Effect of co-digestion of milk-whey and potato stem on heat and electricity generation using biogas as an energy vector

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Abstract

Heat and electricity generation using biogas as an energy vector was analyzed through three different processes: stand-alone potato stem, stand-alone milk whey and co-digestion of both materials. An experimental stage was carried out for determining milk-whey and potato stem characterization. Then, the generation of heat and electricity was simulated based on the characterization of both materials in Aspen Plus, where the economic profit was evaluated in terms of the production cost, capital cost, revenues and net present value. As a result, it was established that the co-digestion of potato stem with milk-whey was differentiated respect to simulation process and economic assessment. The anaerobic co-digestion of potato stem and milk-whey is promising for heat and electricity generation.

Keywords: *Co-digestion; potato stem; milk-whey; heat and electricity; economic assessment.*

1. Introduction

Currently, the implementation of projects focused on reducing dependence on fossil fuels, has created the possibility of establishing new alternatives for energy generation [1]. Industrial waste and lignocellulosic biomass can be transformed into value-added energy products through anaerobic digestion. Anaerobic digestion is a process where a group of specific microorganisms converts biomass to a methane-rich gas called biogas. This gas has a methane concentration of 50-70%, thus giving a high calorific power usable in applications like the generation of heat and electricity [2]–[4]. An interesting alternative for the energy production is milk-whey (MW) through biogas as an energy vector. MW is one of the main residues of the dairy industry, where nine kilograms of whey are generated per kilogram of cheese produced [5]. This residue is not used and it is a source of contamination, given the high organic load. In the same way, the Potato Stem (PS) generated in the harvest stage is attractive for biogas production. This waste is non-treated, causing environmental problems due to the deficient use.

Co-digestion is the combination of biodegradable raw materials to improve the balance of nutrients in anaerobic digestion [6]. This has an influence on the performance of anaerobic digestion, establishing a possibility to increase the potential of biogas as an energy vector. Studies about the benefits of co-digestion can be found in the literature [7]–[10]. However, there is non-report where the PS was as a substrate in anaerobic digestion or anaerobic co-digestion processes. Therefore, the integration of PS and MW is an innovative alternative to recover energy, which can reduce dependence on fossil fuels and to obtain economic incomes. Taking into account the above, the main objective of this study is to investigate the combined production of heat and electricity from biogas as energy vector using PS and MW. All of this, to determine the economic profit within the framework of the waste integration by anaerobic co-digestion.

2. Methodology

Combined heat and electricity generation from PS and MW was evaluated through simulation tool Aspen Plus (Aspen Technology, Inc., Houston, USA). Initially, an experimental step was evaluated in relation to physicochemical characterization of the raw materials. Subsequently, the simulation of the energy production was carried out using the physicochemical characterization of the feedstocks and biogas generated in anaerobic digestion process. In this step, three different process was simulated: stand-alone using PS as a raw material, stand-alone using MW as a raw material and the co-digestion of both feedstocks. Finally, the economic feasibility of the three processes was evaluated with the software Aspen Plus Economic Analyzer (Aspen Technology, Inc., Houston, USA).

2.1 Physicochemical characterization of the raw materials

2.1.1 Potato stem

PS was collected from a farm located in the south west region of Colombia (1°07’37.0’’N 77°32’59.8’’W). The waste was milled with an upper vibratory disk mill (Retsch SR 200) and sieved to a particle diameter of 400 μm. Characterization of PS was realized in terms of moisture, cellulose, hemicellulose, lignin, extractives, ash, total solids (TS) and volatile solid (VS) content. Moisture content was determined using Shimadzu moisture balance MOC-120H at 105 °C. Cellulose and hemicellulose was measured using the process reported by Hames et. al [11]. Lignin content determination was established on a modified version of the TAPPII T222 [12]. Extractives content was determined based on reported of the National Renewable Energy Laboratories (NREL/TP-510-42619) [13]. Ash content was measured according to the experimental procedure proposed by National Renewable Energy Laboratories (NREL/TP-510-42622). TS and VS were measured according to .Shaito et al [14].

2.1.2 Cheese milk whey

Acid milk-whey (MW) (pH = 5.6) was obtained from a cow's milk processing plant to dairy products (especially cheese) in the central region of Colombia (5°03’58’’N 75°29’05’’W). These samples were collected, homogenized and frozen to preserve their physicochemical characteristics. Characterization of MW was realized in terms of moisture, protein, carbohydrates, TS and VS. While inoculum characterization was carried out considering TS and VS. TS and VS were measured according to standard method 2540 B; 2-64 and standard method 2540 E; 2-64. Moisture content was determined using Shimadzu moisture balance MOC-120H at 105 °C. The protein content was measured by Biuret method. Carbohydrates and lactic acid were determined by HPLC system (ELITE LaChrom) using an ORH-801 Transgenomic® column. Lipids content was determined using the norm described by Association of Official Agricultural Chemists (AOAC) - AOAC 925.09 [15]. The results of the characterization of PS and CW are presented in Table 1.

2.2 Simulation process

The production process to generate heat and electricity using biogas obtained from the PS and MW was simulated in Aspen Plus (Aspen Technology, Inc., Houston, USA). The flowsheet model in the software was assumed a continuous mode, based on 8000 hours of work per year [16]. Additionally, important parameter in industrial process are thermodynamic models due to the fact that they can represent experimental data [15]. For this reason, the thermodynamic models for the modeling were established through the property method selection assistant of the software Aspen

Plus. Thus, the non-random two-liquid (NRTL) was used to described the liquid phase, Hayden O´Connel for the vapor phase and Wong-Sandler equation for high pressures (>10 bar). The simulation did not consider energetic optimization for pinch analysis and total energy integration. However, the water recycling in some steps was considered (e.g., anaerobic digestion).

Table 1. Physicochemical characterization of potato stem and milk-whey.

Component	Potato Stem (PS) %	Milk-whey (MW) %
Cellulose	36.03 ± 0.32	-
Hemicellulose	27.18 ± 0.40	-
Lignin	11.45 ± 0.56	-
Extractives	12.47 ± 0.11	-
Ash	2.10 ± 0.21	-
Moisture	9.67 ± 0.02	94.08 ± 0.32
Protein	-	1.43 ± 0.15
Carbohydrates	-	3.65 ± 0.37
Fat	-	0.19 ± 0.20
Total Solids (TS)	92.63 ± 0.05	5.69 ± 0.06
Volatile Solids (VS)	90.06 ± 0.03	5.38 ± 0.04

On the other hand, the simulation consists of two well-defined steps: the anaerobic digestion for biogas production and generation of heat and electricity (Figure 1). The first step was subjected to the type of substrate that input as a raw material at the process, where the reactions involved in the biodigester are influenced by the physicochemical characterization (Table 1). While the second step is subjected to the percentage distribution of methane in the biogas stream of the first step.

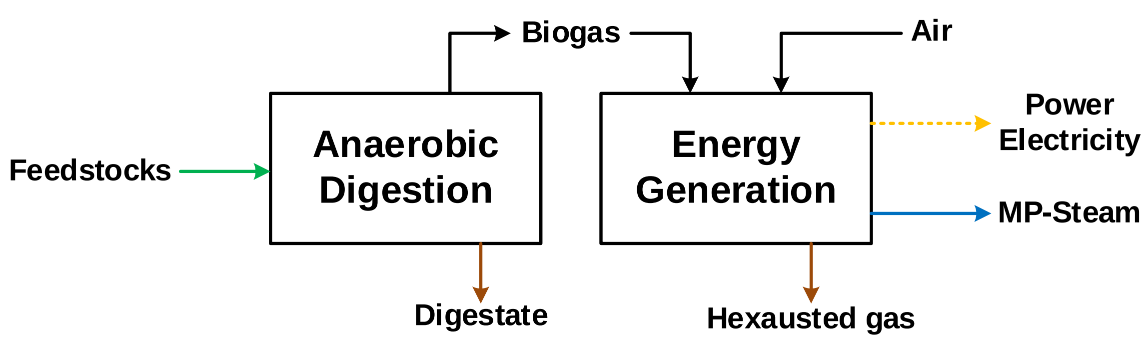

Figure 1. Flowsheet of energy production using biogas as a vector.

2.2.1 Anaerobic digestion for biogas production

Anaerobic digestion process for biogas production was simulated with a modification of the model: A Novel Process Simulation Model (PSM) developed by Rajendran *et. al* [17]. The model considers the four stages of biogas production such as hydrolysis, acidogenesis, acetogenesis and methanogenesis. Therefore, the model transforms these phases into two separate groups of reaction-sets. The first set refers to the hydrolysis phase based on the fractional conversion of the reactants into products. While the second set makes emphasis in the other phases of anaerobic digestion, which were simulated with first-order reactions, collecting the kinetic parameters of previous researchers. The simulation is composed of complex structures of substrates such as carbohydrates, proteins and lipids that are transformed into monomeric compounds. In this sense, for our investigation, different conversion routes are presented for PS and MW (Table 2). For this reason, for the stand-alone process with potato stem, a new conversion reaction for extractives was added to the model. Likewise, our model considered that the protein of MW is soluble protein and that its lipid composition is mainly triolein.

Table 2. Reactions for modeling biogas production from potato stem and milk-whey.

— Reactions used for PS. — Reactions used for MW. — Reactions used for both feedstocks.

		Group of the reactions	Parameter
		Hydrolysis reactions	*Extent of reaction*
1	Cellulose	$(C_6H_{12}O_6)n + H_2O \rightarrow n\,(C_6H_{12}O_6)$	0.4 ± 0.1
2	Cellulose	$C_6H_{12}O_6 + H_2O \rightarrow 2\,C_2H_6O + 2\,CO_2$	0.6 ± 0.0
3	Hemicellulose	$C_5H_8O_4 + H_2O \rightarrow 2.5\,C_2H_4O_2$	0.5 ± 0.2
4	Hemicellulose	$C_5H_8O_4 + H_2O \rightarrow C_5H_{10}O_5$	0.6 ± 0.0
5	Xylose	$C_5H_{10}O_5 \rightarrow C_5H_4O_2 + 3\,H_2O$	0.6 ± 0.0
6	Ethanol	$2\,C_2H_6O + CO_2 \rightarrow 2\,C_2H_4O_2 + CH_4$	0.4 ± 0.1
7	Extractives	$CH_5N + 0.5\,H_2O \rightarrow 0.5\,CO_2 + 0.75\,CH_4 + H_3N$	0.5 ± 0.2
8	Protein	$C_{13}H_{25}O_7N_3S + 6\,H_2O \rightarrow 6.5\,CO_2 + 6.5\,CH_4 + 3\,H_3N + H_2S$	0.9 ± 0.1
9	Fats	$C_{57}H_{104}O_6 + 3\,H_2O \rightarrow C_3H_8O_3 + 3\,C_{18}H_{34}O_2$	0.5 ± 0.2
		Acidogenic reactions	*Kinetic constant*
10	Dextrose	$C_6H_{12}O_6 + 0.1115\,H_3N \rightarrow 0.1115\,C_5H_7NO_2 + 0.744\,C_2H_4O_2 + 0.5\,C_3H_6O_2 + 0.4409\,C_4H_8O_2 + 0.6909\,CO_2 + 1.0254\,H_2O$	9.54*10^{-03}
11	Glycerol	$C_3H_8O_3 + 0.04071\,H_3N + 0.0291\,CO_2 + 0.00005\,H_2 \rightarrow 0.04071\,C_5H_7NO_2 + 0.94185\,C_3H_6O_2 + 1.09308\,H_2O$	1.01*10^{-02}
		Acetogenic reactions	*Kinetic constant*
12	Propionic acid	$C_6H_6O_2 + 0.06198\,H_3N + 0.314336\,H_2O \rightarrow 0.06198\,C_5H_7NO_2 + 0.9345\,C_2H_4O_2 + 0.660412\,CH_4 + 0.160688\,CO_2 + 0.00055\,H_2$	1.95*10^{-07}
13	Isobutyric acid	$C_4H_8O_2 + 0.0653\,H_3N + 0.8038\,H_2O + 0.0006\,H_2 + 0.5543\,CO_2 \rightarrow 0.0653\,C_5H_7NO_2 + 0.8909\,C_2H_4O_2 + 0.446\,CH_4$	5.88*10^{-06}
14	Oleic acid	$C_{18}H_{34}O_2 + 15.2396\,H_2O + 0.2501\,CO_2 + 0.1701\,H_3N \rightarrow 0.1701\,C_5H_7NO_2 + 8.6998\,C_2H_4O_2 + 14.4978\,H_2$	3.64*10^{-12}
		Methanogenic Reactions	*Kinetic constant*
15	Acetic acid	$C_2H_4O_2 + 0.022\,H_3N \rightarrow 0.022\,C_5H_7NO_2 + 0.945\,CH_4 + 0.066\,H_2O + 0.945\,CO_2$	2.39*10^{-03}
16	Hydrogen	$14.4976\,H_2 + 3.8334\,CO_2 + 0.0836\,H_3N \rightarrow 0.0836\,C_5H_7NO_2 + 3.4154\,CH_4 + 7.4996\,H_2O$	2.39*10^{-03}

In view of the above, to simulate the mesophilic biodigester (37 ° C) a stoichiometric reactor was used for the hydrolysis phase and a continuously stirred tank reactor (CSTR) for the other phases. The total number of reactions used in this study for both substrates analyzed (PS and MW) was 16 reactions. Sequentially, the anaerobic digestion is constituted for separation of biogas stream and semiliquid effluent through a flash separator at 37 °C. In addition, before of the stand-alone biogas production from PS was realized a size reduction with a gyratory crushed system until a maximum particle diameter of 1mm.

Additionally, in this study, the scale process for energy production was of 10 m^3/h and 1311.7 kg/day of MW and PS, respectively. The values were estimated for south west region of Colombia, where small industries generated this quantity of MW near large potato crops. Last allows operating the anaerobic digestion with a TS content between 6% and 12%.

2.2.2 Heat and electricity generation

The electricity and heat generation from biogas consisted of two sections: electricity production by means of a gas turbine and heat recovery steam generation. The first section was simulated with a stoichiometric reactor connected to an isotropic turbine with 65% efficiency (this represented to the gas turbine). Initially, the biogas produced in the anaerobic fermentation and preheated air undergo a compression up to 24 bar. The two streams go in a stoichiometric reactor, where the total combustion of methane is carried out with an excess 20% of air under a temperature of 1200-1260 °C. The gases generated (mainly CO_2, H_2O and N_2) are then sequentially expanded into an isentropic turbine with an efficiency of 65% which generates the electricity depending on the biogas flow and its methane content. Sequentially, the exhaust gases are used to provide heat to a series exchangers system. Therefore, the cooling of the gas results in heat being released, which is used to heat the incoming feed water (input at 12 bar pressure) and generate mid-pressure steam at 188 °C. The flowsheet of the heat and electricity generation is showed in the Figure 2.

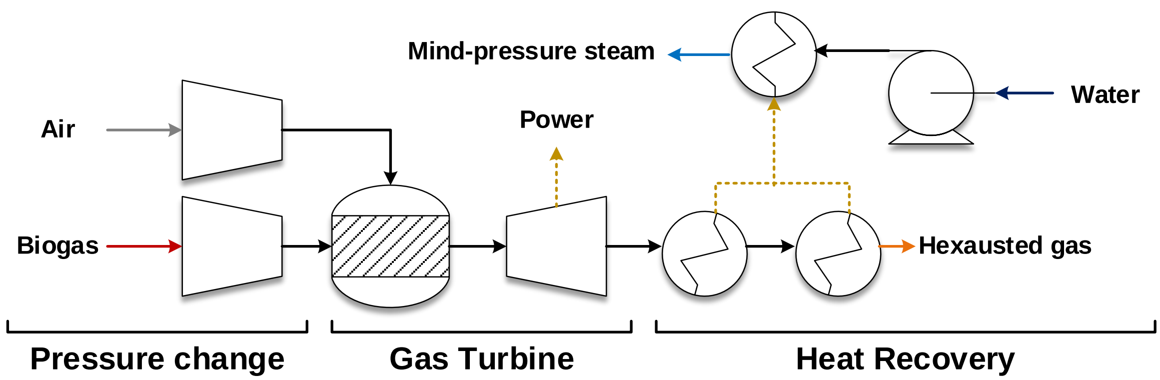

Figure 2. Flowsheet of the heat and electricity generation using biogas as an energetic vector.

2.3 Economic assessment

The process economic assessment consisted of determining the capital costs (CAPEX) and operating costs (OPEX) for each of the simulations. These costs were determined through the tool Aspen Economic Analyzer emphasizing in the economic parameters of South America (Colombia); the number of shifts (3), the annual interest rate (17%), the rate of return (25%), the utilities cost, feedstocks prices, the operative charges, among others. Thus, the mass and energy balances obtained in the simulation together with the unit prices of the different parameters involved (Table 3) were used to establish the CAPEX and OPEX. Also, additional factors that affect the total investment cost and operating costs were evaluated according to Peters *et al.*, [18]. These parameters can be consulted in the annexes of the investigation realized by Moncada *et. at* [19]. Finally, the straight-line method for depreciation was defined with a useful life of the 10-year project to evaluate the economics of the heat and electricity production from co-digestion (MW and PS). It is noted that economic assessment was carried out with a process scale ten times higher than the raised case (1000 m^3/day from MW and 131 ton/day from PS). The above is because there is a better specification of the equipment when working on a large scale in the Aspen Plus software. Therefore, there is no oversizing of the equipment, which would affect the costs (increasing them).

Subsequently, the Net Present Value (NPV) was used as an indicator of the economic feasibility in the stand-alone for MW, stand-alone for PS and co-digestion of MW and PS. Net Present Value (NPV) indicates the potential benefits over the life of the project (10 years) based on the profit on the project, pay-off investment, and normal interest on the investment [20]. The data used in the economic assessment are presented in Table 3.

Table 3. Parameters used in the economic assessment of heat and electricity generation.

Item	Unit	Value	Reference
Investment Parameters			
Tax rate	%	25	[21]
Interest rate	%	17	
Raw materials			
Milk-whey	USD/L	0.02	
Potato Steam	USD/kg	0.08	Average price[a]
Dilution water	USD/m^3	0.80	
Utilities			
Low Pressure steam	USD/ton	7.57	[22]
Mind Pressure steam	USD/ton	8.18	
High Pressure steam	USD/ton	9.86	
Process water	USD/m^3	1.25	Average price[a]
Fuel	USD/MMBTU	88.01	
Electricity	USD/kWh	0.124	
Operation			
Operator	USD/h	2.72	Average price[a]
Supervisor	USD/h	5.00	

[a] Average price in Colombian context.

3. Results and discussion

3.1 Simulation process

The simulation results of the co-digestion and the two individual stand-alone processes were shown in the Figure 3 and Table 4. The Figure 3 showed the mass balance of the three simulations, where can be observed that production of biogas through the co-digestion of PS and MW was of 537.02 kg of biogas. While that its yield (Table 4) was of 137.73 L of biogas/kg feedstock (kg PS + kg MW). Likewise, the biogas production from stand-alone MW and PS were of 41.29 kg and 268.28 kg of biogas, respectively. The above can be explained due to the high content of TS in the PS (Table 1), which increases the available substrate for microorganism consortium in the medium. However, the biogas yield (table 4) is highest in the stand-alone anaerobic digestion with PS (207.21 L biogas/kg feedstock) respect to co-digestion (137.73 L biogas/kg feedstock (kg MW + kg PS)) and stand-alone anaerobic digestion with MW (21.92 L biogas/kg feedstock).

The methane yield calculation was performed from the biogas composition. The methane yield is greater for anaerobic digestion with PS (137.48 L CH_4/kg feedstock), followed by co-digestion (70.39 L CH_4/kg feedstock), and the digestion of MW (16.12 L CH_4/kg feedstock). These results indicate that there is a greater availability of methane when using only PS as a substrate. Therefore, it's possible to generate higher energy per kilogram of raw material. However, in the process is necessary a pretreatment and mixing before the anaerobic digestion process, which can be affect the economic feasibility of the stand-alone process.

In order to allow better comparison of the yields of the biogas simulation, these were normalized in terms of the VS and the methane percentage. Thus, biogas yields in the simulations for MW, PS and co-digestion were 377.95 L biogas/kg VS, 230.23 L biogas/kg VS and, 360.71 L biogas/kg VS, respectively. From these results, it can be concluded that despite the low biogas production in the stand-alone process that involve MW, this process has a higher performance in terms of VS compared to the other two processes. Also, the methane percentage in the biogas for the whey

(73.55%) is higher compared to the digestion of PS (66.35%) and co-digestion of both materials (51.08%).

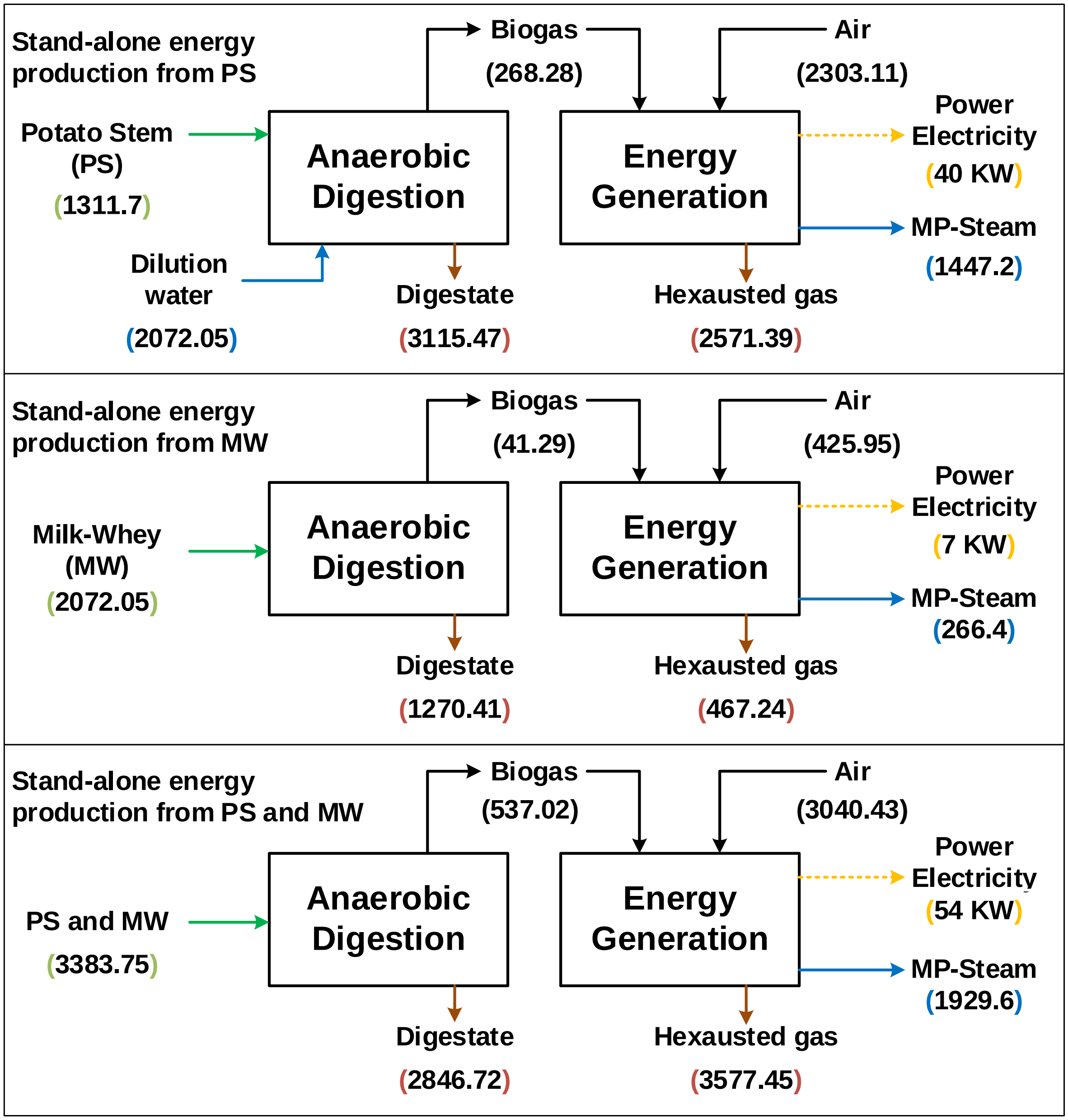

Figure 3. Mass balances of energy production based on biogas from Potato Stem and Milk-Whey, expressed in kg/day. * The balance for HP-Stem in complemented with water for recovery heat.

Conversely, despite the advantages of the individual conversion of whey to biogas, there is a great wastage of water in the process since only 5.59% is organic matter. The above can lead can lead to high production costs due to a great amount of liquid wastewater. Nevertheless, co-digestion to generate energy emerged as an alternative to solved this problem. Where the integrate of two residues with good availability coupled with the anaerobic co-digestion to generate energy are combined to leverage the liquid wastewater. This advantage can be observed when calculating the process productivity in relation to the amount of feedstock. Where the volumetric methane productivity for stand-alone of MW (3.34 m^3 CH_4/m^3.day) is lower compared to the volumetric methane productivity for co-digestion of both materials which is 4.6 times higher.

Based on the above, in the Figure # can be observed that the energy generation from co-digestion of PS and MW is greater compared to stand-alone processes. The biogas of anaerobic co-digestion generated a power electricity of 54 KW, while the stand-alone processes (PS and MW) produced 40 KW and 7 KW, respectively. Likewise, the production of mid-pressure steam (12 bar, 189-195 °C) for simulations of anaerobic digestion de PS and anaerobic digestion of MW have lower yields compared with the co-digestion process. The production of mid-pressure was of 1929.6 kg/day in the integrate feedstocks, 1447.2 kg/day in the stem and 266 kg/day for the whey. In consequence, the greatest generation of energy was obtained with the integration of waste, where 54 KW of power electricity and heat in the shape of mid-pressure steam (292.85 KW) can be generated using 10 m^3 of whey and 1.31 ton of PS.

3.2 Economic assessment

The economic evaluation of the three simulations was determined based on four parameters: capital costs (CAPEX), production costs (OPEX), product revenues (Revenues) and net present value (NPV). CAPEX refers to the initial investment to carry out the process on an industrial scale. OPEX refers to the production costs associated with the project for each year, which takes into account the cost of feedstocks, utilities cost, operating costs, maintenance of equipment, overhead plant and general and administrative expenses. The third refers to the annual net profits for the products sales (electricity and mid-pressure steam). Finally, NPV concerning the net economic benefits (profit or loss) at the end of the project. Table 4 shows the results of these parameters, where the OPEX for the stand-alone process MW was of 8.87 M.USD/Year, which is lower compared to the stand-alone process of PS (16.3 M.USD/Year) and co-digestion of PS and MW (11.31 USD/Year). The above is due to the raw materials cost, which is the most representative cost in the three scenarios (> 80%). However, for stand-alone MW there is no additional reagent (such as stand-alone PS) is added. This leads to a considerable reduction of 6.37% compared to co-digestion and 44.62% for stand-alone PS respect to the raw materials cost. Additionally, for stand-alone process with PS is necessary crushing and mixing the substrate [23]. This increases the economic margin cost reflected in 2.11 USD/Year for stand-alone process and 2.18 USD/Year for the co-digestion.

Table 4. Associated cost with the generation of heat and electricity for stand-alone MW, stand-alone PS and co-digestion of PS and MW.

Feature	Stand-alone MW		Stand-alone PS		Co-digestion of MW and PS		
	M.USD/Year	Share (%)	M.USD/Year	Share (%)	M.USD/Year	Share (%)	
Total Raw Materials Cost	7.78	88	14.05	83	8.31	74	OPEX
Total Utilities Cost	0.35	4	2.11	13	2.18	19	
Operating Labor Cost	0.08	1	0.10	1	0.11	1	
Maintenance Cost	0.08	1	0.24	1	0.26	2	
Plant Overhead	0.08	1	0.13	1	0.18	2	
G and A Cost	0.50	6	0.20	1	0.26	2	
Total Project Capital Cost	8.57	-	14.02	-	15.19	-	CAPEX
Total Products Sales	73.38	-	394.72	-	530.11	-	Revenues
Net Present Value (Finish project)	217.55	-	687.43	-	1794.38	-	NPV

The other essential feature is the numbers of equipment (mixer and crusher) and the greater biogas flow to generate energy, which has a direct influence on the CAPEX. CAPEX for the stand-alone MW (8.57 M.USD/Year) is lower compared to the stand-alone PS (14.02 M.USD/Year) and co-digestion of PS and MW (15.19 M.USD/Year). This result occurs commonly in most biochemical processes, as reported in previous economic studies [24], [16]. Therefore, despite capital and operational costs in the stand-alone MW are low, the sales of products are lower. This represents 81.4% less than the stand-alone PS and 86.16% less for the co-digestion. Likewise, when comparing the co-digestion with stand-alone PS there is a 25.5% increase of first respect to the second. Finally, the economic profits evaluated with the NPV showed in Figure 4, where a positive NPV is obtained in the three processes. This means that at the end of the project (10 years) there is a net profit of 217.55 M.USD, 687.43 M.USD and 1794.38 M.USD for the stand-alone MW, stand-alone PS, and co-digestion.

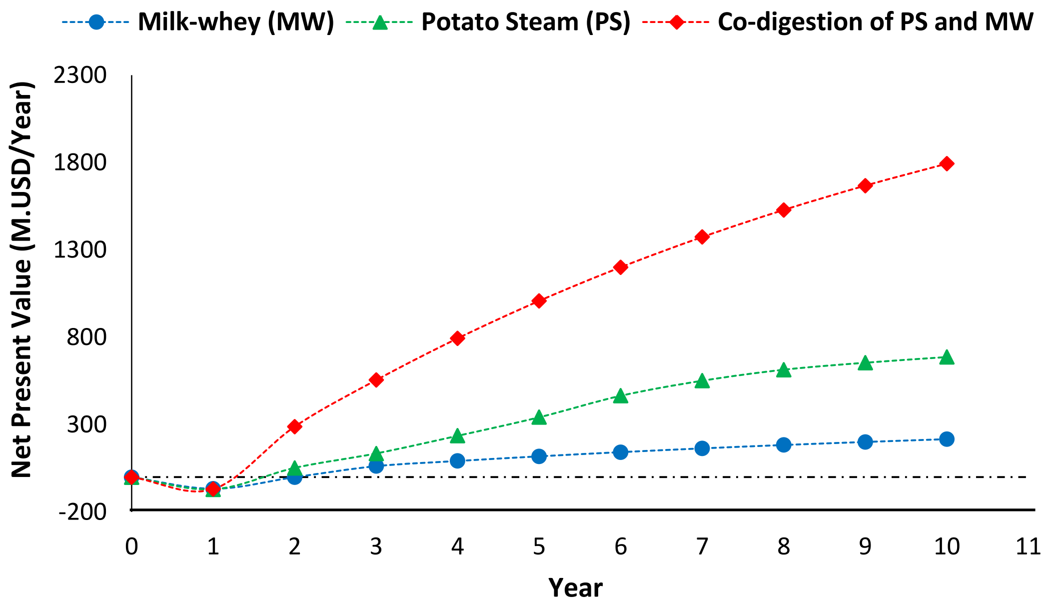

Figure 4. NPV for stand-alone process and co-digestion of potato stem and milk whey.

It should be highlighted that integrating the two residues (PS and MW) is promising for heat and electricity production. This integration represents an increase of 61% in the NPV compared with the other cases. However, the process scale, logistics and transport cost of the feedstocks and biogas purification are non-studied in the framework of this investigation. This can represent an economic deficit when operating on a small scale since the initial investment increases causing a displacement of the NPV and generating a negative economic benefit [19]. This can be observed in recent publications, where the economic profit diminish when scale is reduced.

4. Conclusions

Heat and electricity generation using biogas as an energy vector was analyzed through three different processes: stand-alone potato stem, stand-alone milk whey and co-digestion of both materials. The biogas yield from potato stem was of 207.21 L biogas/kg PS (66.35% CH_4), biogas yield from milk whey was of 21.92 L biogas/kg MW (73.55% CH_4) and co-digestion was 137.73 L biogas/kg feedstocks (51.08% CH_4). Additionally, the volumetric productivity is 4.6 times higher for co-digestion process compared to stand-alone. Regarding energy generation, 54 kW of power electricity and 1929.6 kg/day of MH-Stem are produced with co-digestion process. From an economic pony of view, the generation of heat and electricity through co-digestion of potato stem and milk whey generates a net economic profit of 1794.38 M.USD. In this way, the integration of potato stem and milk whey to generate heat and electricity is a promising alternative due to economic profit.

The results can represent a type of strategy to analyze the integration of different raw material to reach a synergy allowing increasing the economic indexes for new projects. This is of high importance considering the diversity in residues existing mainly in tropical countries where usually scarcity of energy supply is a problem in not interconnected areas.

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