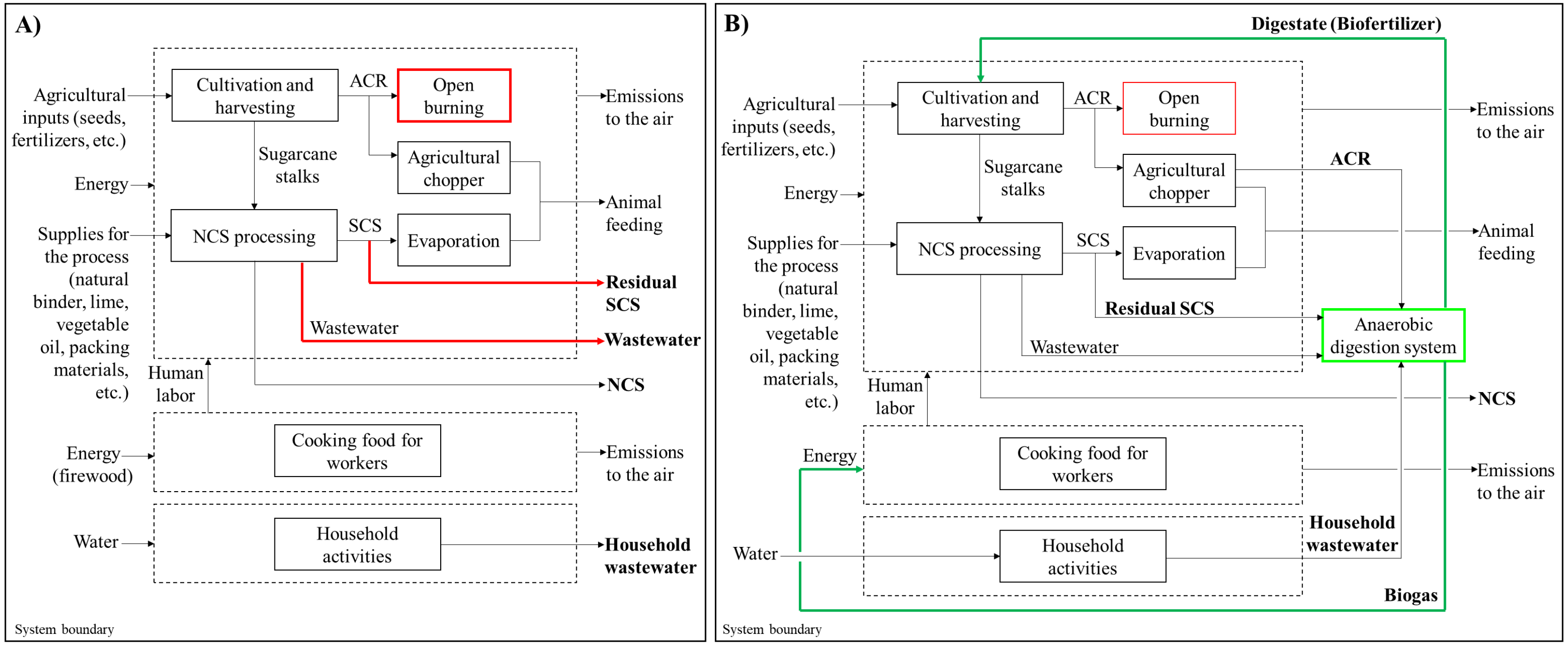

Fig. 2. Potential environmental impacts for the two scenarios considered: non-centrifugal cane sugar (NCS) production with current waste and wastewater management solutions (scenario A); NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B). Values are referred to the functional unit (1 t of NCS).

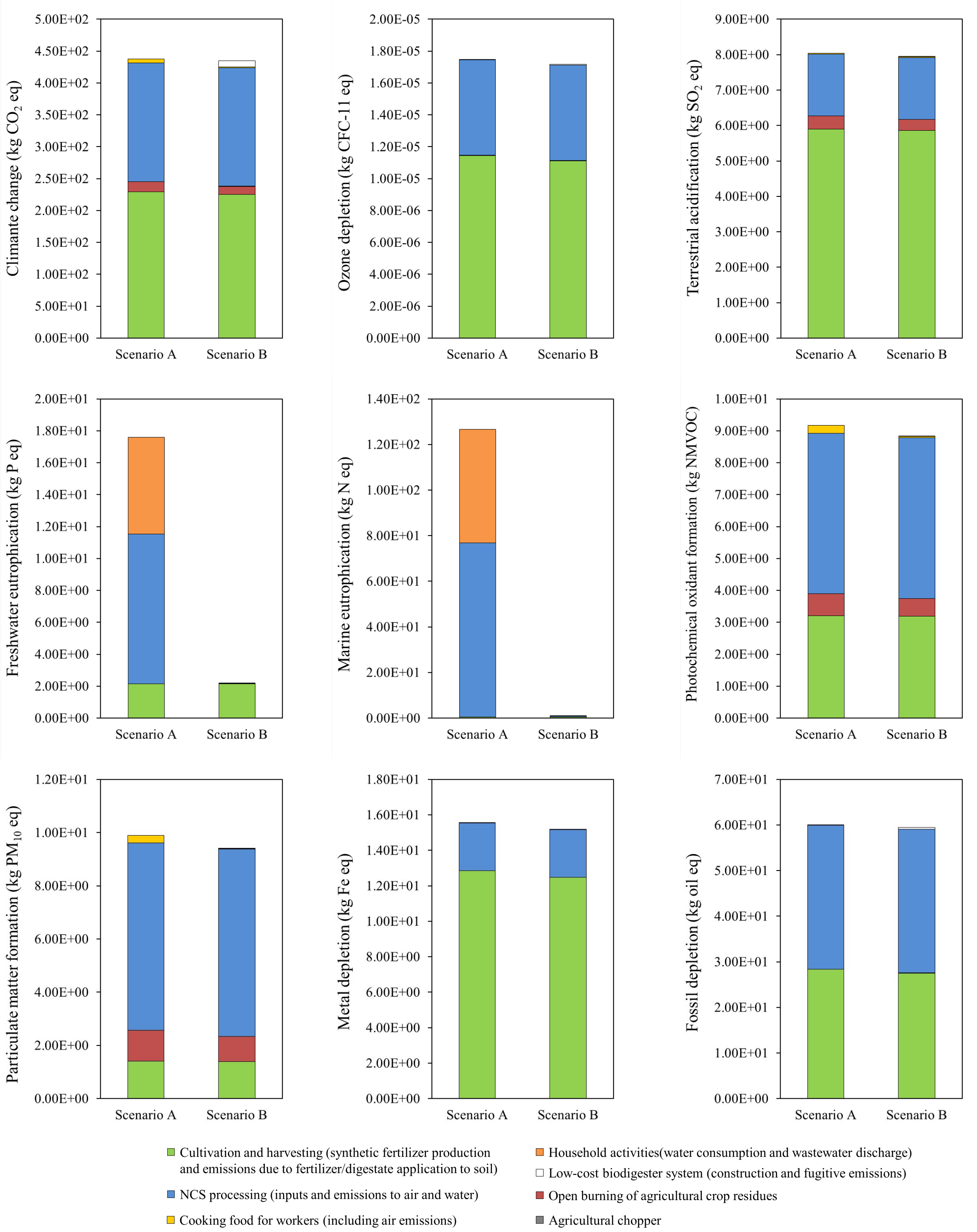

Fig. 3. Normalized potential environmental impacts for the two scenarios considered: NCS production with current waste and wastewater management solutions (scenario A); NCS production with the integration of anaerobic digestion for waste and wastewater treatment (scenario B).