Techno-Economic and Environmental Assessment of Biogas Production from Banana Peel (*Musa paradisiaca*) in a Biorefinery Concept

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Abstract

Two scenarios for the biogas production using Banana Peel as raw material were evaluated. The first scenario involves the stand-alone production of biogas and the second scenario includes the biogas production together with other products under biorefinery concept. In both scenarios, the influence of the production scale on the process economy was assessed and the feasibility limits were defined. For this purpose, the mass and energy balances were established using the software Aspen Plus v8.2 along with kinetic models reported in the literature. The technical and economic analysis of the process was performed considering Colombian economic conditions. As a result, it was found that different process scales showed great potential to biogas conversion. Thus, plants with greater capacity have a greater economic benefit than those with lower capacity. However, this benefit leads to high energy consumption and greater environmental impact.

Keywords: biogas, biorefinery, economic assessment.

1. Introduction

The search for renewable energy as biofuels is an alternative to replace dependence on fossil fuels. Different technologies, raw materials and value-added products are studied in the conversion to biofuels. However, lignocellulosic materials are the most important resources to convert in different products [1]. The high generation of lignocellulosic biomass is interesting for conversion to products such as biogas, ethanol, butanol, among others [2]. Banana (*Musa paradisiaca*) is one of the raw materials that generates high amount of wastes due to high worldwide consumption [3]. Approximately, 780 million pounds of banana peel are wasted annually in the USA [3]. Additionally, banana peels can be used to obtain products such as biogas, ethanol, extractives, butanol, lactic acid, xylitol, among others due to its chemical composition [4]. Therefore, its valorization is a subject of research [5], [6].

On the other hand, the environmental friendly characteristics and the use of industrial wastes to produce biogas as a potential energy carrier to meet current energy deficiencies. This is a product of great interest and it is considered as a clean and renewable energy. It is produced from natural organic sources such as crop residues, animal manure and industrial wastes [7].Thus, it can mitigate the waste generation by obtaining a added-value product useful to society [7], [8].

The high generation of banana peel waste and its application to produce biogas, it is an attractive combination to solve environmental and energy problems of a society. However, the raw material availability and the process scale are key variables to start up a production plant. Additionally, the search for the valorization of this resource becomes more important in terms of the integration of other added-value products to biogas facilities. A modern route to solve this problem is the multiproduct processing through the biorefinery concept. The purpose of the biorefinery is to improve the use of the waste from this agricultural crop [9], [10], [11], [12]. Similar to a conventional process, each biorefinery can have different plant capacities depending on the availability of raw material. It is possible that a small-scale biorefinery can be social and/or environmental beneficial [13], but when the biorefinery scale is very low, the benefits seems to change. In this sense, it is necessary to identify the suitable biorefinery scale considering its sustainability. If the biorefinery scale is very large, it is possible that problems with biomass availability and transport increase [14].

Due to the previously mentioned and despite the large number of developed studies around the biogas production, these researches are emphasized in a particular condition, experimental procedures, theoretical analysis and simulations, as it is found in the literature. However, information regarding the joint analysis of production costs, process scale, new forms of valuation and environmental impact using simulation tools is limited in the literature. Consequently, the aim of this study is to perform the techno-economic analysis of biogas generation from *M. paradisiaca* considering the production costs, process scale and the by-products valorization with emphasis on the biorefinery concept.

2. Methodology

The methodology developed in this work consists of two parts. First, the production of biogas from waste banana peel *(M. paradisiaca)* in stand-alone pathway was analyzed and then, the integrated production of biogas using the same raw material under the biorefinery concept. These scenarios were analyzed taking into account the process simulation and the effect of the hierarchy of products coupled to biogas production based on global economic performance at different scales. At the same time, the environmental impact of each scenario was evaluated with respect to scale. The main objective was to establish economic and environmental sustainability, so that the biogas production is more profitable, considering the scale and the comparison of two scenarios.

Consequently, it is necessary to have the mass and energy balances from which the requirements of raw material and utilities are obtained. Initially, the raw material characterization was used as starting point of the simulation using data reported in the literature [15], [16]. The simulation tool used for this purpose was Aspen plus v8.2 (Aspen Technology, Inc, USA). The non-random two-liquid (NRTL) thermodynamic model was applied to calculate the activity coefficients of the liquid phase and the Hayden-O’Conell equation of state was used to describe the vapor phase. These models have been shown to allow the successful calculation of equilibrium in mixtures containing unconventional compounds [17].

The capital and operating costs were calculated using the software Aspen Economic Analyzer (AspenTech: Cambridge, MA, USA), using the mass and energy balances calculated from the simulation procedure. The techno-economic analysis was evaluated in terms of the net present value (NPV), which allows to analyze the feasibility of a project taking into account the benefit of the project, the investment payment and the normal interest on the investment [18]. In addition, an environmental analysis of the process schemes was performed using the waste reduction algorithm (WAR) algorithm developed by the United States Environmental protection agency.

2.1.Simulation process

In the simulation, two scenarios were evaluated: stand-alone biogas production and the production under the conceptual design of a biorefinery (hierarchy, sequencing and integration) [11]. These scenarios were evaluated at different raw materials flowrates (e.g. 10, 100 and 1000 ton/h). Thus, they are two base scenarios and three sub scenarios for each. These scenarios are presented in Table 1.

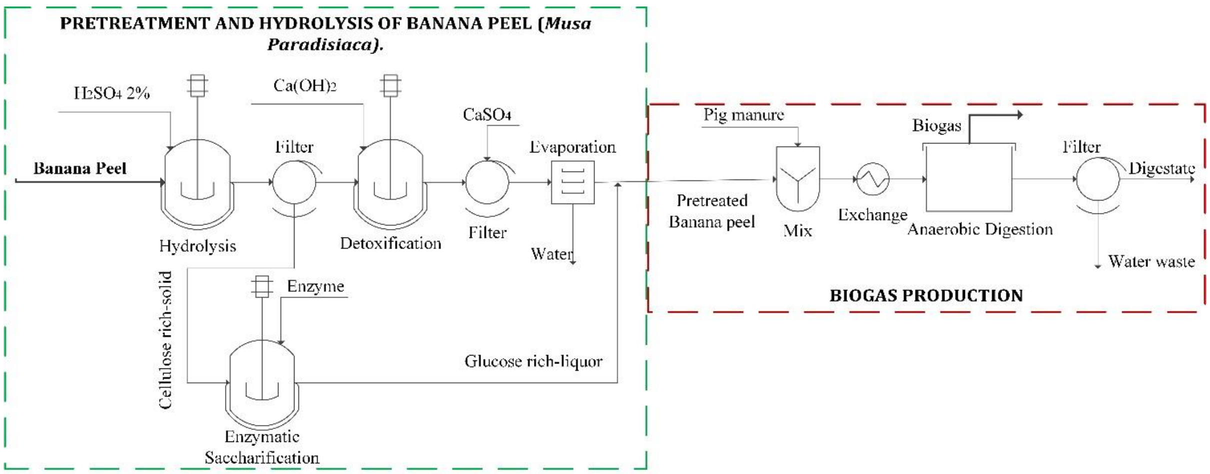
Table 1. Stand-alone and biorefinery scenarios for the biogas production.

Scenario	Sub-scenario	Products	Description
Stand-alone	A (10^1 ton/h)	Biogas	100% Raw material for biogas production.
	B (10^2 ton/h)	Biogas	100% Raw material for biogas production.
	C (10^3 ton/h)	Biogas	100% Raw material for biogas production.
Biorefinery concept	D (10^1 ton/h)	Biogas + Ethanol + Xylitol + Cogeneration	50% hydrolysate for biogas production Remaining hydrolysate for ethanol production (glucose), xylitol (xylose), synthesis gas and electricity (lignin).
	E (10^2 ton/h)	Biogas + Ethanol + Xylitol + Cogeneration	50% hydrolysate for biogas production Remaining hydrolysate for ethanol production (glucose), xylitol (xylose), synthesis gas and electricity (lignin).
	F (10^3 ton/h)	Biogas + Ethanol + Xylitol + Cogeneration	50% hydrolysate for biogas production Remaining hydrolysate for ethanol production (glucose), xylitol (xylose), synthesis gas and electricity (lignin).

In the first three scenarios, the stand-alone production of biogas at different raw material processing-scales was analyzed (**Figure 1**). On the other hand, biogas yield under a biorefinery scheme (**Figure 2**) were analyzed, considering the production of biogas, xylitol, ethanol, synthesis gas and electricity is considered. Similarly, three processing scales are considered. The values of the processing scales are the same as those analyzed in the stand-alone process.

2.1.1. Biogas Production

Figure 1 presents the scheme of biogas production from banana peels through anaerobic digestion technology. In order to achieve a greater accessibility of the microorganisms towards the substrate, a pretreatment of the material consisting of two stages of hydrolysis is carried out. In the first step, the hemicellulose fraction is hydrolyzed with sulfuric acid (2.0% by weight) at a temperature of 100 °C. From the diluted hydrolysis, a solid unconverted fraction and the pentose rich liquor are obtained. The liquid fraction is removed by filtration. The solid fraction, rich in cellulose and lignin, was subjected to an



enzymatic saccharification process at 50 °C using cellulases that are capable to convert the cellulose to glucose. As a result of the sugar decomposition reactions in the dilute acid hydrolysis steps, furfural and hydroxymethyl furfural (HMF) were also obtained. These toxic compounds must be removed from the hydrolyzate to avoid inhibition in other digestion processes by microorganisms. Overliming with lime is one of the most common methods to remove these compounds from hydrolyzates [19].

Figure 1. Flowsheet for biogas production.

On the other hand, to contribute to the decomposition of the organic matter by anaerobic digestion, a microbial source is necessary. In this case, pig manure is used as inoculum. Then, the inoculum and the banana peels were mixed in a ratio of 2:1 (ml inoculum/ml substrate) and maintained at 35 °C and pH between 5 and 7. Finally, the biogas was extracted and the remaining solid fraction was used to obtain the digestate (semi-liquid solid fraction).

2.1.2. Production of ethanol

The production of ethanol using glucose as raw material was carried out through fermentation with *Saccharomyces cerevisiae* as microorganism [20]. The temperature of the process was 35°C. At the end of fermentation, the obtained liquor is submitted to a downstream process where the azeotropic composition is reached. Subsequently, it is sent to molecular sieves reaching the ethanol fuel composition [21].

2.1.3. Production of xylitol

For the production of xylitol, xylose obtained previously in the acid hydrolysis was used. The production of xylitol is carried out in a fermentation process at a temperature of 30°C and using *Candida parapsilosis* as microorganism. The employed kinetics is reported by Aranda-Barradas, J. S., et al (2000) [22]. The solid fraction was separated by centrifugation. The obtained liquid fraction was mixed with ethanol in a 1:1 ratio in order to precipitate the produced xylitol [23]. The precipitated xylitol was separated by filtration.

2.1.4. Cogeneration

The lignin obtained from the solid fraction of the enzymatic hydrolysis was subjected to a gasification process. In this process, a synthesis gas stream was obtained with a high calorific value that was used in the electricity generation [24].

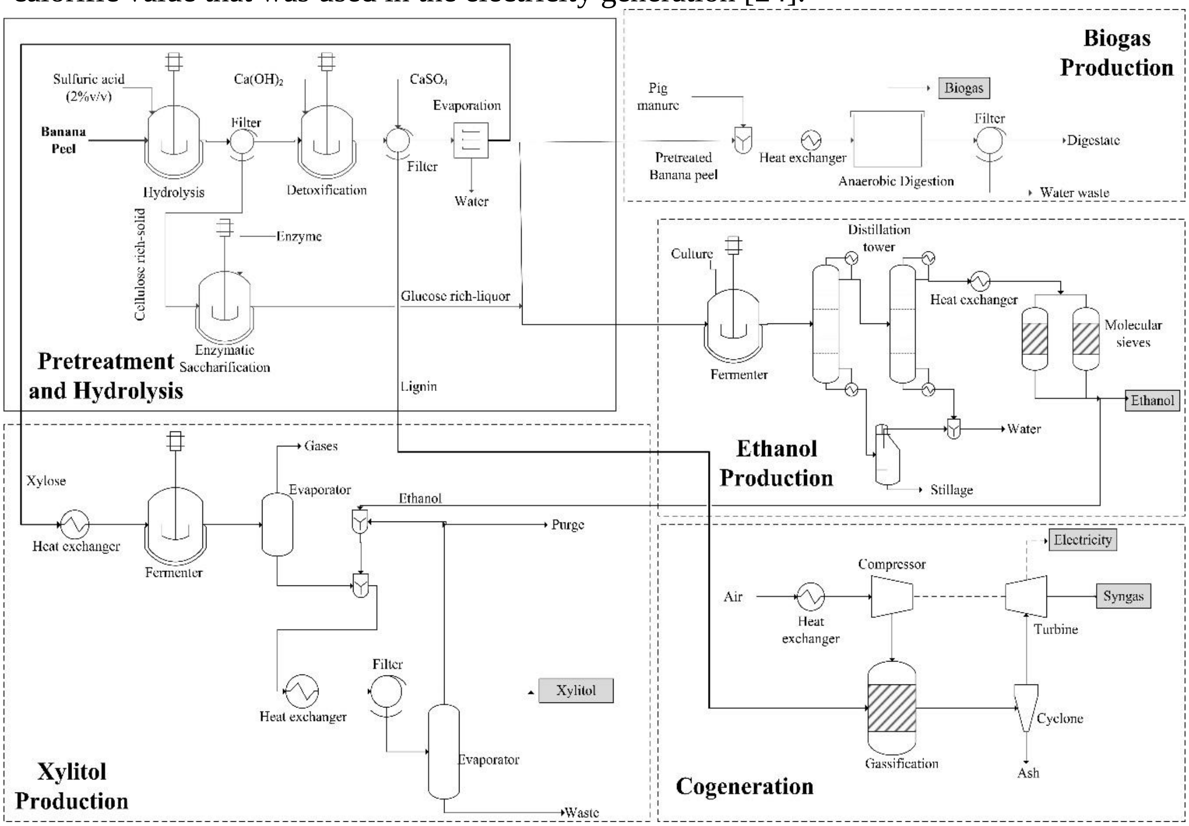


Figure 2. Flowsheet for a biorefinery based on banana peel.

2.2. Economic analysis

The economic was performed taking into account the total production costs influenced by the raw material, inputs (reagents, solvents, etc.), utilities, labor, general plant maintenance and administrative costs. These parameters were determined based on Colombian regulations (tax rate, return interest, operators and supervisors wages, among others). Additionally, the depreciation of the equipment was determined for a 10-year project life. The software used for the analysis was the Aspen Process Economic Analyzer v8.2 (Aspen Technology, Inc, USA) where the mass and energy balances of the simulation process, raw material costs and utilities were used as starting point. As a result, the economic profitability of the proposed scenarios was evaluated considering the production cost of the products (biogas, ethanol, xylitol and electricity) and the Net Present Value (NPV). This parameter indicates the potential benefits over the life of the project (10 years). In addition, the influence of plant capacity on the overall costs of the process was evaluated. The data used in the economic evaluation of scenarios are presented in **Table 2**.

Table 3. Parameters used in the economic analysis.

Item	Unit	Value	Reference
Investment Parameters			
Tax rate	%	25	[25]
Interest rate	%	17	
Raw materials			
Banana peel	USD/kg	0.01	
Sulfuric acid	USD/kg	0.1	[25]
Calcium hydroxide	USD/kg	0.05	
Products			
Ethanol	USD/kg	1.24	[26]
Xylitol	USD/kg	164	[27]
Biogas	USD/L	22.4	
Syngas	USD/ton	37.27	[28]
Electricity	USD/kWh	0.10	[25]
Utilities			
LP steam	USD/ton	1.57	[26]
MP steam	USD/ton	8.18	
HP steam	USD/ton	9.86	
Potable water	USD/m^3	1.25	[25]
Fuel	USD/MMBTU	7.21	
Electricity	USD/kWh	0.10	
Operation			
Operator	USD/h	2.14	[25]
Supervisor	USD/h	4.29	

2.3. Environmental analysis

For the environmental analysis, the Waste Reduction Algorithm (WAR) developed by United States Environmental Protection Agency was used. This tool considers the impact by mass effluents and the impact by energy requirements of a chemical or biochemical process, based on the mass and energy balances [29]. Then the weighted sum of all impacts ends in the final impact per hour, giving the total (PEI). The weights used for each category are equal to 1, indicating that each category has the same influence on the final score. The evaluated categories to determine this impact were: Human Intake Toxicity Potential (HTPI), Human Toxicity Potential by Dermal Exposure and Inhalation (HTPE), Terrestrial Toxicity Potential (TTP), Global Warming Potential (PWG), Potential Ozone Of depletion (ODP), photochemical oxidation potential (PCOP) and acidification potential (AP).

3. Results

In the production of biogas under the stand-alone concept, it is possible to obtain a yield of 0.33 grams of biogas per gram of raw material, whereas a yield of 0.22 grams per gram of raw material under the biorefinery concept is obtained. However, only half of the hydrolyzates were used for biogas production. Thus, in the biorefinery, other value-added products such as ethanol, xylitol and syngas were generated. Based on this statement, yields of 0.04, 0.08 and 1.08 grams per gram of raw material can be obtained for ethanol, xylitol and syngas.

3.1 Economic analysis

Table 3 summarizes the results of the production costs of each of the scenarios. It is noteworthy that the utilities costs are higher due to the high steam requirements in the process. On the other hand, the revenues from products sales are higher when the biorefinery is proposed with a scale of 100 tonne/h of banana peel. In addition, when the sole purpose of the process is to obtain biogas (scenario A, B and C), the production costs are higher due to the low production performance of the process.

Table 3. Economic analysis of the production of ethanol, xylitol, biogas and energy cogeneration from banana peel.

Item	Biorefinery		
	Scenario D (USD/kg)	Scenario E (USD/kg)	Scenario F (USD/kg)
Raw materials	0.742	0.653	0.342
Utilities	0.794	0.673	0.350
Operating labor	0.031	0.003	0.001
Plant overhead	0.061	0.008	0.002
Operating charges	0.008	0.001	0.001
Maintenance	0.091	0.013	0.003
General and administrative cost	0.138	0.108	0.0056
Capital depreciation	0.320	0.053	0.019
Production cost (Total)	**2.186**	**1.512**	**0.774**

During the analysis of the Net Present Value (NPV), it was found that biorefineries only require two years to recover the investment, as can be observed in Figure 3.

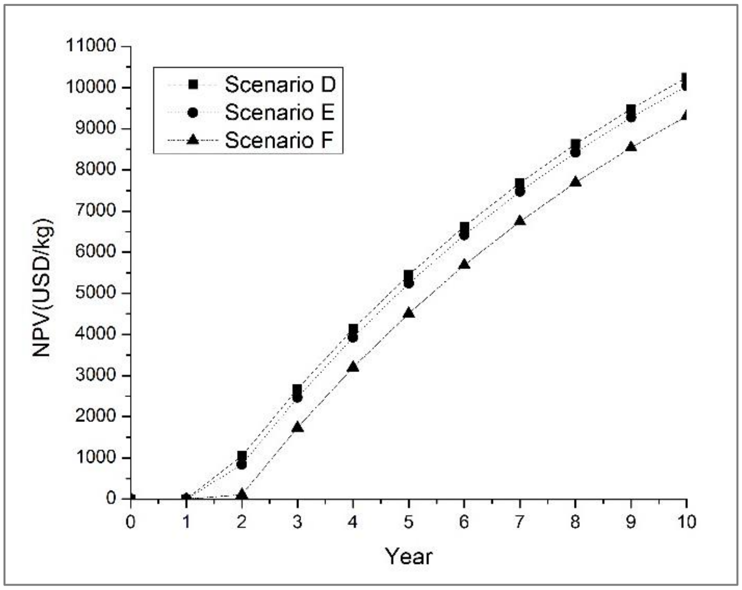


Figure 3. VPN of biorefinery from banana peel.

3.2 Environmental analysis

The environmental analysis evidences that in both scenarios the environmental impact depends on the process scale. The scale is directly related to the evaluated parameters as observed in Figures 4 and 5. Therefore, a smaller process scale has a lower environmental impact than a larger process scale. This phenomenon is explained because the increase in plant capacity also increases the amount of waste, which directly influences the environmental impact.

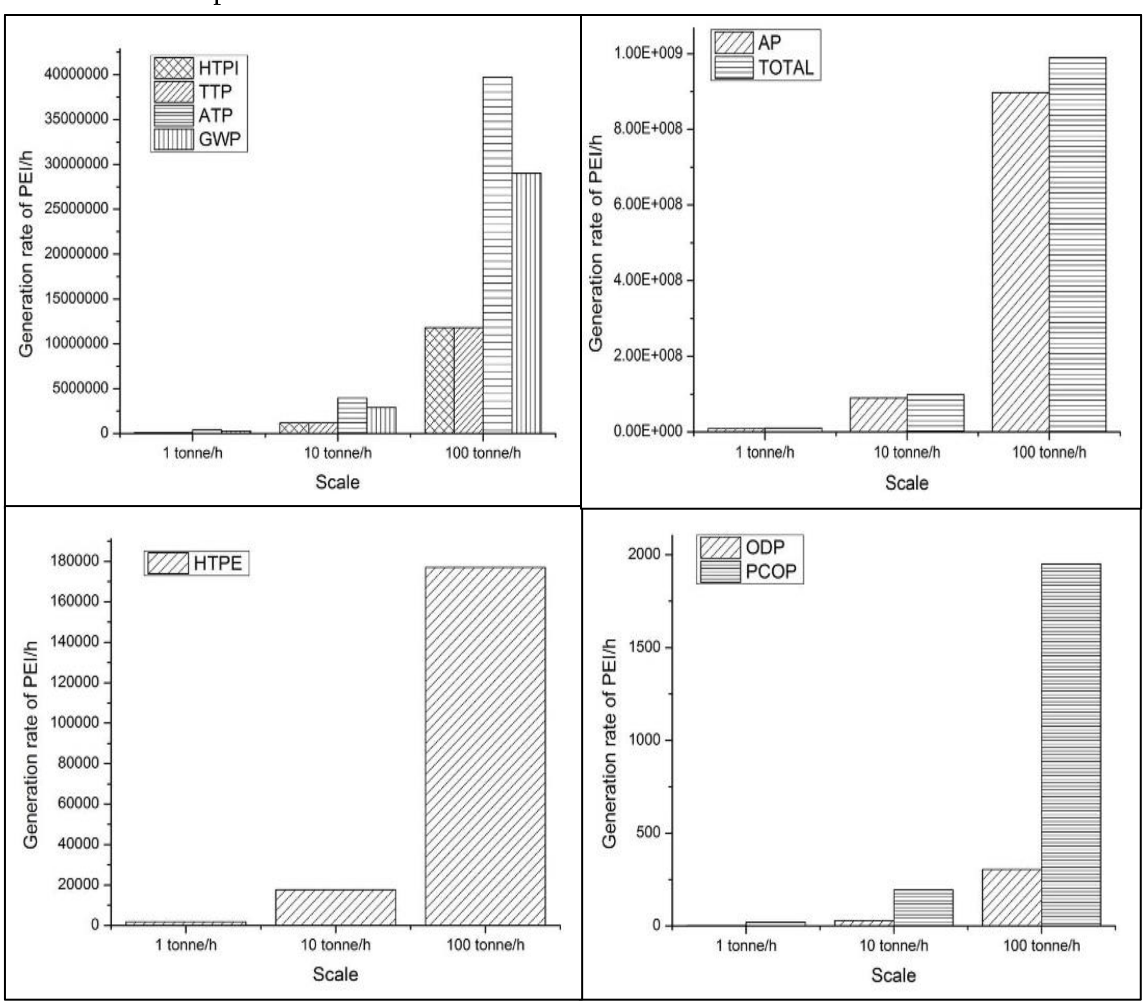


Figure 4. Environmental impact in biogas production (stand-alone).

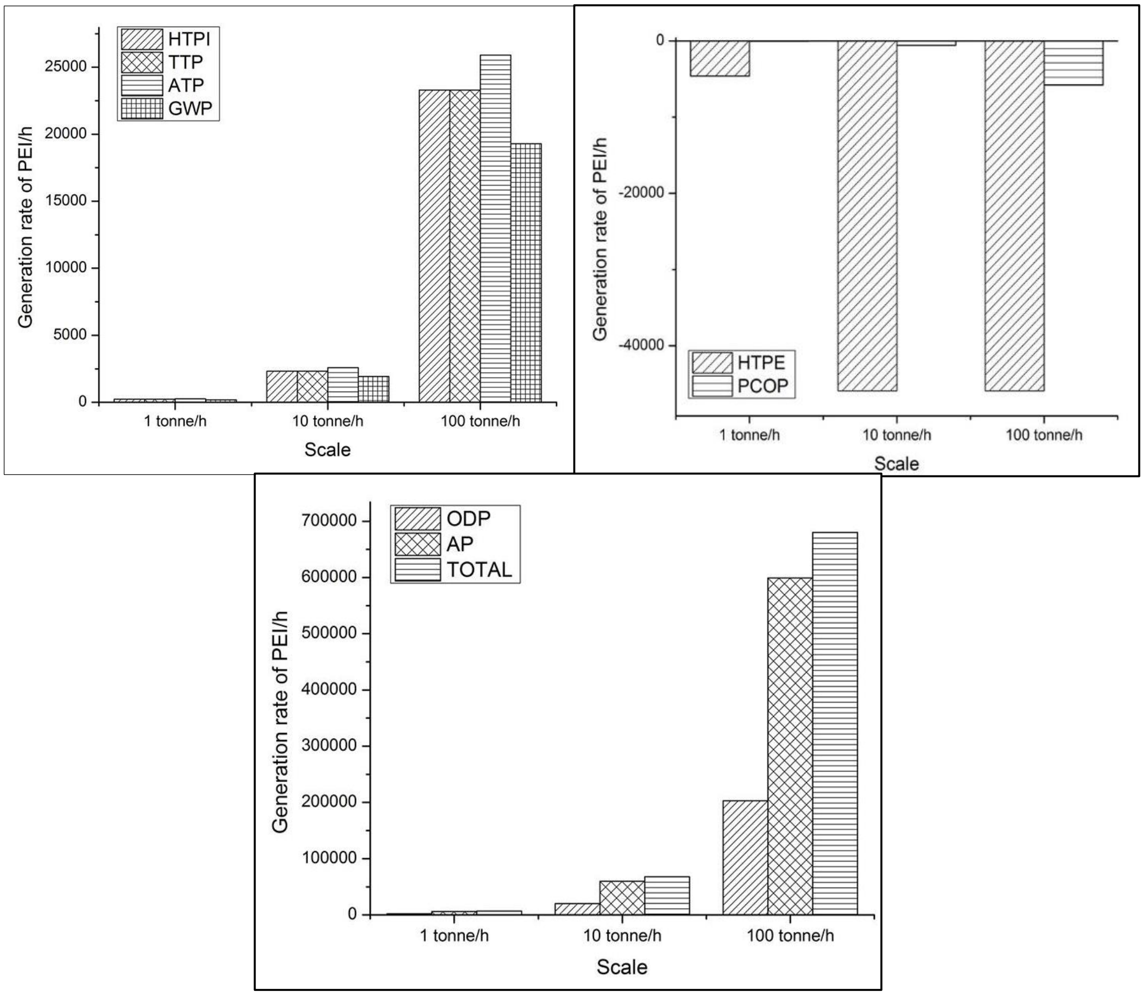


Figure 5. Environmental impact in biogas production (biorefinery concept).

When comparing the stand-alone process (**Figure 4**) with respect to biorefinery (**Figure 5**), significant differences with respect to the evaluated parameters are obtained. In this case, the concept of biorefinery is more environmental friendly than the conventional biogas production. The cumulative potential of environmental parameters is lower when addressing the concept of biorefinery. In turn, this scenario reduces individual impacts by HTPE and PCOP. This can be explained due to the increase of the digestate in conventional process, which has methane and dissolved organic compounds.

Conclusions

The production of biogas under the biorefinery concept is an alternative since it provides high profitability when a high production scales are used. At the same time, it is possible to obtain different products as ethanol, xylitol, syngas and electricity. The biorefinery concept not only provides economic benefits, but also environmental benefits compared to stand-alone processes. On the other hand, the analysis of stand-alone and biorefinery processes are presented as a powerful tool for the determination of economic and environmental feasibility.

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