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Biogas production

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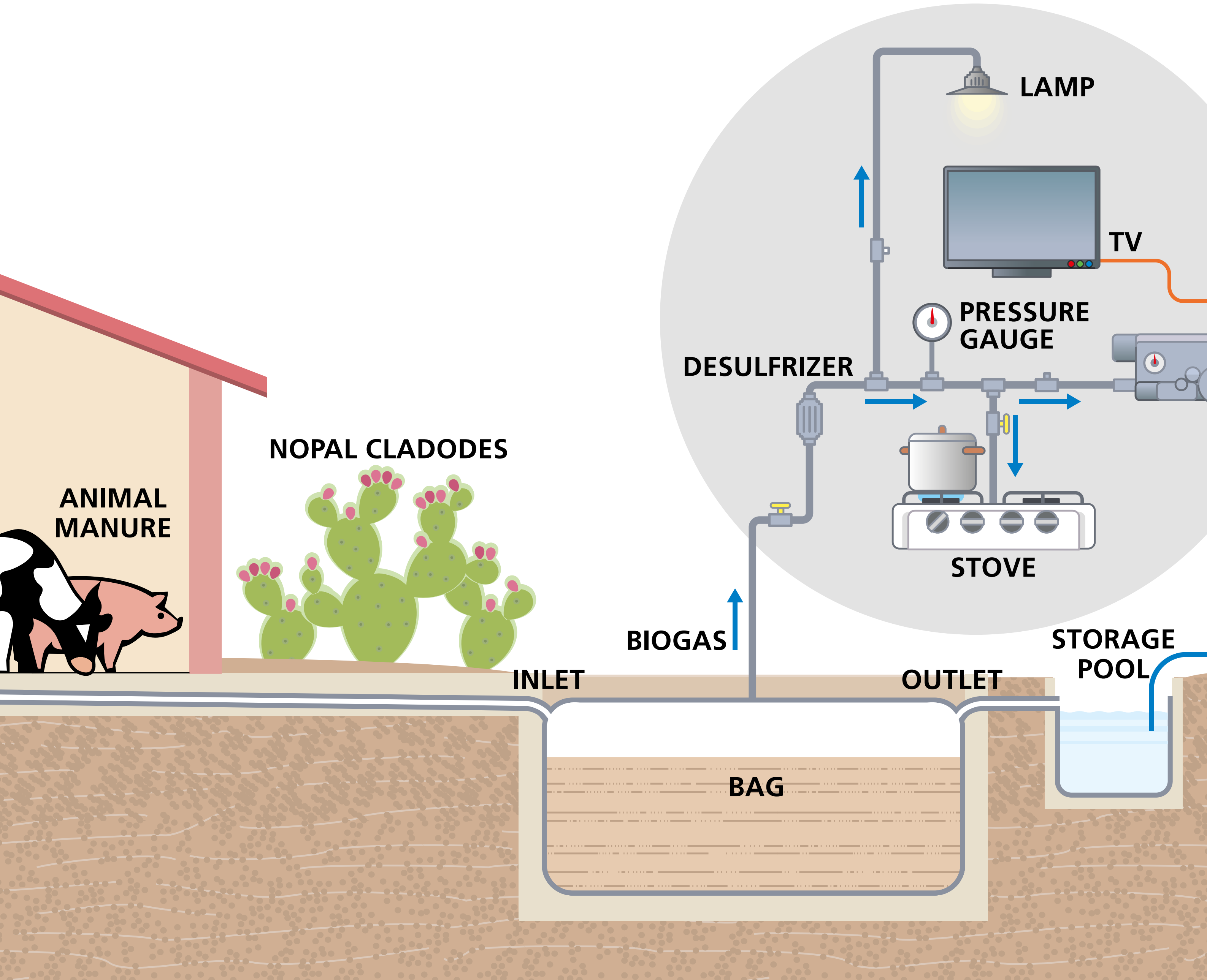

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INTRODUCTION

Non-conventional renewable energy (NCRE) is increasingly prominent, providing an inexhaustible energy source compatible with human and environmental sustainability. The various forms of NCRE include wind, solar, small hydro, tidal, geothermal and biomass. Biomass uses biological, chemical and physical processes to generate liquid or gaseous biofuels, such as biodiesel, bioethanol and biogas.

Biogas is a viable and essential form of energy in agricultural and rural areas, obtained from the processing of organic waste through anaerobic digestion. In addition to biogas (comprising mainly methane and carbon dioxide, plus other trace gases), the process also produces a stabilized organic waste, digestate (also known as biol or biofertilizer), which can be used as a soil conditioner or biofertilizer (Varnero, 1991, 2001).

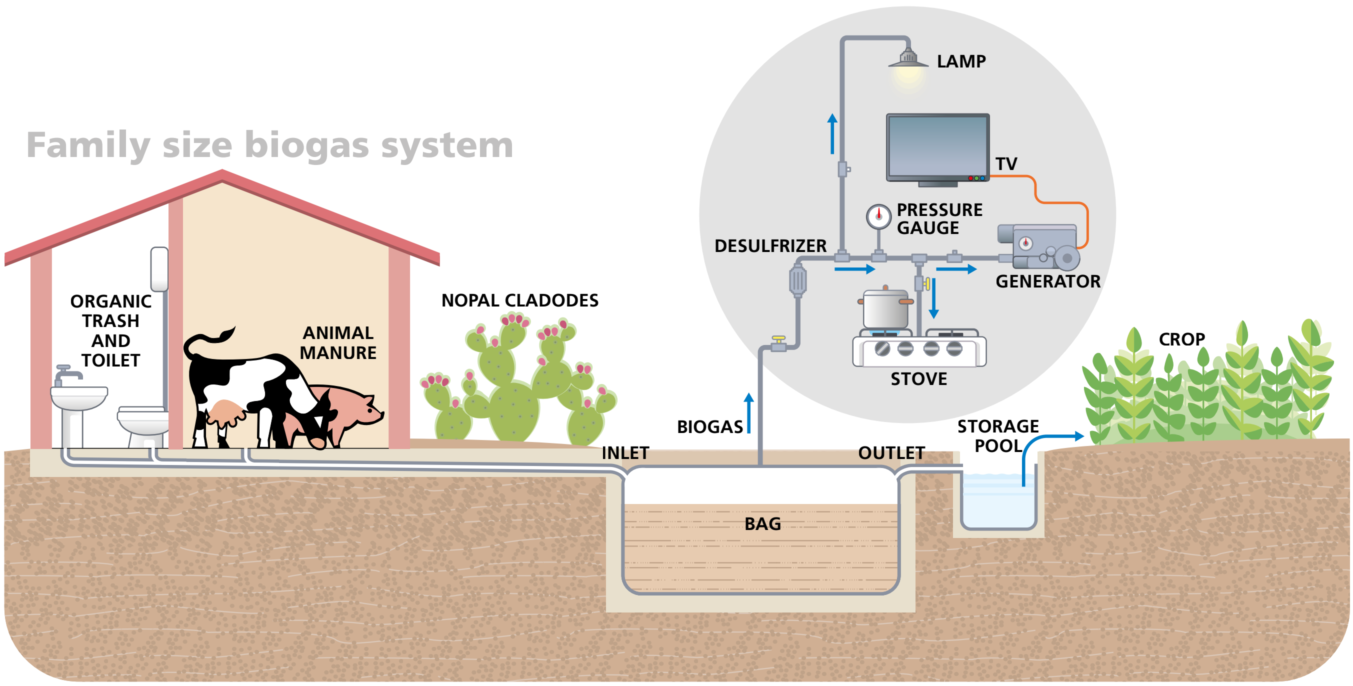
The biodegradation rate of organic residues is related to the microbial activity in the anaerobic system. This activity depends on the type of raw material, the pH of the medium, the total level of solids, the temperature of the process and other parameters that determine the digestion period for the production of biogas and biofertilizer.

USING CACTUS WASTE IN BIOGAS PRODUCTION

Dry climate areas have reduced availability of organic waste – an obvious disadvantage for biogas production. This obstacle can be overcome by developing energy crops well adapted to arid areas. In this context, opuntias – among them, *Opuntia ficus-indica* (L.) Mill. – characterized by crassulacean acid metabolism (CAM), are recommended as an alternative energy source as they have a high potential for biomass production (García de Cortázar and Nobel, 1992; García de Cortázar and Varnero, 1995). Farmers can thus reduce their electricity and gas bills (liquefied petroleum gas, LPG) by producing their own energy, while improving the quality and conditions of the soil by applying the digestate to the fields.

In the Faculty of Agricultural Sciences of the University of Chile, experiments with *Opuntia ficus-indica* (Uribe *et al.*, 1992; Varnero *et al.*, 1992; Varnero and López, 1996; Varnero and García de Cortázar, 1998) indicate that the cladodes are not a good methanogenic material. The quality of the starting material in the digesters, particularly when batch-loaded (Hilbert, 2009), is vital for the process. It is, therefore, necessary to include

Figure 1
Family size biogas system



a particular material derived from another digester and enriched with methanogenic bacteria, or to incorporate a percentage of animal manure. Such adjustments advance the starting time of the methanogenic phase in the digester and increase the production of biogas. Moreover, the pH of the pulp is very low, and this too affects the production of biogas; for this reason it is preferable to mix with other raw materials, mostly animal manure.

The fermentation efficiency of mixtures containing different proportions of cladodes and animal manure showed that it is crucial to maintain the pH of the mixture close to pH = 6 in order to obtain biogas with a methane content of > 60%. The composition of the biogas produced by methanogenic fermentation is closely related to the pH of the raw materials biodigested. At pH < 5.5, biogas is predominantly carbon dioxide, with reduced combustibility and energy content; conversely, with a neutral or basic pH, the biogas is methane-enriched. It is, therefore, important to increase the proportion of animal manure in the mixture and use cladodes older than 1 year. The particle size of the chopped material has no significant influence on the efficiency of the fermentation process (Varnero and López, 1996; Varnero and García de Cortázar, 1998).

During the anaerobic digestion of animal manure, the addition of cactus cladodes promotes the methanogenic fermentation, provided that the pH of the mixtures of these raw materials remains within a neutral or slightly acidic range. Furthermore, adding an appropriate percentage of cladodes to the animal manure helps the fermentation process start earlier (Uribe *et al*., 1992; Varnero *et al*., 1992): the energy and carbon content of the cladodes favours the development of acidogenic bacteria, which generate the substrate required by methanobacteria, thereby accelerating the methanogenic process and reducing the time required for this activity (Varnero and García de Cortázar, 2013).

OPUNTIA SPP. PLANTATIONS FOR BIOGAS PRODUCTION

Opuntias can grow successfully in areas with a range of climates and soils; therefore formal plantations can be established to optimize biomass production. Its economic evaluation is still pending.

Studies have shown that 1 ha of *Opuntia* over 5 years old can produce up to 100 tonnes of fresh cladodes per year in areas with little rainfall (≤ 300 mm) (García de Cortázar and Nobel, 1992). In some semi-arid parts of Mexico, cladodes are traditionally collected from wild cactus plants as a source of forage; regular pruning boosts yield and improves fruit or *nopalitos* quality.

Pruning can yield approximately 10 tonnes of dry matter (DM) ha^{-1} $year^{-1}$, and the prunings can be used for biogas, compost or animal feed (García de Cortázar and Varnero, 1995). Pruning can also provide the raw material to feed digesters, combined with animal manure. Mature cladodes (1 year old) can be cut, chopped and fed directly into the digesters. It is important to use them as soon as they have been chopped, in order to reduce biodegradation and improve the efficiency of biogas and biofertilizer production. If the capacity of the digester is not sufficient for immediate use, the cladodes can be stored in a shaded, cool, dry place for several days (Varnero and García de Cortázar, 2013).

As the plantation matures, the growth of the cladodes slows, because the net photosynthetic

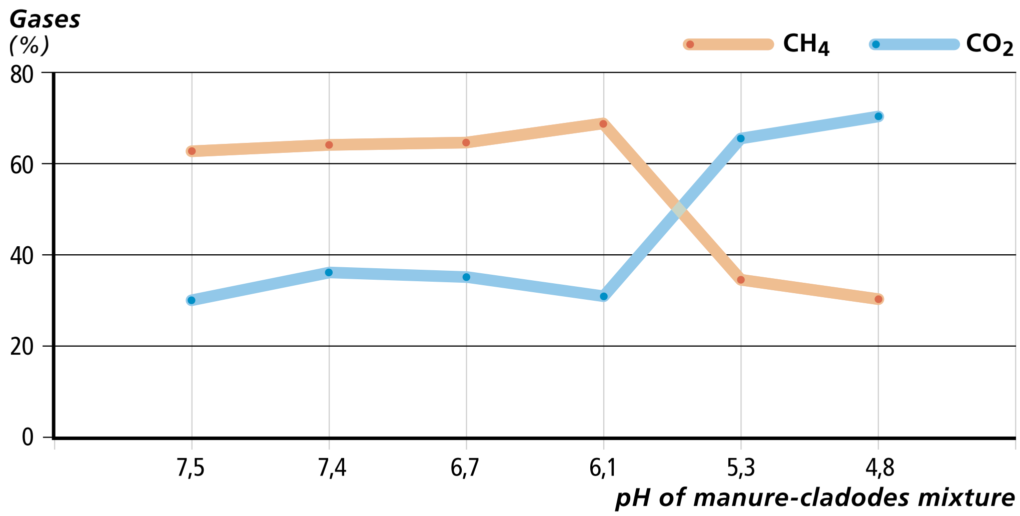


Figure 2
Biogas composition as a function of pH of manure-cladode mixture (Varnero and Arellano, 1991)

rate decreases due to the shading effect of the upper cladodes (Acevedo and Doussoulin, 1984). The dry matter content is not affected, however, as growth continues throughout the year. In Chile, the maximum commercial fresh fruit yield is estimated at 16 tonnes ha^{-1} for plants 16-20 years old under good management. This begins to decline between 21 and 35 years of age, reaching 8 tonnes ha^{-1} (Acevedo and Doussoulin, 1984; Pimienta Barrios, 1990). During the January-April harvest season, yield is 5-16 tonnes ha^{-1}, while and in June-September, it is just 0.5 tonnes ha^{-1} (Sudzuki *et al.*, 1993).

Tohá (1999) indicates that 3 kg of dried cladodes produce 1 m^3 of biogas, which is equivalent to an output of 10 kWh. Moreover, Baeza (1995) indicates that the calorific value of biogas from cactus is 7 058 kcal m^{-3} (range of 6 800-7 200 kcal m^{-3}) and the biogas potential of *Opuntia* is equivalent to 0.360 m3 kg^{-1} DM.

- **Scenario 1: low production.** With a yield of 10 tonnes DM ha^{-1} year^{-1}, the potential biogas production is equivalent to 9.86 m^3 biogas day^{-1} (27.40 kg DM day^{-1}, with a potential estimated 0.36 m^3 biogas kg^{-1} (27.40 × 0.360 = 9.86 m^3 biogas day^{-1}).
- **Scenario 2: intermediate conditions.** Pruning waste production of 18 tonnes ha^{-1} year^{-1} generates 17.75 m^3 biogas day^{-1} and 49.3 kg DM day^{-1}.
- **Scenario 3: optimum production.** A commercial plantation with irrigation and fertilization can produce ≤ 30-40 tonnes DM ha^{-1} (García de Cortázar and Nobel, 1992; Franck, 2006). Production of 30 tonnes year^{-1} is equivalent to 82.2 kg day^{-1}, which can be used as raw material for biogas production with a potential of 29 m3 day^{-1} (82.2 × 0.360 = 29 m^3 biogas day^{-1}), or 10 885 m^3 ha^{-1} year^{-1} biogas – comparable to 6.4 tonnes of oil (Varnero, 1991).

There is a significant difference in biogas production between the best and worst scenario as a result of the constraints involved.

Based on the family biogas system for small operations illustrated in **Figure 1**, organic waste can be collected by connecting the bathroom to the digester, and/or by accumulating kitchen waste. Furthermore, if there are animals (e.g. one cow and two pigs), they too provide organic matter (**Table 2**). This would give a biogas potential of 1.05 m^3, leaving a further 2.6 m^3 to achieve the 3.61 m^3 needed. In order to determine the minimum cactus plantation area required to supply enough raw materials to achieve this amount, it should be considered that a maximum of 3 kg of cactus is necessary to produce 1 m^3 of biogas. The digester must, therefore, be provided with 7.1 kg day^{-1}; this is obtained in an area of 0.28 ha, assuming an availability of 10 tonnes of cladodes ha^{-1} year^{-1}, equivalent to 27.47 kg ha^{-1} day^{-1}.

Practical example

TABLE 1 Average consumption of biogas energy in a family of 5 people

	Average biogas consumption	Cactus biogas consumption
	Calorific value 5 000 kcal m^{-3}	Calorific value 7 058 kcal m^{-3} (75% of CH_4)
Kitchen (5 hours)	0.30 m^3 h^{-1} × 5 h = 1.50 m^3 day^{-1}	0.21 m^3 h^1 × 5 h = 1.05 m3 day^1
3 lamps (3 hours)	0.15 m^3 h^1 × 3 h × 3 = 1.35 m^3 day^{-1}	0.11 m^3 h^1 × 3 h × 3 = 0.99 m^3 day^1
Cooling medium	2.20 m^3 h^1 × 1 = 2.20 m^3 day^1	1.57 m^3 h^{-1} × 1 = 1.57 m^3 day^{-1}
Total	**5.05 m^3 day^{-1}**	**3.61 m^3 day^{-1}**

Source: Baeza, 1995.

TABLE 2 Summary of the calculations

	Quantity (units)	kg unit^{-1}	kg	Potential biogas (m^3 biogas kg^{-1})	Biogas (m^3)
Kitchen waste	5	0.56	2.8	0.092	0.26
Human faeces	5	0.13	0.65	0.092	0.06
Cow manure	1	10	10	0.04	0.40
Pig manure	2	2.8	5.6	0.06	0.336
				subtotal	**1.053**
Cladodes	0.28	27.47[a]	7.7	0.3	2.60
		total	**26.64**		**3.62**

[a] 10 tonnes ha^{-1} year^{-1} (364 days).

On the basis of the biogas production described above, 0.45 m^3 of gas is obtained per m^3 of digester; the minimum size of the digester is, therefore, 8 m^3. In addition, a daily load of 26.24 kg must be incorporated, combined with sufficient water for a solid concentration of 7%: equivalent of 221 litres (also equivalent to the digester's volume, divided by 35 days, i.e. the time required to degrade organic matter). When loading the digester with 221 litres, the same amount of biofertilizer is produced, which can be used for irrigation, fertilization and organic matter input (5.20 g N kg^{-1}, 3.90 g P kg^{-1}, 3.60 g K kg^{-1} and 561 g Mo kg^{-1} DM).

BIODIGESTERS DESIGN AND OPERATION

The biodigester must have certain characteristics:

- Airtight – to prevent both output of undesirable gas and intake of unwanted air.
- Thermally insulated – to avoid major temperature changes.
- Fitted with safety valve.
- Easily accessible – for loading and unloading of the system with raw material, removal of digester scum and maintenance of the digester (Varnero, 1991, 2001).

There is extensive information available in various countries, including India, China and Germany, on the design of biodigesters (García de Cortázar and Varnero, 1995). While most production and use of biogas is obtained from family biodigesters (**Figure 1**), community digesters may also be feasible in some situations, in particular when large amounts of raw material and technological expertise are available.

There are two types of digester: continuous and batch (discontinuous).

- **Continuous.** Material loading is frequent (daily or weekly), each load replacing approximately 5-15% of the total volume. The solids concentration is low (6-8% of the volume), and once the digestion process starts, the biogas production rate is relatively constant (this is mainly dependent on temperature). Continuous digesters are best suited to situations where there is a constant production of material for biodigestion, i.e. if cladodes are collected throughout the year. They are also suited to small properties where household waste can be added as a raw material – for example, incorporating faeces produced by the farm animals or through a connection between the bathroom and digester (Varnero and García de Cortázar, 2006; FAO, 2011). Three models of continuous digester are available:
  - Taiwan type, made of plastic sleeves (polyethylene) (**Figure 4a**);
  - Indian type (**Figure 3a**) – gasometer included in the digester in the form of a floating bell; and
  - Chinese type (**Figure 3b**) – closed, with gas accumulation at the top, while the Indian digester.
- **Batch.** Discontinuous digesters (**Figure 3c**) comprise a sealed battery of tanks or deposits, with a gas outlet connected to a floating gasometer, where the biogas is stored. With multiple digesters, one is always loading or unloading while the others are in biogas production. Feeding or charging the digester with the raw material, which has a higher concentration of solids (40-60%), is done only once, since there is no recharging during the fermentation process. The stabilized organic material is discharged once the biogas production is complete. Biogas production has an initial waiting period, during which fermentative hydrolysis, organic acid formation and methane formation take place. Most of the biogas production then occurs, be-

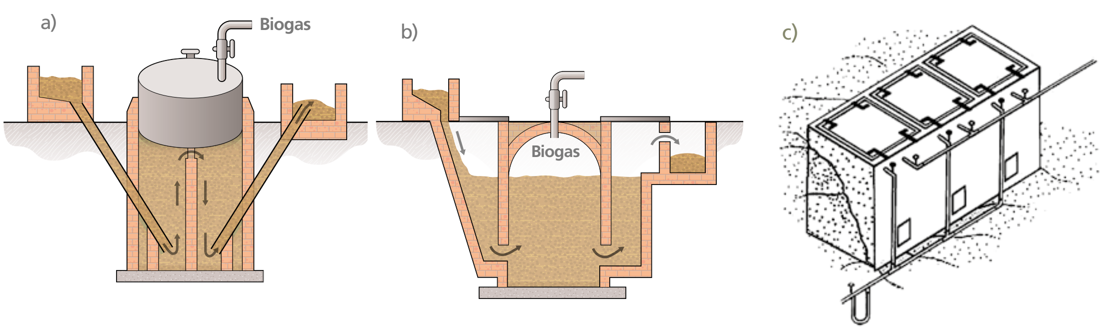


Figure 3
a) Indian digester;
b) Chinese digester;
c) Batch digester

fore slowing down and eventually decreasing to almost zero, as the batch-loaded materials run out. The total duration of the process depends on the temperature. The discontinuous system is suited to certain situations, for example, when: raw materials exhibit handling problems in continuous systems; materials are difficult to digest by methanogenic fermentation; or raw materials are available intermittently. Raw material from the cladode harvest is available once or twice a year (Varnero and García de Cortázar, 2006; FAO, 2011).

Under optimal conditions and for the same volume of dry matter, the two types of digester produce the same amount of biogas. Therefore, the choice should be based on the frequency of waste production (in this case, cladodes) and the availability of water.

For small and medium-sized producers, a wide range of materials may be used for constructing a biogas digester. The most economical continuous types are made from low-cost polyethylene tube (or EPDM, PVC, HDPE) as shown in **Figure 4a**. Known as the Taiwan type, it is widespread in Asia and some Latin American countries. The material costs for this type are US$7 m^{-3}. The Indian or Chinese models can be made with different materials (**Figures 4b-f**).

ECONOMIC ASPECTS

The initial cost of biogas production in rural households is around US$50 per biodigester (Bui Xuan An *et al.*, 1999). This cost is recovered within 9-18 months through savings in fuel costs. In rural areas where the main fuel is wood, the use of biogas reduces ecosystem damage (less deforestation and contamination) and leads to time savings of up to 5 hours a day per household – time which can be used for other more productive tasks (Rutamu, 1999). To calculate the economics of using biogas, it is assumed that one pound (0.45 kg) equals 1 m^3 of biogas; therefore a theoretical calculus of 3.61 m^3 day^{-1} would correspond to 3.61 pounds (1.63 kg) of gas daily, with a value of approximately US$2.98 day^{-1}, or US$1 078 $year^{-1}$.

The residue obtained from digestion processes (**Figure 5b**) has a high nutrient content; it is, therefore, a valuable fertilizer and allows to save on the expense of commercial fertilizers. According to Varnero (1991), 1 tonne of biofertilizer is equivalent to 40 kg of urea, 50 kg of potassium nitrate and 94 kg of triple superphosphate. International fertilizer prices vary from US$255 to US$380 $tonne^{-1}$ (Indexmundi, 2015). Assuming an average price of US$0.32 kg^{-1} of fertilizer, each tonne of biofertilizer saves US$58.8 on fertilizers costs; this saving is in addition to the important

Figure 4
Different materials used for the construction of biodigesters:
a) plastic sleeves;
b) brick;
c) concrete;
d) recycled plastic drums;
e) recycled metal drums;
f) prefabricated

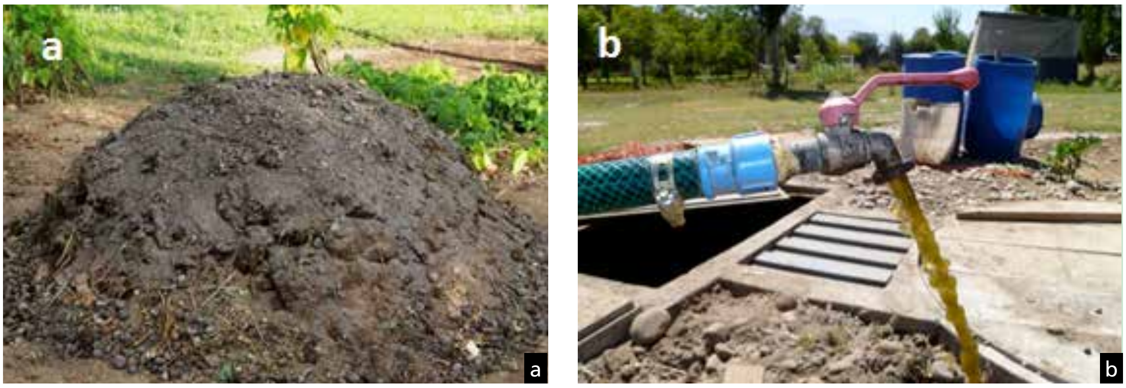


Figure 5
a) Solid digestate; b) biofertilizer (biol or liquid digestate)

contribution in terms of microorganisms and organic material, as well as the possibility of obtaining solid materials when emptying the digester (**Figure 5a**).

OTHER BIOENERGY USES

Cactus cladodes have other bioenergy uses, such as biodiesel or ethanol production. With an annual production of 40 tonnes ha^{-1} in crops grown specifically for energy use or 10 tonnes ha^{-1} in pruning waste from fruit plantations, energy can be obtained through direct burning. The cladodes are harvested, sun-dried and crushed, then used in direct burning or cogeneration mix coal-fired; the calorific value is 3 850-4 200 kcal kg^{-1}.

The technology for ethanol production is more complex than that for biogas production; it therefore adapts better to a larger scale, given the high investment costs, and produces concentrations of > 98% ethanol. At fermentation, specific yeast is required to maximize the alcohol production. The ethanol concentration at fermentation is 8-12% (García de Cortázar and Varnero, 1995), attainable only by distillation to achieve the required concentration of ethanol as fuel.

Estimates indicate that cactus mucilage can be used to produce small amounts of ethanol: about 20 ml kg^{-1} of mucilage. On the other hand, 8.6 litres were produced from 100 kg of dried cladodes, and 24.7 litres from 100 kg of dried fruits, and so it is not considered competitive compared with production from fermented fruits. With a density of 635-5 000 plants ha^{-1}, if only the cladodes are used (Retamal *et al.*, 1987), an average of 300-3 000 litres of ethanol can be obtained from non-irrigated and irrigated plantations, respectively.