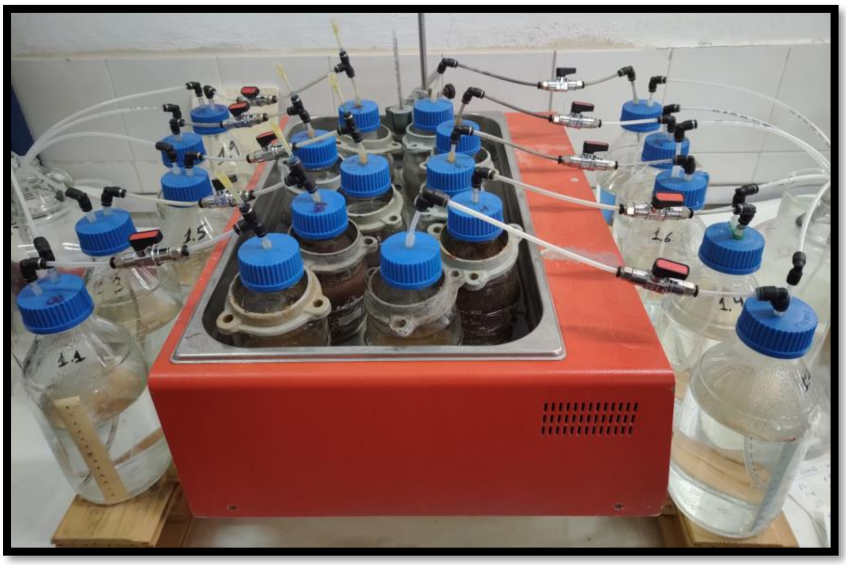
2021

Study of the energy recovery of animal by-products and analysis of the energy matrix for the energy self-sufficiency of industrial animal slaughter and processing



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Abstract

Tenerife is one of the main islands of the Canary Islands, which, due to its characteristics as the outermost region, has a high energy dependence as well as a limitation on available territory; in addition to being designated as a Remote Zone, the elimination of Animal By-Products (ABPs) in landfills is permitted. This treatment does not contribute to the current trend of a circular economy and negatively harms the environment. The energy recovery of this waste through anaerobic digestion for the production of biogas would enhance the use of renewable energies, contributing the meat industry to energy independence and better management of the waste generated, promoting an energy transition towards cleaner energies in line with the Sustainable Development Goals, especially SDG 7, "Affordable and non-polluting energy". The study of the potential for biomethanization of these by-products has been carried out both separately and in co-digestion in search of the best biogas production. Of the samples studied, only biogas was obtained in the anaerobic digestion of the rumen content, sewage sludge and for the co-digestion of viscera (cattle, pigs, goats, sheep and rabbit), raw blood and sewage sludge. Highlighting, for the latter shows a production of 972 mL of biogas / g VS of the mixture and this would have a total of 499 MWh_e of electrical energy for the estimated waste of Tenerife during the year 2019.

Keywords: waste-to-energy, Tenerife, anaerobic digestion, animal by-products, slaughterhouse, renewable energy

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1. Introduction

Higher population growth, globalization and technological developments producing an increasing of energy demand, waste generation and anthropogenic emissions [1]. The energy production scenarios are very polluting because of majority are produced with fossil fuels, a non-renewable fuel. In Spain, only the 37.5% of the electric energy comes of renewable sources [2]. In 2017, for example, 73.9 % of the fuel needed for generating primary non-renewable energy was obtained from Algeria, Saudi Arabia, Nigeria, Mexico and Peru, among others [3]. On the other hand, waste is very important because the landfill uses up a large amount of land that could be used for other productive activities such as agriculture. On the other hand, the Spanish tax on landfill was higher than 50% in 2019 [3], [4]. In addition, landfills cause environmental problems as bad smells and methane emissions, one of the most pollutant gases.

Landfills are not the best treatment for waste, because they do not follow the circular economy where waste is transformed into a resource to be used again in the same process or in other processes. One of the most widely used treatments today is to transform this waste into energy, known in the literature as waste-to-energy (WTE). There are different waste-to-energy alternatives to produce energy from biomass sources, grouped in thermochemical processes and bioconversion processes [5]. Where adequate technology depends on the biomass characteristics and properties. Bioconversion processes, such as anaerobic digestion, are more appropriate for biomass sources containing more than 50% moisture, whereas thermochemical processes, such as biomass combustion, are a better option. Although, there are other technologies with less maturity like pyrolysis, gasification, and fermentation [5].

The high nutritional value of meat, i.e. high protein, bioavailable minerals and vitamins content, results in an increasing demand for livestock products and consequently, in increasing animal by-products generation originating in slaughterhouses [6]. Management of animal by-products for food industry is very important to ensure the safety of the human and animal food chain [7]. The animal by-products (ABPs) in slaughterhouses are waste from the process of meat industry. The Figure 1 shows that meat production is growing, and according to the Food and Agriculture Organization (FAO), in 2029 there is going to be an 80% increase compared to the average values of the 2017-2019 series. For that, the amount of waste produced will also rise.

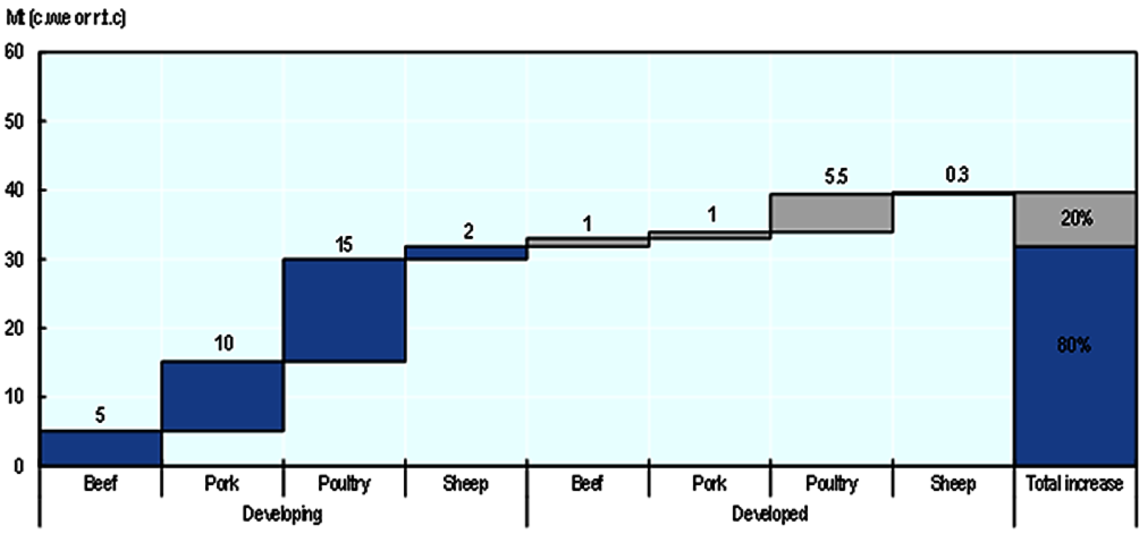

Figure 1. *Growth of meat production by region and meat type in 2029 from 2017 and 2019 average data for the world for each animal. Source:* [8].

Then, ABPs are necessary sanitary rules to prevent and minimize risks to public and animal health to preserve the safety of the food and the animal chain [9]. There are two rules, one of this is Regulation (EC) 1069/2009, which ABPs are categorises based on their risk[10] and Regulation (EC) 142/2011, which establishes health rules for animal by-products and derived products not intended for human consumption [11], [12]. This regulation was adapted to Spanish legislation by Royal Decree 1528/2012 [13].

ABPs are classified into three groups (categories 1, 2 and 3) according to Regulation (EC) 1069/2011, where decreasing order signifies an increase in dangerousness. Following that, Regulation (EC) 142/2011 describes the management of these by-products, such as the necessary pre-treatment to use them in an application, such as energy recovery or animal food. As energy pre- treatment is necessary to ensure food safety in the process, avoiding the transfer of possible diseases from animals to people, these pre-treatments can be thermal or thermochemical [14]. Numerous studies have been conducted to examine the effect of pre-treatment on biogas production in order to find the best method for improving anaerobic digestion performance. *Carrere et al.* have carried out a study for the different pre-treatments, observing that with thermochemical pre-treatments, better results are obtained in the production of biogas [14]. It is highlighted that with animal by-products, the thermochemical pre-treatments present better results on a laboratory scale, highlighting the combination of thermal pre-treatment and saponification, due to the high fat content of these by-products. Emphasizing that pre-treatment can improve the potential for biomethanization by up to 50% [15].

The agriculture and livestock waste are generated in huge quantities worldwide and possess serious environmental and health risks. Therefore, solutions have been developed for this problem. Anaerobic digestion is one of the solutions to convert a waste that has no value into other by-products that do [16]. Currently, most developing countries have already used the anaerobic digestion process as a unique way to implement waste-to-energy technologies to generate clean energy [17]. In particular, the case of animal by-products that are produced from slaughterhouses has a great potential for the generation of biogas [18], [19]. In this sector, there are numerous investigations where studies of different anaerobic digestion technologies such as batch and semi-batch digestion have been carried out [17-20]. In addition, there are configurations in which the stages of digestion are separated into two reactors, as is the case with the anaerobic membrane digester [24]. On the other place, the control of anaerobic digestion with the regulation of parameters such as pH and temperature is important for the optimal evolution and growth of methanogenic bacteria, which provide the greatest composition of biogas. *Schmidt et al.* carry out a study of the effect of seasonal temperature variations on the anaerobic digestion process where it is observed that at low ambient temperatures, they generate a negative impact on biogas production and process stabilization [25]. Apart from the animal by-product recovery study, there are articles in which energy recovery by anaerobic digestion of slaughterhouse sludge is studied, where anaerobic upflow reactors have been used [26] or studies of cogeneration with other agricultural elements that allows for better performance [27]. Experiments have also been made with other waste such as waste from a poultry industry [28]. Then, all are focused on the optimization and characterization of waste potential or in the general analysis of the potential in a country like Indonesia or Iran [17], [29].

On the other hand, the process of anaerobic digestion is a biological process, then conditions of how it develops are important since they affect the production of biogas by the microbial community. Therefore, working conditions are under continuous investigation as they depend on each raw material used in the process. *Mao et al.* analyse the study parameters of anaerobic digestion that must be optimized to achieve better performance, with pH, C/N ratio, organic load and retention time [30]. In addition, due to the high volatile fatty acid content of slaughterhouse waste [31] the co-digestion of these residues with other agro-industrial wastes (such as olive leaves and orange peel) and also adjusting the C/N ratio are studied [6]. *Rodríguez-Abalde et al.* study the optimization of anaerobic digestion previously pasteurized with pork slurry and glycerine [32]. Another alternative to co-digestion has been seen that it is anaerobic digestion in multistage where production is improved. A case is anaerobic digestion in two stages unified with temperature variation, thermophilic temperatures (55 °C) during the phase of hydrolysis and acidification of the material and mesophilic conditions subsequently (35 °C), ensuring greater stability and diversity of methanogenic bacteria in the methane production phase [33]. Another way to give stability to the process is by adding inoculum, which being the already digested matter where the ecosystem of bacteria that feeds on the other matter that is added to it has been created [18].

1.1. The case of Canary Islands

The Canary Islands are one of the outermost regions of European Union. They face persistent and combined difficulties that hinder their socio-economic development: great remoteness, insularity, small area, complex orography and economic dependence on a small number of products. For this reason, Canary Islands is called Remote Area from 1 of March of 2012 [7] and it has been extended several times and nowadays it is until 15 of June of 2022 [34]. This name was declared by the Canary Islands Administration because of the special orographic conditions of the Canary Islands for the operations of withdrawal, transport, handling, and storage of animal by-products, together with the remoteness and insularity of the territory. Then, animal by-products can be taken to the landfill whenever environmental complexes have environmental authorization, and removal and transfer of such by-products from generating activities to environmental complexes were carried out by companies authorized for the purpose. To this form to ensure traceability and relevant controls by means of the corresponding records and documents [34].

A part of this, each island that compose Canary Islands forms an isolated energy system with an external energy dependence of fossil fuels and a limitation of the territory. Each energy system must tend to energy transition towards a cleaner one, favouring the penetration of renewables with a manageable renewable energy like biogas. This is in line with the goal of the Sustainable Development Goal (SDG) number 7, "Ensure access to affordable, reliable, sustainable and modern energy for all". Likewise, complying with law published the 21 of May of this year, Law 7/2021 called "Climate Change and Energy Transition Law", which highlights the steps for a clean energy transition.

In the present study, the available data on waste generated and disposed in the landfill by the slaughterhouse on the island of Tenerife is collected and analysed. Subsequently, it is experimentally determined with samples supplied by the slaughterhouse how much energy that is possible to obtain from the wasted by-products. This information will make it possible to determine the self-generation capacity available in this type of industrial activity using its own animal by-products.

2. Materials and methods

2.1 Quantification of animal by-products in Tenerife

The Canary Islands Government has a quantification of the number of animal (head) slaughtered in Tenerife, which includes bovine, porcine, goat and ovine and rabbit. This study is carried out with the data collected for the first time during the year 2019.

The estimation of the quantity (kg/head) of animal by-products is estimated following published parameters (to see Table 1). Then, each animal was used a parameter of bibliography by head. For bovine and porcine, the parameters of the head are studied by Sagastume *et al.* [35]. In the case of goat and ovine considered as a small ruminants with a median weight of 40 kg, 50% of viscera and 3% of blood [17], [36]. Finally, the rabbits have a median weight of 2.30 kg and a 40% waste rate [37].

Table 1. *Parameters used to estimate quantity of animal by-products.*

Species	***Viscera (kg/head)***	***Blood (kg/head)***
Bovine	91.80	17.20
Porcine	9.22	4.35
Goat-Ovine	20.00	1.20
Rabbit	0.92	-

2.2 Anaerobic digestion

2.2.1 Raw materials

In Tenerife, to send animal by-products to the landfill, the slaughterhouse has to pays an authorized manager to transport them to the landfill. On the other hand, because the waste must be solid material to be eliminated on the landfill, the blood is dehydrated using steam at 180ºC for 40 minutes to send to the landfill. Consequently, the effect of raw and dehydrated blood on biogas production was investigated in this study.

These animal by-products must be sanitized, according to Regulation (EU) 142/2011, and the pre-treatment used in this study was pasteurisation for 24 hours at 85 ºC to ensure that a temperature of 70 °C is reached inside the sample for one hour. Before that, animal by-products must be cut into pieces smaller than 12 mm.

The animal by-products used are the mix of viscera by each animal (bovine, porcine, goat, ovine and rabbit) and, the blood and sewage sludge of a mix of all animals. The viscera proportion was according to the distribution of viscera quantity of each animal.

2.2.1 Preparation of biodigester

ISO bottle were used as biodigesters. In each digester, 60 g of animal by-products pasteurized were placed, except the biodigester with rumen content due to its low density only were placed 15 g. Then, 290 mL of distilled water was added, and the content was shaken and the pH was measured. After that, 4.8 g NH_4Cl (purity 99.5 %, Panreac) were added to provide the medium with a nitrogen source, 540 mg of $CaCO_3$ (purity 99.0 %, Panreac) and 10 mL of buffer solution (pH=7.0 (20ºC), Scharlau) were subsequently added to act as a buffer and pH was measured again. In the case of the rumen content was added 2.4 g NH_4Cl, 270 mg of $CaCO_3$ and 10 mL of buffer solution of 7.0 pH. 4M NaOH solution (purity 99.0%, Scharlau) was added if necessary to achieve a pH in the range of 7.5-8.5. After that, biodigesters were hermetically sealed with a GL45 cap and vacuumed. Afterwards, biodigesters were filled with nitrogen and purge it three times to avoid oxygen inside of biodigester. Each sample was duplicated because one digester is disturbed to extract gas volume for composition analysis in the chromatograph and another is only for gas volume measurements. Finally, the biodigesters were introduced into thermostatic water baths with a temperature of 32 ºC and were connected to the metering system.

The samples were prepared according to the proportions of animal by-products that Table 2 shows.

Table 2. *Composition of the samples according to the types of animal by-products.*

Animal by-products	***Bovine***	***Porcine***	***Caprine-Ovine***	***Rabbit***	***Raw blood***	***Dehydrated blood***	***Sewage sludge***
Viscera	40.2%	39.5%	15.5%	4.8%	-	-	-
Viscera and raw blood	35.9%	35.3%	13.9%	4.3%	10.6%	-	-
Viscera and dehydrated blood	35.9%	35.3%	13.9%	4.3%		10.6%	-
Viscera, raw blood and sewage sludge	28.5%	28.0%	11.0%	3.4%	8.5%	-	20.6%

2.2.2 Reactivation of biodigester

The pH is a parameter that must be controlled for an optimal ecosystem for methanogenic bacterias. When gas production was stopped, the pH was measured and if it was below 7.5 a 4M solution of NaOH was added to achieve the range 7.5-8.5. After that, each digester was sealed and vacuumed and then was bubbled with nitrogen and purged three times to avoid oxygen inside of the biodigester. Then, biodigesters were introduced into thermostatic water baths and were connected to the metering system.

All samples were reactivated (Table 3) except rumen content (sample 2), sewage sludge (sample 4), and of viscera, sewage sludge and raw blood (samples 15 and 16) samples.

Table 3. *Samples reactivated in this study.*

Sample composition	***Sample number***
Rumen content	Sample 1
Sewage sludge	Sample 3
Raw blood	Sample 5
	Sample 6
Dehydrated blood	Sample 7
	Sample 8
Viscera	Sample 9
	Sample 10
Viscera and raw blood	Sample 11
	Sample 12
Viscera and dehydrated blood	Sample 13
	Sample 14

2.2.3 Quantification of gases

The gases produced by digesters were measured by volume displacement in a one-litre ISO glass bottle. They were filled with distilled acidulated water (HCl with a purity of 37%, Merck) to prevent carbon dioxide from becoming diluted in the water to shift the CO_2/HCO^{-3} equilibrium completely to the left. In this way, each bottle was calibrated with a scale of 12 centimetres where it can measure the difference in height. Then, the volume of cylinder displaced is proportional to the volume of biogas produced and it is accumulated in other bottles.

The measure of volume is taken according to gas production and each two days on average and at the same hour in most cases from Monday to Friday. The content of the bottle is stirred to facilitate the release of the gas dissolved in the solution and then the value of height is taken. The volume is quantified by the equation (1):

$$V\ (mL) = \frac{\pi}{4} \cdot D^2 \cdot H = \frac{\pi}{4} \cdot (9.2)^2 \cdot H = 66.48 \cdot H \qquad (1)$$

Where H is the height, in centimetres of displaced gas.

2.2.4 Composition of gases

Composition of gases of each sample was measured with a gas chromatograph (Agilent 7820A GC) with a thermal conductivity detector (TCD). This is composed with two capillary columns working in parallel, CP-Molsieve 5 Å (30 m, 0,53 mm DI, 0,53 µm) and CP-PoraBond Q (packed column), which allow measurement to CH_4, CO_2, CO, O_2 and N_2. The analysis was realized with operating condition as follow: oven temperature isothermal at 40ºC; injector temperature at 175ºC; TCD temperature at 180ºC and helium as carrier gas with a flow rate of 36 mL min^{-1} and at 9 psi pressure.

The composition analysis was carried out with a gas sample volume of 1 mL.

2.2.5 Analysis of total, volatile and fixed solids.

To characterize each sample and its potential for biogas conversion, a solid analysis (total, volatile and fixed solids) has been carried out according to standard method 2540 G [38]. In particular, volatile solids are susceptible to being transformed into biogas. Therefore, samples were analysed before and after the process of anaerobic digestion relating the amount of volatile solids consumed to the volume of biogas produced.

In this process, 1 g of animal by-product was added to each sample in the crucibles and then these samples were heated at 105ºC for 24 hours. After that, crucibles were put into the dryer until the ambient temperature was achieved and then, were weighted. Finally, after one hour in the muffle at 550ºC, the crucibles were placed in the dryer again until the ambient temperature was reached and were weighed again. Equations 2, 3, and 4 were used to calculate each percentage of total, volatile and fixed solids, respectively.

$$\% \, TS = \frac{B - A}{M} \times 100 \qquad (2)$$

$$\% \, VS = \frac{B - C}{B - A} \times 100 \qquad (3)$$

$$\% \, FS = \frac{C - A}{B - A} \times 100 \qquad (4)$$

Where:

A is the weight of the empty crucible.

B is the weight of the crucible after staying on the heater and dryer.

C is the weight of the crucible after staying in the muffle and dryer.

M is the weight of only the animal by-products.

3. Results and discussion

3.1 Quantification of animal by-products in Tenerife

On the island of Tenerife, the quantity of animal by-products was calculated using the parameters shown in Table 1 and with the data published by the Government of the Canary Islands from the survey of the number of heads of animals slaughtered in slaughterhouses for the island of Tenerife according to species. [39]. Table 4 shows the total quantity of each animal by-product produced per kilograms and month, where it is generated in kilograms in the slaughterhouse. The blood and viscera data were estimated on the basis of bibliographic parameters, but the sewage sludge is a real production by a slaughterhouse.

Table 4. *Estimation of the quantity of animal by-products, in kilograms, by each animal produced in the slaughterhouse.*

	Bovine		*Porcine*		*Goat-Ovine*		*Rabbit*
Month	**Viscera (kg)**	**Blood (kg)**	**Viscera (kg)**	**Blood (kg)**	**Viscera (kg)**	**Blood (kg)**	**Viscera (kg)**
January	27,540.00	5,160.00	23,095.30	10,906.11	8,720.00	523.20	3,741.64
February	27,723.60	5,194.40	22,625.28	10,684.16	10,120.00	607.20	3,511.64
March	24,235.20	4,540.80	23,371.78	11,036.67	12,500.00	750.00	3,737.04
April	28,733.40	5,383.60	29,021.18	13,704.45	8,220.00	493.20	4,426.12
May	24,694.20	4,626.80	28,486.66	13,452.03	8,000.00	480.00	3,232.88
June	25,245.00	4,730.00	24,708.10	11,667.71	10,760.00	645.60	3,236.56
July	25,153.20	4,712.80	27,795.46	13,125.63	7,940.00	476.40	3,757.28
August	24,235.20	4,540.80	24,450.05	11,545.86	7,300.00	438.00	2,404.88
September	25,887.60	4,850.40	25,906.18	12,233.47	8,820.00	529.20	2,684.56
October	27,723.60	5,194.40	27,242.50	12,864.51	12,920.00	775.20	3,009.32
November	30,477.60	5,710.40	25,989.12	12,272.64	8,540.00	512.40	2,240.20
December	37,362.60	7,000.40	43,720.70	20,645.89	29,800.00	1,788.00	3,045.20

The total amount, in metric tonnes, of viscera, blood and sewage sludge generated in Tenerife for 2019 are shown in Table 5.

Table 5. *Total of animal by-products in Tenerife in 2019.*

Month	***Viscera (t)***	***Blood (t)***	***Sewage sludge (t)***
January	63.10	16.59	16.80
February	63.98	16.49	16.80
March	63.84	16.33	19.20
April	70.40	19.58	15.00
May	64.41	18.56	22.50
June	63.95	17.04	22.50
July	64.65	18.31	22.50
August	58.39	16.52	22.50
September	63.30	17.61	15.00
October	70.90	18.83	37.50
November	67.25	18.50	15.00
December	113.93	29.43	15.00

In agreement with these total quantities, the proportion of each animal by-products is 64.1%, 17.3% and 18.6%, viscera, blood and sewage sludge, respectively. The viscera are abundant and therefore, they are crucial to improve the transformation process with this waste.

The total quantity of 1,292 tonnes of animal by-products (bovine, porcine, ovine, caprine and rabbit) was generated according to the estimation for 2019 in Tenerife.

3.2 Anaerobic digestion

3.2.1 Gas production

Table 6 shows the gas production measured every two days, as well as the total gas production during the study period.

Table 6. *Gas production and period of time by sample.*

Samples	***Time (days)***	***Sample number***	***Production (mL/g VS)***
Rumen content	189	Sample 1	1,094.54
	183	Sample 2	690.85
Sewage sludge	183	Sample 3	1,465.29
	183	Sample 4	329.45
Raw blood	115	Sample 5	205.33
	115	Sample 6	296.06
Dehydrated blood	115	Sample 7	51.81
	115	Sample 8	77.72
Viscera	161	Sample 9	59.35
	118	Sample 10	31.35
Viscera and raw blood	160	Sample 11	122.21
	116	Sample 12	156.32
Viscera and dehydrated blood	93	Sample 13	113.49
	168	Sample 14	131.19
Viscera, raw blood and sewage sludge	98	Sample 15	972.25
	53	Sample 16	189.27

In order to improve biogas production from samples such as viscera, co-digestion is important to compensate for anaerobic digestion inhibitors. Therefore, samples with mix of animal by-products as well as by-products alone were studied to seek energy recovery from all animal by-products converting waste into resources.

3.2.1.1 Rumen content

Rumen content samples have a one of the higher biogas productions per gram of volatile solids despite the fact that the weight of the added in the biodigester is less than other, only 15 g, due to low density. The distilled water volume was the same that other samples, then the organic load rate was lower than others.

The biogas accumulated production of these samples is shown in Figure 2, with a total period of 189 days approximately. Sample 2 was reactivated due to the drop of the pH value below 7.5 after 72 days. In contrast, for sample 1 the reactivation was not necessary. The accumulated volumes of biogas were of 1,094 and 690 mL/ g VS from samples 1 and 2, respectively.

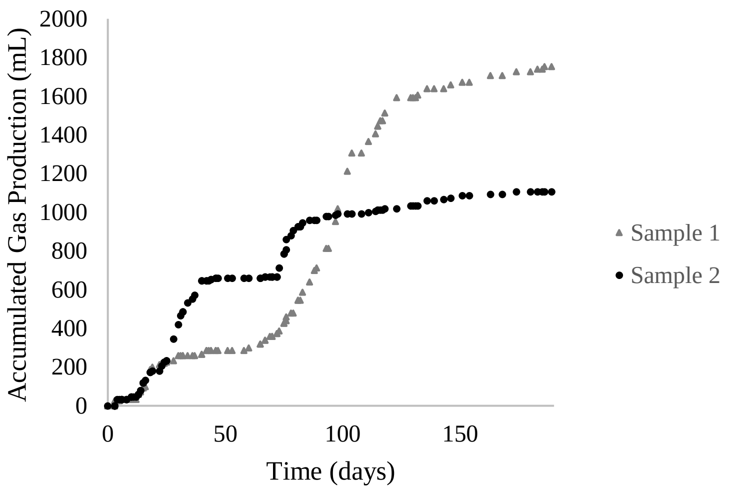

Figure 2. *Accumulated gas production for rumen content samples.*

3.2.1.2 Sewage sludge

In slaughterhouses, a large volume of water is used and as result a large amount of the by-product of water sewage sludge is produced.

In Figure 3, biogas accumulated production is shown with a total volume of 1,465 and 329 mL/g of VS, samples 3 and 4, respectively. In this period was not necessary the reactivation of the samples, but sample 4 stopped biogas production although its final pH was 8.35. An experimental error could explain this behaviour.

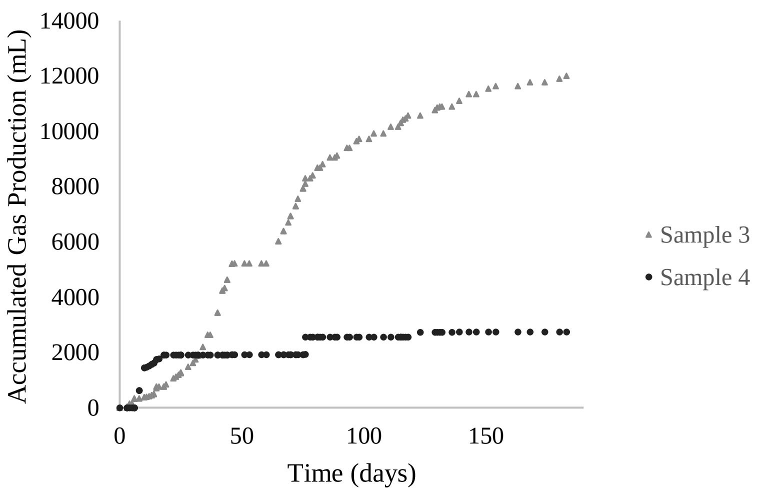

Figure 3*. Accumulated gas production for sewage sludge samples.*

3.2.1.3 Raw blood

Other animal by-products generation is blood and, its accumulated gas production is shown in Figure 4. Exponential growth can be seen in that samples in the first week followed by a more gradual increase. The gas production was 205 and 296 mL/g of VS, for samples 5 and 6, respectively. In the period of 115 days of digestion, no reactivation of samples was required.

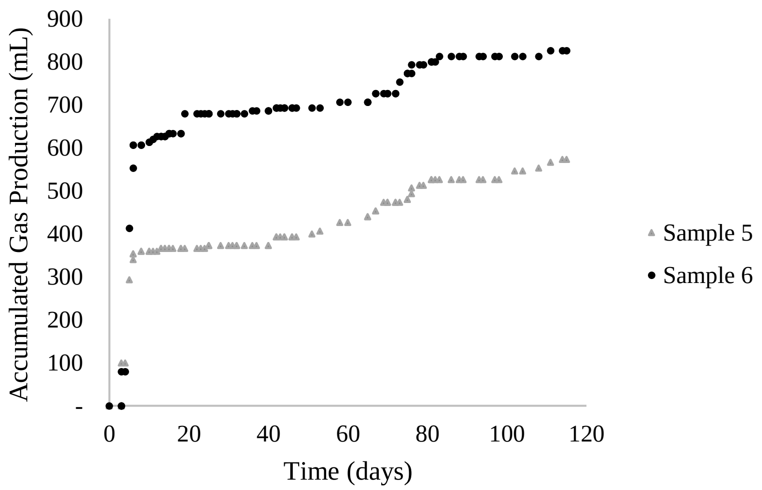

Figure 4. *Accumulated gas production* for raw blood samples.

3.2.1.4 Dehydrated blood

The dehydrated blood is the same blood as raw blood but it is pre-treated to remove moisture, so that its transport can be optimised, in additions to this, liquid waste cannot be taken to the landfill. The gas production was 51 and 77 mL/g of VS, for samples 7 and 8, respectively. The behaviour of these gas production is shown in Figure 5. It is observed that the gas production is higher during the first month approximately and then the gas production rate decreased. After 75 days both samples were reactivated but quickly inhibited and the production stopped.

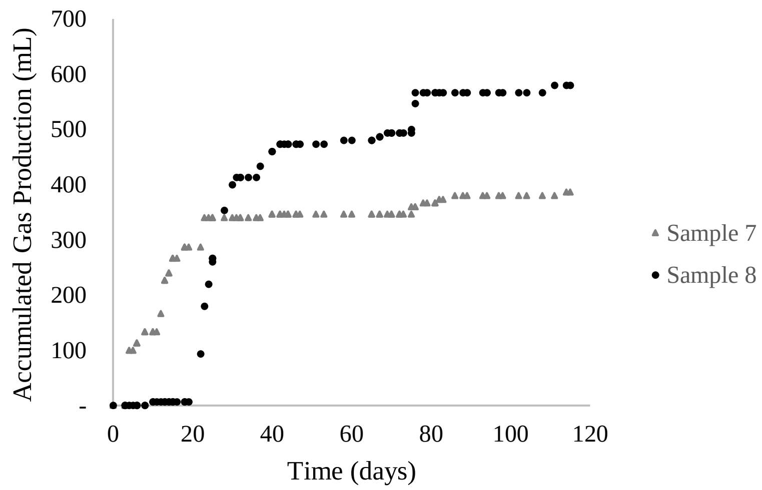

Figure 5. *Accumulated gas production of dehydrated blood samples.*

3.2.1.5 Viscera

This sample is a mix of the viscera of bovine, porcine, goat, ovine and rabbit. The accumulated gas production has an exponential initial behaviour similar to raw blood with a very fast initial production.

As shown in Figure 6, both samples are reactivated twice after 62 and 102 days, resulting in two changes in the gas production curve, with the first reactivation increasing gas production was higher than in the second. The gas production of viscera samples was 59 and 31 mL/g of VS for samples 9 and 10, respectively.

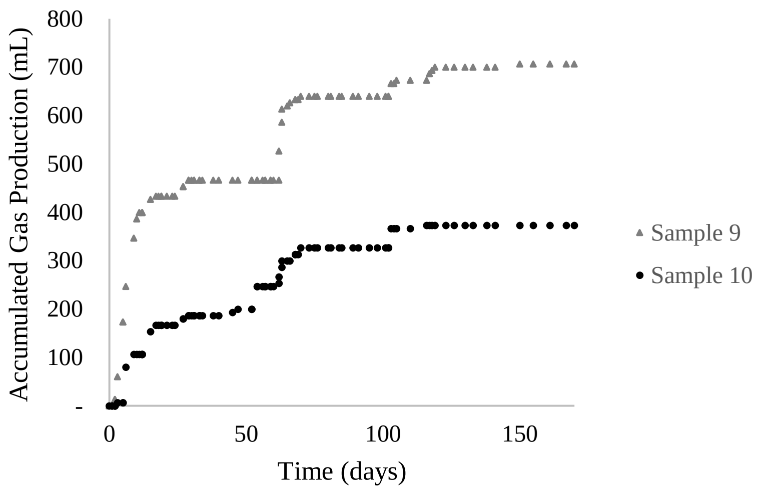

Figure 6. *Accumulated gas production for viscera samples.*

3.2.1.6 Viscera and raw blood

The co-digestion of viscera with raw blood can show the effect of the blood gas production with respect to viscera samples. Add blood to the viscera improve digestion because the gas production increase, but the growth rate was slower at the beginning and then it was higher than the viscera alone. In Figure 7 shows the behaviour of this mixtures. Both samples were reactivated after 61 days, but sample 12 remained nearly constant then, another agent other than pH could explain the momentary increase in gas production, that was 122 and 156 mL/g of VS, for samples 11 and 12, respectively.

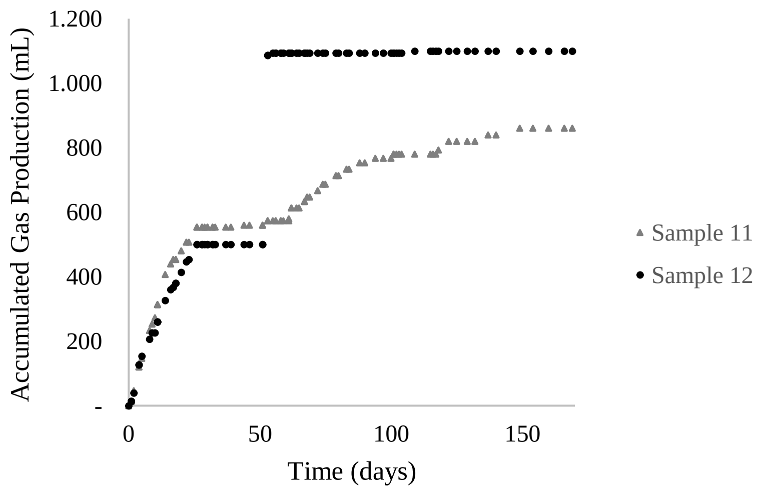

Figure 7. *Accumulated gas production for viscera and raw blood samples.*

3.2.1.7 Viscera and dehydrated blood

The behaviour of co-digestion of viscera with dehydrated blood is the same as that of only dehydrated blood, and the pre-treatment has a negative impact on gas production.

Because the pH is less than 7, both samples should be reactivated after 60 days. Then, gas production levelled off. After that, the gas production did not increase as much as the other samples.

The gas production of these mixtures was 113 and 131 mL/g of VS for samples 13 and 14, respectively. The production behaviour is shown in Figure 8, with an exponential gas growth on the first twenty days and then stabilized.

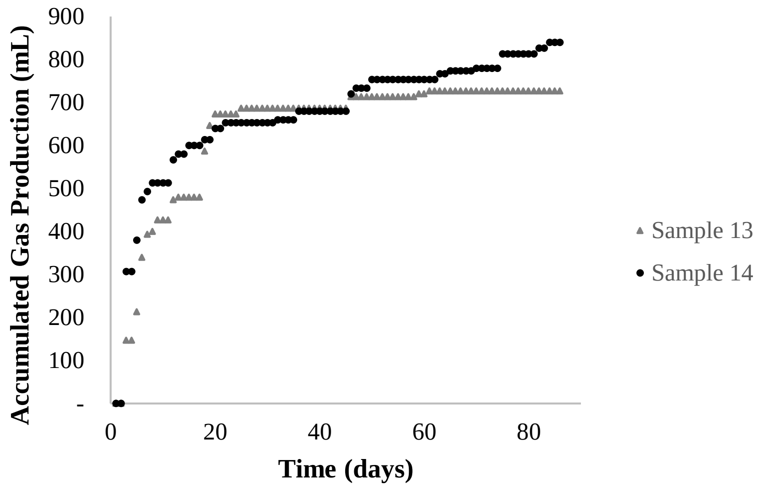

Figure 8. *Accumulated gas production for viscera and dehydrated blood samples.*

3.2.1.8 Viscera, raw blood and sewage sludge

In order to represent the digestion of all animal by-products generated in Tenerife was analysed this sample for the purpose of assess the energy potential allowing for the energy valorisation of these animal by-products.

The biogas production of these samples was 972 and 189 mL/g of VS, for sample 15 and sample 16, respectively. Sample 15 is the third sample with more biogas production and the only one of the co-digested samples in which more biogas was obtained. In comparison to viscera and raw blood mixture, in this case the gas production is slower and achieves high values. These samples, however, have produced for a long time without being reactivated. The behaviour of the biogas production is shown in the Figure 9, where there are some peaks of production that can be related with a self-adjustment of the ecosystem of methanogenic bacteria.

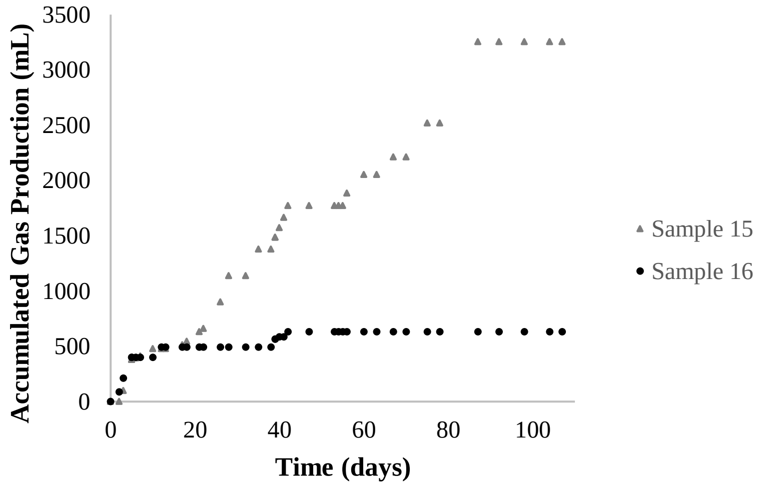

Figure 9. *Accumulated gas production for viscera, raw blood and sewage sludge samples.*

3.2.2 Gas composition

Table 7 shows the average methane composition obtained in this study.

Table 7. *Average and maximum methane composition obtained of each sample.*

Sample	***Average of methane composition (%)***	***Maximum methane composition (%)***
Rumen content	34.13	64.74
Sewage sludge	48.74	68.92
Raw blood	3.66	16.46
Dehydrated blood	0.04	0.18
Viscera	0.03	0.32
Viscera and raw blood	13.36	32.29
Viscera and dehydrated blood	3.14	28.31
Viscera, raw blood and sewage sludge	42.99	69.19

Only rumen content, sewage sludge, and the co-digestion of viscera and raw blood with sewage sludge produced biogas because its methane composition is higher than 55%. Therefore, they have the potential to be used to obtain electrical or thermal energy, because methane is a gas with a high energy potential. Currently, the rumen content with a high vegetal biomass composition is used in aerobic digestion as compost, and then it is used as a biofertilizer in agriculture. Although with anaerobic digestion the by-product is the same as biofertilizer, but this process generates energy too. Others, like raw blood, co-digestion of viscera with raw blood or co-digestion of viscera with dehydrated blood the methane concentration is lower than 55% as well. Samples that lead to lower methane, therefore gas rich in carbon dioxide can be used to transform this CO_2 to other products with higher energy value as dimethyl ether (BioDME), where the gas is converted to methanol with a catalytic process before BioDME production, additionally biomethanol (Bio-MeOH) also can be obtained.

3.2.3 Total, volatile and fixed solids

Solid analysis is necessary for determining the amount of degradation of organic materials.

Table 8 shows the solid analysis before and after digestion anaerobic process with total, fixed and volatile solids.

Table 8. *Solid content before and after anaerobic digestion.*

Sample	TS_{feed} (%)	FS_{feed} (%)	VS_{feed} (%)	TS_{out} (%)	FS_{out} (%)	VS_{out} (%)
Rumen content	93.5	8.0	92.0	6.6	19.4	80.6
Sewage sludge	97.5	20.4	79.6	14.5	34.6	65.4
Raw blood	22.3	4.2	95.8	2.1	43.8	56.2
Dehydrated blood	24.9	0.0	100.0	1.9	50.0	50.0
Viscera	42.7	3.6	96.4	3.3	50.0	50.0
Viscera and raw blood	38.2	2.6	97.4	3.0	33.3	66.7
Viscera and dehydrated blood	39.8	3.7	96.3	3.4	30.6	69.4
Viscera, raw blood and sewage sludge	46.8	12.6	87.4	5.4	24.5	75.5

From these data, the decrease in volatile solids can be calculated, which will give an idea of the degradation of the solids. The results obtained are presented in Table 9.

Table 9. *Decrease in volatile solids.*

Sample	***volatile waste (g /100g digestate)***	ΔVS (%)
Rumen content	5.32	93.82
Sewage sludge	9.48	87.78
Raw blood	1.18	94.48
Dehydrated blood	0.95	96.18
Viscera	1.65	95.99
Viscera and raw blood	2.00	94.63
Viscera and dehydrated blood	2.36	93.84
Viscera, raw blood and sewage sludge	4.08	90.03

Anaerobic digestion is a process in which organic material can be reduced, and the results show that the reduction is between 90.0 and 96.2%, been the higher for dehydrated blood and the lower for the mixture of viscera, raw blood and sewage sludge. Nevertheless Table 9 show that there are still a relative high proportion of volatile in the digestate to be able to continue the digestion process. The digestate with the highest proportion of volatile solids is the rumen content, although the one with the highest content of volatile solids per 100 grams of digestate is the sewage sludge.

Besides, anaerobic digestion by-products, the digestate, can be used like fertilizer in the agriculture in agreement progress with of the circular economy concept.

3.3 Energy production of biogas

From the point of view of energy recovery from biogas some of the samples used produce a gas with a methane composition greater than 55%, which can then be used to obtain thermal and electrical energy through cogeneration. In the case of slaughterhouses both types of energy are necessary and the biogas generated could be used. The energy can be estimated by the next equation:

$$E_{biogas} = C \times CH_4 \times P \times \eta \qquad (4)$$

where E_{biogas} is the quantity of electricity or heat energy produced (kWh/year); C represents the lower calorific value of methane, which was considered as 36 MJ (or 10 kWh) per cubic meter of methane (1 m^3 CH_4 = 36 MJ; 1 kWh = 3.6 MJ; 1 m^3 CH_4 = 10 kWh); CH_4 represents the methane content; P is the amount of biogas produced per year or the biogas potential as described in Eq. (4) (m^3/year); and η represents the overall efficiency of the conversion of biogas (%). It is noted that the η values (η_e or η_c) were considered as η_e = 25% (efficiency of heat-to-electricity conversion) and η_c = 80% (efficiency of the combustion process), respectively, for electric and thermal energies [40].

In this paper, the results from each sample were analysed to estimate the energy production using equation (4. Table 10 the estimation of energy production with co-generation, electrical and thermal energy. The samples mixture of the principal animal by-products (viscera, sewage sludge and raw blood) has the highest energy production transforming in a good alternative to reduce the waste generated in the slaughterhouse, allowing the generation of 499 MWh/year and 5,747 GJ/year electrical and thermal energy in 2019, respectively.

Table 10. *Energy estimation results obtained.*

Samples	*Electrical energy (kWh/year)*	*Electrical energy (MWh/year)*	*Thermal energy (MJ/year)*	*Thermal energy (GJ/year)*
Sewage sludge	333,034	333	3,836,552	3,837
Raw blood	397	0.40	4,571	4.57
Dehydrated blood	1,9	1.95E-03	22	0.02
Viscera	16	1.62E-02	186	0.19
Viscera and raw blood	14,063	14	162,002	162
Viscera and dehydrated blood	3,166	3	36,477	36
Viscera, raw blood and sewage sludge	498,876	499	5,747,051	5,747

Overall, the biological methane potential (BMP) is usually important in the anaerobic digestion analysis to characterize each waste. In this study, Table 11 shows the BMP for each sample in mL g VS^{-1} where the range of values is in the range from 49.5 to 650.9 $mLCH_4$ gVS^{-1} [41].

***Table 11**. Biochemical methane potential of each sample studied.*

Sample	***Methane production (mL/g VS)***
Rumen content	374
Sewage sludge	714
Raw blood	8
Dehydrated blood	-
Viscera	-
Viscera and raw blood	16
Viscera and dehydrated blood	4
Viscera, raw blood and sewage sludge	418

Currently, there are some studies on energy mix for self-sufficient slaughterhouse to reduce the impact of this industry on the environmental.

A part of the anaerobic digestion as manageable renewable energy due to biogas can be storaged. Although this renewable energy reduces emissions compared to other treatments, its emissions are not zero, so alternatives are sought to reduce the energy consumption needed to keep the reactor temperature constant. According to *Darwesh et. al.* the biogas production can use solar energy as its main energy source to provide the mesophilic temperatures needed for fermentation [42]. Other study used photovoltaic thermal technology, Concentrated Photovoltaic Thermal (CPVT) collectors, to produce electricity to upgrading biogas to biomethane and heat for heating the biodigester [43].

A part of this, in accordance with “Projected Costs of Generating Electricity 2020” the value of levelized cost of energy for photovoltaic is lowest price of low-carbon technologies to produce energy because it has had a huge fall in prices. Then, the mix of photovoltaic with biogas can be a good choice. In fact, according to the Photovoltaic Geographical Information System (PVGIS) at the location of the main slaughterhouses in Tenerife, the photovoltaic resource is very good with a monthly average global irradiation per square meter of 172 kWh/m2 with an optimal fixed slope of the modules of 23ºC.

To know the viability of this energy generation system, it is necessary to design the system following the energy demand of the slaughterhouses. If so, this system would make the meat industry more sustainable from an environmental and economic point of view.

4. Conclusions

The animal by-products have a potential for energy recovery through anaerobic digestion. As a result, this process is an approach to the treatment of waste dumped in landfills, avoiding transport and landfill emissions and financial expenses to pay an agent to carry out the transport of the goods. In addition, the blood does not have to submit to a thermal process because it does not improve the co-digestion of ABPs and energy would be wasted.

A mixture of the majority of animal by-products generated in Tenerife, with an estimation of 1,292 tonnes for 2019, and a proportion analysed in this text, generate a biogas production of 580 mL/g SV and a biochemical methane potential of 418 mL CH_4 / g SV. Afterwards, animal products will generate an average of 499 MWh/year and 5,747 GJ/year of electrical and thermal energy.

Overall, with this alternative of treatment of animal by-products converting this waste into a resource in the energy recovery to supply the meat industry energy demand, turning this industry into a more sustainable and more self-sufficiency favouring the circular economy.

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6. References

[1] R. Loganath and J. Senophiyah-Mary, "Critical review on the necessity of bioelectricity generation from slaughterhouse industry waste and wastewater using different anaerobic digestion reactors," *Renew. Sustain. Energy Rev.*, vol. 134, 2020, doi: 10.1016/j.rser.2020.110360.

[2] wwwreees, "Las energías renovables en el sistema eléctrico español 2019.," 2019.

[3] R. Medina-Mijangos and L. Seguí-Amórtegui, "Technical-economic analysis of a municipal solid waste energy recovery facility in Spain: A case study," *Waste Manag.*, vol. 119, pp. 254–266, 2021, doi: 10.1016/j.wasman.2020.09.035.

[4] "The Environmental Implementation Review 2019." Accessed: May 31, 2021. [Online]. Available: http://europa.eu.

[5] A. Sagastume Gutiérrez, J. J. Cabello Eras, L. Hens, and C. Vandecasteele, "The energy potential of agriculture, agroindustrial, livestock, and slaughterhouse biomass wastes through direct combustion and anaerobic digestion. The case of Colombia," *J. Clean. Prod.*, vol. 269, 2020, doi: 10.1016/j.jclepro.2020.122317.

[6] I. Moukazis, F.-M. Pellera, and E. Gidarakos, "Slaughterhouse by-products treatment using anaerobic digestion," *Waste Manag.*, vol. 71, pp. 652–662, 2018, doi: 10.1016/j.wasman.2017.07.009.

[7] "Sandach." https://www.gobiernodecanarias.org/ganaderia/temas/sandach/ (accessed May 29, 2021).

[8] O. E. C. Development and F. A. O. U. Nations, *OECD-FAO Agricultural Outlook 2020-2029*. FOOD \& AGRICULTURE ORGN, 2020.

[9] "Subproductos Animales No Destinados al Consumo Humano (SANDACH) y Residuos." https://www.miteco.gob.es/es/calidad-y-evaluacion-ambiental/temas/prevencion-y-gestion-residuos/flujos/sandach/ (accessed Jun. 05, 2021).

[10] "Animal by-products." https://ec.europa.eu/food/food/animal-products_en (accessed Jun. 05, 2021).

[11] "EU Rules." https://ec.europa.eu/food/food/animal-products/eu-rules_en (accessed Jun. 05, 2021).

[12] O. V. Okoro, Z. Sun, and J. Birch, "Meat processing waste as a potential feedstock for biochemicals and biofuels – A review of possible conversion technologies," *Journal of Cleaner Production*, vol. 142. pp. 1583–1608, 2017, doi: 10.1016/j.jclepro.2016.11.141.

[13] "BOE.es - BOE-A-2012-14165 Real Decreto 1528/2012, de 8 de noviembre, por el que se establecen las normas aplicables a los subproductos animales y los productos derivados no destinados al consumo humano." https://www.boe.es/buscar/doc.php?id=BOE-A-2012-14165 (accessed Jun. 05, 2021).

[14] H. Carrere *et al.*, "Review of feedstock pretreatment strategies for improved anaerobic digestion: From lab-scale research to full-scale application," *Bioresour. Technol.*, vol. 199, pp. 386–397, 2016, doi: 10.1016/j.biortech.2015.09.007.

[15] X. Liu, T. Lendormi, and J. L. Lanoisellé, "Overview of hygienization pretreatment for pasteurization and methane potential enhancement of biowaste: Challenges, state of the art and alternative technologies," *J. Clean. Prod.*, vol. 236, p. 117525, Nov. 2019, doi: 10.1016/j.jclepro.2019.06.356.

[16] K. Moustakas, M. Loizidou, M. Rehan, and A. S. Nizami, “A review of recent developments in renewable and sustainable energy systems: Key challenges and future perspective,” *Renew. Sustain. Energy Rev.*, vol. 119, 2020, doi: 10.1016/j.rser.2019.109418.

[17] S. M. Safieddin Ardebili, “Green electricity generation potential from biogas produced by anaerobic digestion of farm animal waste and agriculture residues in Iran,” *Renew. Energy*, vol. 154, pp. 29–37, 2020, doi: 10.1016/j.renene.2020.02.102.

[18] V. C. Hernández-Fydrych, G. Benítez-Olivares, M. A. Meraz-Rodríguez, M. L. Salazar-Peláez, and M. C. Fajardo-Ortiz, “Methane production kinetics of pretreated slaughterhouse wastewater,” *Biomass and Bioenergy*, vol. 130, 2019, doi: 10.1016/j.biombioe.2019.105385.

[19] I. Moukazis, F. M. Pellera, and E. Gidarakos, “Slaughterhouse by-products treatment using anaerobic digestion,” *Waste Manag.*, vol. 71, pp. 652–662, Jan. 2018, doi: 10.1016/j.wasman.2017.07.009.

[20] S. Borowski and P. Kubacki, “Co-digestion of pig slaughterhouse waste with sewage sludge,” *Waste Manag.*, vol. 40, pp. 119–126, 2015, doi: 10.1016/j.wasman.2015.03.021.

[21] P. W. Harris, T. Schmidt, and B. K. McCabe, “Evaluation of chemical, thermobaric and thermochemical pre-treatment on anaerobic digestion of high-fat cattle slaughterhouse waste,” *Bioresour. Technol.*, vol. 244, pp. 605–610, 2017, doi: 10.1016/j.biortech.2017.07.179.

[22] A. Hejnfelt and I. Angelidaki, “Anaerobic digestion of slaughterhouse by-products,” *Biomass and Bioenergy*, vol. 33, no. 8, pp. 1046–1054, Aug. 2009, doi: 10.1016/j.biombioe.2009.03.004.

[23] L. Morgadinho, C. Oliveira, and A. Martinho, “A qualitative study about perceptions of European automotive sector’s contribution to lower greenhouse gas emissions,” *J. Clean. Prod.*, vol. 106, pp. 644–653, 2015, doi: https://doi.org/10.1016/j.jclepro.2015.01.096.

[24] D. Yu, J. Liu, Q. Sui, and Y. Wei, “Biogas-pH automation control strategy for optimizing organic loading rate of anaerobic membrane bioreactor treating high COD wastewater,” *Bioresour. Technol.*, vol. 203, pp. 62–70, 2016, doi: 10.1016/j.biortech.2015.12.010.

[25] T. Schmidt, P. Harris, S. Lee, and B. K. McCabe, “Investigating the impact of seasonal temperature variation on biogas production from covered anaerobic lagoons treating slaughterhouse wastewater using lab scale studies,” *J. Environ. Chem. Eng.*, vol. 7, no. 3, 2019, doi: 10.1016/j.jece.2019.103077.

[26] R. Loganath and D. Mazumder, “Performance study on organic carbon, total nitrogen, suspended solids removal and biogas production in hybrid UASB reactor treating real slaughterhouse wastewater,” *J. Environ. Chem. Eng.*, vol. 6, no. 2, pp. 3474–3484, 2018, doi: 10.1016/j.jece.2018.05.031.

[27] A. E. Maragkaki, M. Fountoulakis, A. Gypakis, A. Kyriakou, K. Lasaridi, and T. Manios, “Pilot-scale anaerobic co-digestion of sewage sludge with agro-industrial by-products for increased biogas production of existing digesters at wastewater treatment plants,” *Waste Manag.*, vol. 59, pp. 362–370, 2017, doi: 10.1016/j.wasman.2016.10.043.

[28] E. Salminen and J. Rintala, “Anaerobic digestion of organic solid poultry slaughterhouse waste - A review,” *Bioresour. Technol.*, vol. 83, no. 1, pp. 13–26, 2002, doi: 10.1016/S0960-8524(01)00199-7.

[29] M. Khalil, M. A. Berawi, R. Heryanto, and A. Rizalie, “Waste to energy technology: The potential of sustainable biogas production from animal waste in Indonesia,” *Renewable and Sustainable Energy Reviews*, vol. 105. pp. 323–331, 2019, doi:

10.1016/j.rser.2019.02.011.

[30] C. Mao, Y. Feng, X. Wang, and G. Ren, “Review on research achievements of biogas from anaerobic digestion,” *Renewable and Sustainable Energy Reviews*, vol. 45. Elsevier Ltd, pp. 540–555, May 01, 2015, doi: 10.1016/j.rser.2015.02.032.

[31] M. Ortner, D. Wöss, A. Schumergruber, T. Pröll, and W. Fuchs, “Energy self-supply of large abattoir by sustainable waste utilization based on anaerobic mono-digestion,” *Appl. Energy*, vol. 143, pp. 460–471, 2015, doi: 10.1016/j.apenergy.2015.01.039.

[32] Á. Rodríguez-Abalde, X. Flotats, and B. Fernández, “Optimization of the anaerobic co-digestion of pasteurized slaughterhouse waste, pig slurry and glycerine,” *Waste Manag.*, vol. 61, pp. 521–528, Mar. 2017, doi: 10.1016/j.wasman.2016.12.022.

[33] P. A. Cremonez, J. G. Teleken, T. R. Weiser Meier, and H. J. Alves, “Two-Stage anaerobic digestion in agroindustrial waste treatment: A review,” *Journal of Environmental Management*, vol. 281. Academic Press, p. 111854, Mar. 01, 2021, doi: 10.1016/j.jenvman.2020.111854.

[34] “BOC - 2018/112. Martes 12 de Junio de 2018 - Anuncio 2760.” http://www.gobiernodecanarias.org/boc/2018/112/004.html (accessed Jun. 06, 2021).

[35] A. Sagastume Gutiérrez, J. J. Cabello Eras, L. Hens, and C. Vandecasteele, “The energy potential of agriculture, agroindustrial, livestock, and slaughterhouse biomass wastes through direct combustion and anaerobic digestion. The case of Colombia,” *J. Clean. Prod.*, vol. 269, p. 122317, Oct. 2020, doi: 10.1016/j.jclepro.2020.122317.

[36] M. M. Ali, M. Ndongo, B. Bilal, K. Yetilmezsoy, I. Youm, and M. Bahramian, “Mapping of biogas production potential from livestock manures and slaughterhouse waste: A case study for African countries,” *J. Clean. Prod.*, vol. 256, 2020, doi: 10.1016/j.jclepro.2020.120499.

[37] “Ch03.” http://www.fao.org/3/x5082e/X5082E03.htm (accessed Jun. 13, 2021).

[38] “2540 SOLIDS*.” http://edgeanalytical.com/wp-content/uploads/Inorganic_SM2540.pdf (accessed Jun. 30, 2021).

[39] “Sacrificio de ganado en Canarias.” https://www.gobiernodecanarias.org/agp/sgt/temas/estadistica/ganaderia/sacrificio.html (accessed Jun. 30, 2021).

[40] M. M. Ali, M. Ndongo, B. Bilal, K. Yetilmezsoy, I. Youm, and M. Bahramian, “Mapping of biogas production potential from livestock manures and slaughterhouse waste: A case study for African countries,” *J. Clean. Prod.*, vol. 256, May 2020, doi: 10.1016/j.jclepro.2020.120499.

[41] A. Ware and N. Power, “Biogas from cattle slaughterhouse waste: Energy recovery towards an energy self-sufficient industry in Ireland,” *Renew. Energy*, vol. 97, pp. 541–549, 2016, doi: 10.1016/j.renene.2016.05.068.

[42] M. R. Darwesh and M. S. Ghoname, “Experimental studies on the contribution of solar energy as a source for heating biogas digestion units,” *Energy Reports*, vol. 7, pp. 1657–1671, Nov. 2021, doi: 10.1016/j.egyr.2021.03.014.

[43] B. Su, H. Wang, X. Zhang, H. He, and J. Zheng, “Using photovoltaic thermal technology to enhance biomethane generation via biogas upgrading in anaerobic digestion,” *Energy Convers. Manag.*, vol. 235, p. 113965, May 2021, doi: 10.1016/j.enconman.2021.113965.