Chapter 2

# The Potential for Biogas Production from Agriculture Wastes in Mexico

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75457

**Abstract**

An important objective of the Mexican Energy National Strategy (ENS) is to produce around 35% of energy from clean technologies in 2024. This goal implies challenges from scientific and technologic perspectives. Besides solar and wind energies, different initiatives have been implemented to promote biofuels, mainly, biodiesel, bioethanol and biogas. Agriculture and livestock wastes are being used as biogas source to produce energy in small and medium scale. Also, some industries use biogas to provide a part of the energy required in their processes. But in general, the potential of biomethane production is not well seized yet. In the context of the ENS, biogas should be considered as an important topic due to the existence of several economical activities producing a lot of organic wastes. In this document, an analysis of the biogas from agricultural wastes is performed in order to identify the current status and opportunities for the next years.

**Keywords:** waste to methane, biofuel, agri-waste

## 1. Introduction

### 1.1. Objective of this study

The main sources of energy in Mexico are fossil fuels since there are, in some regions of the country, important reserves of oil, natural gas and even shale gas. However, from some years ago, a recurrent concern is the depletion of fossil fuels and the necessity of alternatives to provide the increasing energy demand.

From some years ago, renewable sources are considered as a real alternative to deal with the society requirements. In 2010, the National Strategy for Energy (NSE) has been designed in order to state directives concerning the generation and management of the energy. An important objective of this strategy is to produce around 35% of energy from clean technologies in 2024. This goal implies challenges from scientific and technologic perspectives. Besides solar and wind energies, different initiatives have been implemented to promote biofuels, mainly, biodiesel, bioethanol and biogas. Agriculture and livestock wastes are being used as biogas source to produce energy in small and medium scale. Also, some industries use biogas to provide a part of the energy required in their processes. But, in general, the potential of biomethane production is not well seized yet. In the context of the ENS, biogas should be considered as an important topic due to the existence of several economical activities producing a lot of organic wastes.

In this work, an analysis of the biogas from agricultural wastes is performed in order to identify the current status and opportunities for the next years in Mexico. Agriculture is an economic activity all around the country; besides products (fruits, vegetable, fodder), a large amount of wastes is generated in each stage of this activity: raising, harvesting and distribution. Only in the harvesting, it is estimated a production of 75 Mt of agricultural wastes. Many of them are traditionally used as fodder; some others are left in crop lands in order to promote the soil recovery and to improve the soil production. A few of them are studied as raw material to synthesize chemical products at industrial level. Then, only a small part of agricultural wastes is available as raw material for biogas production. However, it is necessary to assess the biomethane potentials in the national and international energy context.

### 1.2. Anaerobic digestion for biogas production

Anaerobic digestion (AD) is the process for wastes transformation into biogas. It is a natural mechanism of Earth to re-integrate organic wastes into the ecosystem dynamics. This process has been studied from many years ago, nowadays is well known and it is an active scientific topic [1–3]. AD is developed by many interdependent micro-organism communities, living in an environment free of oxygen, to transform complex substrates in four main stages: hydrolysis, acetogenesis, acidogenesis and methanogenesis; each stage has specific dynamics and three main phenomena are involved: physicochemical, hydrodynamic and biological. In optimal conditions, AD produces a biogas mainly composed of methane (50–80%) and carbon dioxide (48–18%); depending on the substrate, some other components ($NO_x$, $SO_x$) are also present in low concentration (1–2%).

It has been determined that hydrolysis and methanogenesis are the limiting steps of AD. Hydrolysis is the stage where most complex substrates should be transformed, if there is an excess of complex molecules, the hydrolytic bacteria may become saturated and then inhibited; a consequence of this situation is the stopping of the complete AD process. On the other side, methanogenesis is the slowest stage and then the most important for the process stability; it is very sensitive to variations in the operating conditions such as: pH, temperature, overload on substrate concentration, etc. Then, these two stages receive special attention in order to improve them and consequently enhance the global methane production yields.

AD imposes several challenges in different aspects of the process; some of them, which are specially related to transformation of agriculture wastes, are [3–6]:

- Wastes composition
- Combination of substrates for co-digestion
- Development on solid-state anaerobic digestion
- Reduction of inhibitory components.

## 2. Methods

The information used to develop the analysis was taken from official organisms such as:

- Ministry of Environment and Natural Resources (SEMARNAT)
- Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA)
- Agrifood and Fisheries Information Service (SIAP)
- Ministry of Energy (SENER)
- Federal Electricity Board (CFE)
- National Water Board (CONAGUA)
- National Institute of Statistics and Geography (INEGI).

Also, a workshop was organized in order to verify and complement the official information; the participants of the workshop were specialized people such as industrialists, farmers and stockbreeders from different regions of the country.

Four topics were considered in order to assess the biogas situation as follows:

**a.** Feedstock. The production of agriculture wastes is computed from data provided by official organisms (usually until 2015). Three kinds of wastes are included since it is considered that its gathering is technically and economically feasible: i) rising and harvest wastes: products which are lost in the raising and harvest due to mechanical damages or products selection, ii) postharvest wastes: products that do not reach the market standards or that perish before the sell points and iii) foliage: biomass and all organic matter which is leaved in soil in the harvest stage.

**b.** Potential for biogas production. The assessment of the energy potential is done considering the amount of wastes and the efficiency reported from experiments of biogas transformation in different regions of the country; when this efficiency is unknown a typical one (from specialized literature) is used.

**c.** Technology for biogas utilization. The mechanisms currently used for biogas utilization were obtained directly from users.

**d.** Perspectives. Alternatives and strategies to implement systematically the biogas technology are presented.

## 3. Results and discussion

### 3.1. Feedstock

The available surface for agriculture in Mexico is around 27 Mha and it is distributed all around the country. Due to the weather and geographic conditions, a large diversity of plants is raised: fruits, vegetables, grains, ornamental plants, etc. According with the SIAP, there were 326 crops in 2015 with a global production of around 677.76 Mt.

A relative classification of these products is presented in **Figure 1**. The most abundant are fruits and ornamental plants: 69 different kinds of fruits are raised, corresponding to 22% of the agriculture products; a similar amount is obtained for ornamental plants. Besides, the categories vegetables and grain and seeds concentrate 32% of products, aromatic herbs and fodder correspond to 15%. The item Other includes products such as agave, Christmas tree

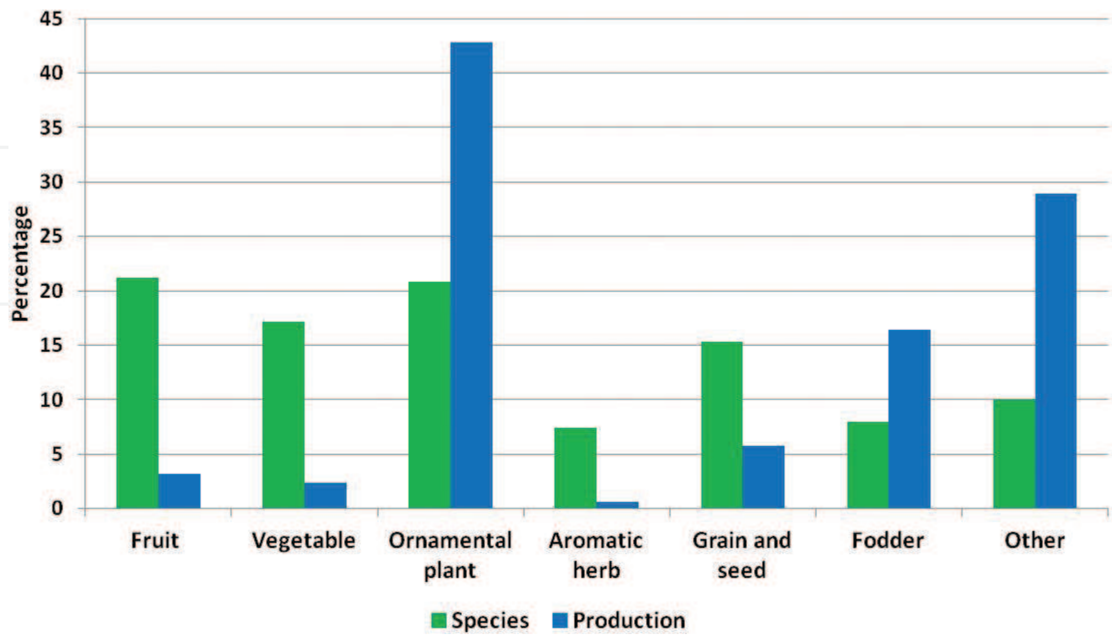


**Figure 1.** Relative classification of products from agriculture in Mexico.

and medicinal plants. Concerning the mass production, 290 Mt of ornamental plants were obtained in 2015, which correspond to the 40% of the total agriculture production in that year.

The categories which are not considered as raw material for biomethane production are Aromatic herb, Grain and seed, Fodder and Other. The reason for this exception is since either the wastes production is negligible (the case of most of aromatic herbs) or the wastes are used for specific applications. For example, most of wastes from grains crops are used as fodder. Also, most of those wastes are hard to be transformed into biogas due to the low moisture and high fiber content.

Although it is possible to transform these kinds of wastes into biogas by anaerobic digestion, they are better situated for other type of processes, such as thermochemical ones (combustion, pyrolysis and gasification), or fermentation with a previous treatment.

As said before, although there is a large production of wastes, only a fraction of them could be available for biomethane production. In the case of aromatic herbs, almost all the plant is profitable; that means, the organic wastes production is negligible. Besides, most of wastes from grains and seeds crops are used as fodder either in small or large scale. Also, an amount of the produced wastes from crops of fruits, vegetables and even fodder are left in the soil in order to protect the surface and to keep the productivity. In addition, it is not possible to collect all the produced wastes.

Then, a selection of crops was done considering the generation of wastes, the feasibility to collect them and its suitability to be transformed into biogas. On the basis of these criteria, 36 species were considered as source of wastes for biomethane production. The selected species are among fruits, vegetables and ornamental plants.

An estimation of the wastes production from these crops is done by using Eq. (1).

$$AW = AP \cdot WF \tag{1}$$

where $AW$ is the agricultural wastes, $AP$ is the agricultural production and $WF$ is a waste factor which determines the amount of wastes produced from a specific crop. Then, the total waste production ($AW_T$) is obtained with:

$$AW_T = \sum_i AP_i \cdot WF_i \tag{2}$$

The respective waste factors were deduced from information reported in different works [7–14]. Based on an analysis of the reported information, in this work a general formula to calculate the waste factors is proposed as follows:

$$WF = 0.5 \cdot W_H + 0.5 \cdot W_{PH} + 0.6 \cdot W_{FB} \tag{3}$$

where $W_H$ represents the wastes obtained in the harvesting stage, $W_{PH}$ the wastes generated in the post-harvest stage and $W_{FB}$ the wastes from plants foliage. It has been considered that 50% of the wastes from harvest and post-harvest stage are available for biogas production; the other 50%

could be used as traditionally. Besides, foliage which could be collected and transformed into biogas is around 60% and the other 40% can be used as nowadays. The amount of foliage ($W_{FB}$) is computed on the basis of the harvesting index, which relates the total biomass in a plant [14–16]. The wastes generated in the post-harvesting stage ($W_{PH}$) are estimated according with [7]. Also, the next expression to estimate the wastes from harvesting stage is proposed:

$$W_H = P \cdot \left(\frac{100}{100 - WI} - 1\right) \quad (4)$$

*WI* is the waste index, which is deduced from information reported in [7].

The information corresponding to the agricultural wastes produced from the selected species is presented in **Table 1**.

The Production column contains the reported production on the official records of SIAP. The Harvest, Post-harvest and Foliage columns include the estimation of wastes on the corresponding stage. The last column presents the estimation of wastes available for biogas production. A total of 12.7 Mt of wastes from the considered crops was estimated. This amount could provide either fuel or electricity to cover a fraction of the energy demand in the agriculture activities, as shown below.

### 3.2. Potential for biogas production

There exist different works related to biogas production from agriculture wastes [17–24], the yield depends on specific operating conditions and raw materials. In order to ease the data processing, in this study, the estimation of the biogas production from the selected agriculture wastes is done by following an experimental method developed for energy production from wastes in an herbalist facility [25]. This is based on the total solids, the biodegradable solids on the raw material (the fraction of biomass which can be transformed into biogas by anaerobic bacteria) and a conversion efficiency factor. Then, the estimation of biogas is done with the next equation:

$$V_{biogas} = \gamma \cdot VBS \quad (5)$$

where $V_{biogas}$ is the estimated biogas production, $VBS$ the biodegradable volatile solids in the raw material and $\gamma$ the conversion efficiency factor. $VBS$ are computed as follows:

$$VBS = \alpha_1 \cdot \alpha_2 \cdot TS \quad (6)$$

where $TS$ is the total solids and $\alpha_1$ and $\alpha_2$ are coefficients related to the fraction of volatile solids in total solids and the fraction of biodegradable solids in volatile solids, respectively.

On the other side, the estimation of the energy content on the produced biogas is done considering a concentration of 50% of methane. This value is easily reached in anaerobic digestion processes. The equation to obtain the potential of energy generation ($E_{biogas}$) is:

$$E_{biogas} = CH_4 \cdot HV_{methane} \cdot V_{biogas} \quad (7)$$

http://dx.doi.org/10.5772/intechopen.75457

| Species | Production | Harvest | Post-harvest | Foliage | Available |
|---|---|---|---|---|---|
| Apple | 750324.85 | 187581.21 | 60025.99 | | 123803.60 |
| Apricot | 1086.55 | 271.64 | 86.92 | | 179.28 |
| Asparagus | 198075.04 | 49518.76 | 15846.00 | 222315.00 | 166071.38 |
| Avocado | 1644225.86 | 411056.47 | 131538.07 | | 447229.43 |
| Banana | 2262028.25 | 565507.06 | 180962.26 | | 615271.68 |
| Broccoli | 449185.37 | 112296.34 | 35934.83 | 1310124.00 | 908252.82 |
| Dragon fruit | 4542.28 | 1135.57 | 363.38 | | 1235.50 |
| Cabbage | 226702.39 | 56675.60 | 18136.19 | 343680.00 | 267871.05 |
| Cauliflower | 68832.29 | 17208.07 | 5506.58 | 5490.43 | 22016.64 |
| Carrot | 318365.81 | 47571.90 | 41387.56 | 314500.00 | 264006.32 |
| Chayote | 163743.50 | 40935.88 | 13099.48 | 66525.00 | 84453.23 |
| Courgette | 456570.28 | 114142.57 | 36525.62 | 658025.00 | 519002.12 |
| Cucumber | 817799.83 | 204449.96 | 65423.99 | 658025.00 | 617256.55 |
| Grapefruit | 424315.36 | 106078.84 | 33945.23 | | 115413.78 |
| Green tomato | 683984.96 | 170996.24 | 54718.80 | 1681234.00 | 1194784.31 |
| Guava | 294422.68 | 73605.67 | 23553.81 | | 80082.97 |
| Lettuce | 437561.70 | 109390.43 | 35004.94 | 30356.80 | 137230.86 |
| Mammee apple | 18321.03 | 4580.26 | 1465.68 | | 4983.32 |
| Mandarin orange | 291078.27 | 72769.57 | 23286.26 | | 79173.29 |
| Mango | 1775506.77 | 443876.69 | 142040.54 | | 482937.84 |
| Melon | 561891.31 | 140472.83 | 44951.30 | 457650.00 | 427424.44 |
| Ornamental plants | 358799.76 | | | 71759.95 | 71759.95 |
| Orange | 4515520.33 | 1128880.08 | 361241.63 | | 1228221.53 |
| Papaya | 883592.54 | 220898.14 | 70687.40 | | 240337.17 |
| Peach | 176302.74 | 44075.69 | 14104.22 | | 47954.35 |
| Pear | 24679.04 | 6169.76 | 1974.32 | | 6712.70 |
| Pineapple | 840486.46 | 210121.62 | 67238.92 | | 228612.32 |
| Plum | 72206.82 | 18051.71 | 5776.55 | | 19640.26 |
| Potato | 1727345.51 | 258109.10 | 224554.92 | 1228180.00 | 1145494.70 |
| Prickly pear cactus | 408445.05 | 102111.26 | 32675.60 | | 111097.05 |
| Rambutan | 8840.97 | 2210.24 | 707.28 | | 2404.74 |
| Sapota | 17167.30 | 4291.83 | 1373.38 | | 4669.51 |
| Spinach | 39738.91 | 9934.73 | 3179.11 | | 10808.98 |

| Species | Production | Harvest | Post-harvest | Foliage | Available |
|---|---|---|---|---|---|
| Soursop | 16620.91 | 4155.23 | 1329.67 | | 4520.89 |
| Strawberry | 392625.19 | 98156.30 | 31410.02 | 99650.00 | 166584.05 |
| Tangerine | 195111.08 | 48777.77 | 15608.89 | | 53070.21 |
| Tomato | 3098329.41 | 774582.35 | 247866.35 | 1936556.00 | 2004679.20 |
| Watermelon | 1020268.73 | 255067.18 | 81621.50 | 863525.00 | 795628.09 |
| **Total** | **25644645.13** | **6115714.51** | **2125153.20** | **9947596.18** | **12700876.13** |

**Table 1.** Production of wastes from agriculture (t).

where $CH_4$ is the methane concentration in biogas and $HV_{methane}$ is the heat value of pure methane, which is 8840 kcal (36.9 MJ). The results of this estimation are presented in **Table 2**.

The biogas which could be produced from these agricultural wastes is estimated on 4953 × $10^9$ $m^3$ and the energy content is around 100 GJ. The production of electricity considering typical efficiency of internal combustion engines and electric generators is around 8300 GWh. This amount of energy is a little value in comparison of the total primary consumption in the country, which is near to 11,000 PJ per year. However, a systematic transformation of biomass for biogas production could be an interesting alternative not only for the energy generation but also for the environmental sector since it represents a mechanism for wastes management.

At present time, different biogas processes have been identified at different production scales. Some examples of them are shown in **Table 3**.

### 3.3. Technology

Biogas is a versatile fuel which can be transformed into energy by following different pathways [26, 27]. **Figure 2** includes a schematic representation of the biogas applications in the context of agriculture wastes transformation.

Thermal and electrical energy are the main alternatives to take advantage of biogas. The former can be employed for heating services either in farms or in residential applications; also, it can be used as energy source for food cooking and even for lighting through lamps fueled by biogas. The last one can be used to provide energy for household applications. In a larger scale, it is feasible to inject it to the national energy grid in order to be managed by the National Energy Board in Mexico (CFE); this is nowadays possible thanks to the recent modifications to the energy management laws. In next paragraphs, technologies currently used, and some alternatives, to profit the biogas potentials in Mexico are briefly described.

#### *3.3.1. Thermal energy*

Thermal energy is obtained from a biogas combustion process; the technology depends on the final applications. Among the alternatives, it is possible to find burners, stoves and lamps.

| Species | Wastes (t) | Biogas (m³) | Energy (MJ) |
|---|---|---|---|
| Apple | 123803.60 | 48283404.10 | 979911686.16 |
| Apricot | 179.28 | 69919.49 | 1419016.10 |
| Asparagus | 166071.38 | 64767838.82 | 1314463288.93 |
| Avocado | 447229.43 | 174419479.23 | 3539843330.95 |
| Banana | 615271.68 | 239955956.76 | 4869906142.44 |
| Broccoli | 908252.82 | 354218599.07 | 7188866468.22 |
| Dragon fruit | 1235.50 | 481845.06 | 9779045.54 |
| Cabbage | 267871.05 | 104469709.53 | 2120212754.94 |
| Cauliflower | 22016.64 | 8586490.41 | 174262822.90 |
| Carrot | 264006.32 | 102962465.54 | 2089623238.04 |
| Chayote | 84453.23 | 32936760.48 | 668451553.94 |
| Courgette | 519002.12 | 202410825.30 | 4107927699.51 |
| Cucumber | 617256.55 | 240730055.97 | 4885616485.84 |
| Grapefruit | 115413.78 | 45011373.39 | 913505822.93 |
| Green tomato | 1194784.31 | 465965880.56 | 9456777545.90 |
| Guava | 80082.97 | 31232357.89 | 633860703.47 |
| Lettuce | 137230.86 | 53520036.34 | 1086189137.44 |
| Mammee apple | 4983.32 | 1943494.86 | 39443228.23 |
| Mandarin orange | 79173.29 | 30877582.88 | 626660544.58 |
| Mango | 482937.84 | 188345758.16 | 3822477161.89 |
| Melon | 427424.44 | 166695530.16 | 3383085784.69 |
| Ornamental plants | 71759.952 | 27986381.28 | 567983608.08 |
| Orange | 1228221.53 | 479006396.61 | 9721434819.13 |
| Papaya | 240337.17 | 93731496.64 | 1902280724.37 |
| Peach | 47954.35 | 18702194.66 | 379561040.61 |
| Pear | 6712.70 | 2617952.56 | 53131347.27 |
| Pineapple | 228612.32 | 89158803.68 | 1809477920.62 |
| Plum | 19640.26 | 7659699.47 | 155453600.65 |
| Potato | 1145494.70 | 446742934.57 | 9066647857.10 |
| Prickly pear cactus | 111097.05 | 43327850.90 | 879338734.10 |
| Rambutan | 2404.74 | 937850.10 | 19033667.73 |
| Sapota | 4669.51 | 1821107.18 | 36959370.30 |
| Spinach | 10808.98 | 4215503.57 | 85553645.01 |
| Soursop | 4520.89 | 1763146.13 | 35783050.77 |

| Species | Wastes (t) | Biogas ($m^3$) | Energy (MJ) |
|---|---|---|---|
| Strawberry | 166584.05 | 64967780.16 | 1318521098.25 |
| Tangerine | 53070.21 | 20697383.37 | 420053395.42 |
| Tomato | 2004679.20 | 781824887.81 | 15867136098.16 |
| Watermelon | 795628.09 | 310294956.88 | 6297436149.85 |
| **Total** | **12700876.13** | **4953341689.58** | **100528069590.05** |

**Table 2.** Estimation of the biogas production from agricultural wastes.

| Raw material | Escala | Potential biogas ($m^3$ $m^3$) | Potential electricity kWh $m^{-3}$ |
|---|---|---|---|
| Mango wastes | Laboratory | 3.14 | 7.74 |
| Residuos de cultivo de jitomate | Laboratory | 0.911 | 2.24 |
| Residuos de papaya | Semi-pilot | 1.59 | 3.92 |
| Residuos de plátano | Semi-pilot | 4.6 | 11.35 |
| Residuos de brócoli | Pilot | 40 | 100 |
| Nopales | Commercial | 68.75 | 197 |
| Algas | Laboratory | 85.5 | 85.7 |

**Table 3.** Processes for biogas production from agriculture wastes identified in Mexico.

*3.3.1.1. Burners*

There exist commercial biogas burners which provide heat in conditioning thermal systems. For example, EcoFlam and Sayercen. EcoFlam is an Italian enterprise offering medium- and large-scale burners employing gaseous fuels including biogas. The thermal power is ranged from 7 kW to 25 MW. They can be easily adapted for households and industrial applications such as boilers, calefaction and drying systems, furnaces, greenhouses and heat regeneration systems, among others. Besides, Sayercen is a Mexican enterprise focused on the management of organic wastes in farms for production and utilization of biogas. They have integrated different technologies to produce, heat, steam and flames which are employed in farms and slaughterhouses.

In addition, biogas could be used by devices designed for natural gas applications; in this case, the injection conditions should be modified. Due to the different composition and lower calorific value of biogas, a larger input flow is required; also, the air content should be more than 20% and the pressure should be among 7 and 20 mbar.

*3.3.1.2. Stoves*

Biogas stoves are an interesting alternative for small facilities, e.g. rural towns and small farms. There are not national commercial devices, but there exist different Chinese organizations, such as Puxin, Xunda, Huamei and Taiyangyan, offering biogas stoves.

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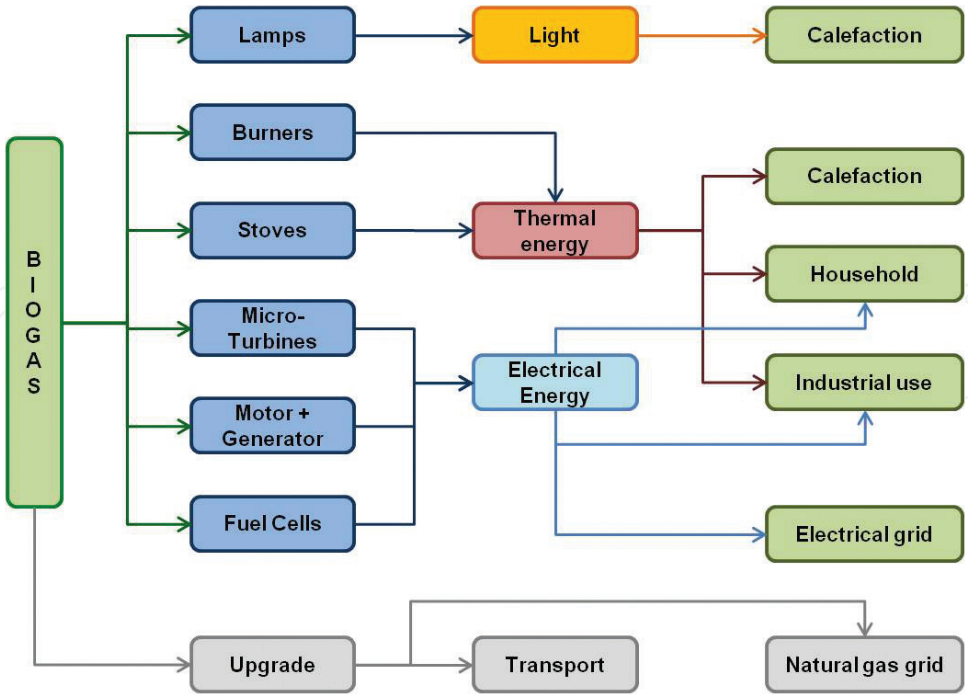


**Figure 2.** Biogas to energy alternatives.

On the other side, the adaptation of natural gas stoves to biogas is not complex [27]. Two alternatives are identified in order to allow the biogas to produce a similar flame as the one from natural gas: adaptation or replacement of burners. First one requires to increase the diffuser vent diameter and to regulate (decrease) the air in the mix biogas/air to reach a good flame quality. Replacement of burner implies also a replacement of the biogas pipeline; either stainless steel or PVC pipes are better situated for biogas flows since they are more tolerant to corrosive elements on biogas. As for the previous case, it is necessary to regulate the relation biogas/air.

### 3.3.2. Lighting

Lighting is produced by biogas lamps. Its efficiency is low (30–50%); however, this is a good alternative to facilities outside the national electrical grid coverage, and also for some specific situations in farms. Light is produced from the luminosity properties of materials such as lanthanum, cerium and thorium when they are exposed to high temperature (provided in this case from the biogas combustion). With these materials, it is possible to obtain light in the range of 400 and 500 lm, which is similar to 25–75 W. There are some commercial alternatives of biogas lamps, such as Puxin, Xunda, Taiyangyan, Rupak and Huamei. Coleman offers a variety of gas lamps, which could be adapted for biogas.

### 3.3.3. Electrical energy

Electricity from biogas can be obtained by two alternatives: electromechanical systems and electrochemical devices. Electromechanical systems require the combustion of fuels to produce mechanical energy which is transformed in electricity by the electromagnetic induction

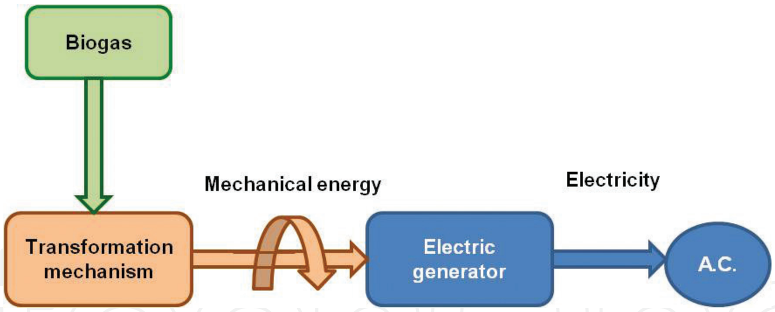


**Figure 3.** Electricity production from electromechanical devices.

principle (**Figure 3**). The alternatives for biogas transformation into mechanical are internal combustion engines, Stirling engines and turbines. In Mexico, internal combustion engines are preferred for electricity generation in comparison with the other two options.

*3.3.3.1. Internal combustion engines*

These engines have been studied from many years ago. They operate under the ignition by compression (Diesel cycle) or spark (Otto cycle).

The oil and diesel engines are modifiable to operate with biogas [28]. The injection system should be adapted to allow a larger gas flow and reach the adequate relation in the mixture fuel/air. In addition, it is necessary to synchronize the injection with the compression stage. Another alternative is to purify biogas in order to separate the $CO_2$ and to allow the methane to be the only component in the mix fuel/air for the thermodynamic cycle.

There are several commercial biogas engines for electricity generation. In Mexico, the most used are Mopesa, Cummins (adapted), Guascor and Jenbacher:

- Mopesa offers power plants of 30 and 60 kW, 220 V and 60 Hz known as Econogas Power Plants; the first system includes a 4.07 L 4 cyl biogas engine coupled to a synchronous generator of 30 kW; the second one uses a 5.8 L 6 cyl biogas engine with a 60 kW synchronous generator.
- Cummins. Diesel engines have been adapted to operate with biogas and they are connected to Marathon electric generators; the power is ranged among 40 and 100 kW and they are designed to be connected to the federal grid. The required biogas should content at least 55% of methane in order to reach the claimed efficiency.
- Guascor. These engines have been designed specifically to operate with biogas. The power capacity is ranged from 150 to 1240 kW. The biogas Guascor engines have been implemented in cogeneration or single generation configurations.
- GE-Jenbacher. Even if these engines are designed to operate with biogas from landfills and wastewater treatment plants, they are an alternative for biogas from other kind of wastes. The production power is ranged from 250 kW to 3 MW; that means, the engines are ideal for large scale applications. This technology could be employed either in single generation or in cogeneration operation modes.

- Caterpillar. The electric power plants offered by Caterpillar are fuel-flexible; then, they can operate with biogas. The main detected applications are in power generation with biogas from landfills, wastewater treatment plants and animal wastes; however, they could operate with any biogas containing the adequate methane concentration. The power generation is ranged from 64 to 3770 kW.

**Table 4** includes a relationship of the equipment implemented in Mexico for electricity generation from biogas.

From this information, it can be deduced that the commercial power electric plants are available for more than 30 kW. This implies an approximate consumption of biogas of 12 $m^3 h^{-1}$. For applications less than 30 kW (a fewer capacity to produce biogas), other alternatives should be explored. For example: a) the adaptation of small either diesel or oil engines to allow them to operate with biogas; after that, it is advisable to connect them to small electric generators. Even if the conversion efficiency decreases, it is a feasible option to produce electricity from biogas at small scale; b) the use of biogas only to produce thermal energy; for low biogas production, the thermal energy is the best option since only a combustion process is required and there are not large lost of the potential energy and c) the methane up-grade in biogas, this allow to get a better quality fuel since the calorific value increases; a direct benefit of this situation is the reach large efficiencies at low scale. Nevertheless, this alternative requires more research at technological transfer: in fact, it is necessary to develop efficient devices to up-grade biomethane in biogas.

*3.3.3.2. Stirling engines*

External combustion engines can be used for energy production with biogas [29]. The Stirling cycle is based on the work produced form the expansion and contraction of a gas from a cold point to a hot one. The temperature on the hot point can be provided by the combustion of biogas, which takes place outside the engine.

| Equipment | Number of implemented engines | Installed capacity |
|---|---|---|
| Mopesa | 11 | 720 kW |
| Jidoka | 16 | 1095 kW |
| Cummins | 1 | 100 kW |
| Jenbacher | 13 | 13.68 MW |
| Guascor | 3 | 2.85 MW |
| Caterpillar | 5 | 4.3 MW |
| Confidencial | 3 | 1.28 MW |
| Other | 107 | 6.42 MW |

**Table 4.** Biogas engines coupled to electric generators implemented in Mexico.

Only one Stirling engine operating with biogas to energy production has been identified in Mexico. This use the biogas obtained from animal wastes. These kinds of engines are easy to design and to operate. Then, they present clear opportunities from scientific and technologic developments.

*3.3.3.3. Microturbines*

Turbines are well-known technology to produce energy at large scale. The fundamentals of them are based on the transformation of the kinetic energy of a fluid (water, steam, gas) into a mechanical energy. Nowadays, there are commercial developments which can operate at medium scale. Biogas is a feasible fuel for this kind of technology [30].

There are different commercial microturbines, such as Capstone and Siemens, which can be considered as an alternative to take advantage of biogas for a power production (more than 30 kW).

In Mexico, a beer company obtains biogas from the produced wastes in the beer production processes; the biogas is used to produce 6% of its energy consumption. The transformation is done by using biogas and steam in a cogeneration system.

*3.3.3.4. Fuel cells*

Fuel cells are electrochemical devices, which allow the energy of a chemical reaction to be transformed directly into electricity; they operate while being supplied with fuel and oxygen, then they do not neither become ended nor require to be recharged like conventional batteries. A basic operation principle of fuel cells is shown in **Figure 4**.

Research on this type of devices has made remarkable progress in recent years. Specifically, solid oxide (SOFC) cells have received special attention because they offer very high efficiency with relatively low sensitivity to the chemical composition of the fuel. The high operating temperature (700–1000°C) allows flexibility in relation to the fuel to be used. This implies that it is possible to use biogas, which cannot be used in other types of cells. SOFCs can be used in small power applications, stand-alone systems and remote systems [31]. Different research teams in Mexico deal with fuel cells.

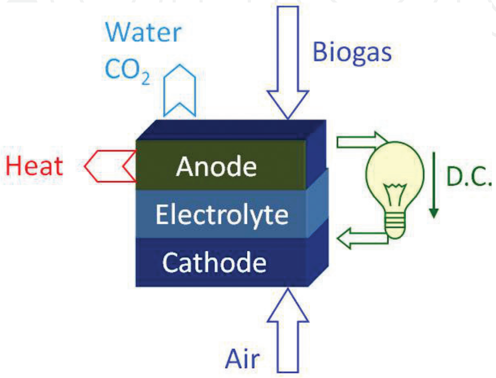


**Figure 4.** Electricity generation principle from electrochemical devices.

### 3.4. Perspectives

The potential of biomass for energy production in Mexico is large; besides agriculture, there are many other activities producing organic wastes. Since a single biogas production scheme may require high investment and operational costs some other complementary approaches should be explored. In this context, a national strategy should be implemented in order to achieve an optimal use of organic wastes, not only for energy production but for added value product generation. Based on the experience of some other countries all around the world, among the main topics which should be systematically addressed in Mexico the next could be considered: biorefinery approaches, biomethane upgrading, energy crops and technology development. This is schematized in **Figure 5**.

#### *3.4.1. Biorefinery approaches*

The schemes for integral revalorization of biomass, known as biorefineries, are considered as a promising alterative to develop a global industry based on biomass [32]. These schemes combine different biomass conversion processes in order to produce biofuels and chemical products in an analogue structure of oil refineries. Anaerobic digestion has been identified as a biological pre-treatment that ease the subsequent transformation of the diverse components of biomass. Then, biogas can be only one of the multiple products which can be synthesized. Some other biofuels such as ethanol, hydrogen and butanol could be obtained. Besides, chemical products or precursors such as organic acids, biopolymers and biofertilizers are possible to be produced [33].

At current time, there are several reports concerning the development of biorefineries in Mexico [34]. Most of them are in the conceptualization stage; there are different efforts related to experimental studies in order to identify the best operating conditions. Some of them are

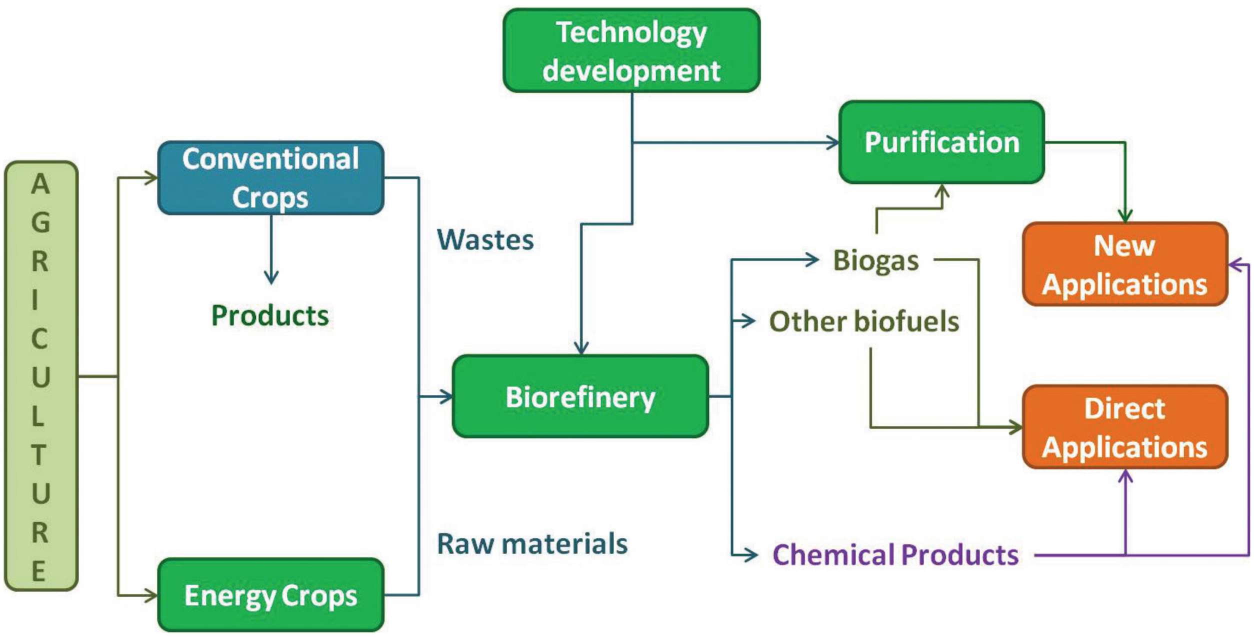


**Figure 5.** Strategy for transformation of agriculture wastes and energy crops products.

briefly described. The Nerixis project has been developed by an interdisciplinary work team, and the objective was to develop the concept of a based agriculture wastes biorefinery; the structure included pre-treatment, saccharification, fermentation, separation, biogas, hydrogen and electricity co-production, enzyme enhancement, synthesis of lignine-based products, plant design and life cycle assessment (LCA); the considered raw material was wheat including streams of wastewater [35]. Additional schemes have been implemented from this project [36]. Other work explores the wastes of algae from a biodiesel productions process as raw material for ethylene and bioplastic production [37]. Mango wastes have been employed as raw material for bioethanol and food supplement production in a biorefinery scheme [38]. Other research deals with the evaluation of biohydrogen production from agro-industrial wastewaters and by-products; six different wastewaters and industrial by-products coming from cheese, fruit juice, paper, sugar, fruit processing and spirits factories were evaluated [39].

Besides the technical feasibility analysis, the economic, environmental and social aspects of biorefineries should be assessed. This is a topic considered in different Mexican studies. A multi-feed biorefinery (MPB10) for producing bioethanol from lignocellulosic residues and simultaneously treating agro-industrial wastes (cheese whey and tequila vinasses) was proposed. It was concluded that the most important sustainability indicators were the End-use Energy Ratio for the environmental aspect and Yield together with total production cost (TPC) per energy unit produced for the economic domain [35]. Other work is related to the sustainability assessment of a switchgrass-based biorefinery. Among the main results, it can be mentioned that some indicators such as the employment extent and raw materials consumption need to be improved in order to avoid risks; increasing operational jobs within the plant, increasing crop productivity or increasing the cropland surface may lead to better results on these indicators. Indicators concerning social domain are difficult to set on a sustainability scale, because commonly there is no possible definition for the ideal sustainability and/or the critical value [40].

Even if more research is required to consolidate the biorefineries topic, the next step in Mexico is the knowledge transfer for scaling up of processes. This is not an easy task since many factors should be in synchronization: government, farmers and academic sector.

#### *3.4.2. Biogas purification*

As said previously, biogas composition depends on the raw materials. The presence of compounds other than methane reduces the calorific value. The elimination of those compounds is a research topic with scientific and technologic interest. There are two main approaches relating biogas purification: biomethane upgrading and biogas cleaning [41].

The increase in the methane grade, known also as upgrading or enrichment, refers to the separation of the methane from the biogas in order to have a compound with higher energy potential. The idea is to recover methane in order to conserve the material representing the highest calorific value in biogas. There are different methods for this effect:

- Adsorption is known as pressure swing adsorption (PSA).
- Absorption with water traps.

- Absorption with organic solvents.
- Membrane technology.

Concerning biogas cleaning, the issues are related with the elimination of corrosive compounds, which affect the equipment used in the energy generation stage. Among the harmful agents, most commonly found in biogas are sulfur and nitrogen compounds. Methods to remove these chemical compounds are studied. The compound that receives most attention is $H_2S$ due to its impact on the mechanical parts of the devices as well as on the environment:

- Biological desulfurization.
- Chemical precipitation with ferrous compounds.
- Chemical reaction using iron compounds.
- Combination of adsorption and catalytic oxidation.

Biogas cleaning and upgrading is few addressed in Mexico; however, it is an important issue which could diversify the use of biogas and even to promote the transformation of agriculture waste into biogas.

#### *3.4.3. Technology development*

Although there is some equipment designed for national entrepreneurs, most of the commercial technology associated to the biogas life cycle is foreign. At present time, commercial globalization and the international free trade agreements allow to get low prices for several products. However, since the biogas topic is not really spread at small and medium size, the importation of technology increases the initial investment for projects.

Then, the development of technology is a topic which should be addressed in Mexico, especially for small applications such as burners, furnaces, stoves, lamps, small engines for mechanical energy, and power plants for a generation less than 30 kW.

Due to the geographic characteristic of the country, the production of agriculture wastes is not uniformly distributed. This implies an additional issue on the collection stage for large size biogas facilities. Then, it is advisable to consider a distributed generation approach; that means, to implement small-scale facilities transforming small quantities of biomass and producing small quantities of energy, but near to the final users. This allows a better management of resources. Then, the distributed structures are designed to avoid logistic problems for transportation which demand energy, time and other resources. For this reason, the availability of technology for medium and small size is an important aspect to be considered.

#### *3.4.4. Energy crops*

Energy crops should be also a developing topic for biogas production, preferentially in biorefinery schemes.

Currently, there exist around 5 nopal (*Opuntia*) crops for electricity production; the selected plant is not edible specie which has been modified to eliminate thorns and make it easier to handle. Also, some studies have been carried out to evaluate the potential of the species *Opuntia* spp. for the production of biofuels. It has been reported that 1 ha of nopal can produce more than 100 t of biomass [42]. Experimental results show that a methane content of more than 70% can be achieved when a mixture of nopal and manure is used in a 3:1 ratio at a temperature of 30°C. Another study indicates a biogas production of 0.861 $m^3 kg^{-1}$ of volatile solids with 58.2% of methane [43, 44].

On the other side, algae have been also identified as feasible plants for energy crops [45]. In Mexico, this raw material is mainly studied for the production of hydrogen, biodiesel and bioethanol. The production of biogas from algae is little studied; however, the potential is important, especially in biorefinery schemes. Currently, different laboratory experiments have been carried out using substrates that include algae. Different aspects of the transformation are considered such as the sequestration of carbon dioxide ($CO_2$) from different industrial emissions to use as a nutrient in the growth of algae, the selection of the site for the installation of biorefineries as well as transportation costs [46]. Other project is developed in order to evaluate the performance of a biorefinery at laboratory and pilot plant level producing biogas, biodiesel from microalgae and hydrogen from algae residues, using municipal wastewater.

There are different plants which could be produced in energy crops such as jatropha, moringa, savage castor oil plant and others. Even if these plants do not involve a direct food competition, they induce an indirect food competition due to the soil and resources requirements. For these reasons, more studies should be addressed in order to take appropriate decisions concerning the implementation of energy crops.

## 4. Conclusions

Among more than 300 species cultivated in Mexico, 39 were selected for this assessment due to its characteristics, production amount and availability for biogas production. It was deduced that around 12.7 Mt of wastes available for biogas are produced. From those wastes, a total of 450 GWh could be produced from these wastes.

Currently, the generation of energy from agricultural wastes is less than 10% of the estimated potential.

The main applications of biogas are thermal and electric energy generation. However, some other potential applications should be explored, such as light and heat for cooking at low size and the obtaining of added value products from biorefinery schemes at larger scales.

It is important to remark that a national strategy is required to take advantage of the potential of biogas. Some independent efforts have been done: government has promoted new legislations to motivate the development of biofuels; academic sector addressed from different perspectives the knowledge generation related to bioenergy; enterprises are searching for alternatives to implement bioenergy projects. However, an integrated strategy is necessary for more strong and efficient collaboration. The adequate transfer of technology and knowledge is essential, which requires a dynamic collaboration between academy, productive sector and government.

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