Prospective of biogas production in the Mexican agroindustry: the traditional tortilla manufacturing sector

Mónica Soria Baledón

Master’s programme
Science for Sustainable Development

Master’s Thesis, 30 ECTS credits
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Supervisor: Jörgen Ejlertsson

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ABSTRACT

This thesis presents an assessment of the availability and quality of biomass from the wastewaters in a traditional corn mill in Mexico City for biogas production. To date, these wastewaters (called *nejayote*) are discharged untreated to the sewer with a chemical composition that surpasses the maximum permissible levels of pollutants established in the Official Mexican Standards (NOMs). From the study case four scenarios were proposed to tackle this problem: 1) separate the suspended solids (SS) by sedimentation in order to reduce the organic content of *nejayote*, 2) recover a protein-rich microbial biomass for animal feed through the aerobic treatment of these wastewaters, 3) produce biogas to cover part of the energy demand of the corn mill under study, and 4) switch to the alkaline extrusion of corn as an alternative the traditional corn-cooking technique known as *nixtamalization*. Despite their environmental benefits, none of the proposed scenarios offer, separately, the economic incentives to change the business as usual in this traditional corn mill. Yet, biogas production can be combined with other alternatives like the alkaline extrusion of corn in a two-stage technological package. This processing technology would completely eliminate *nejayote* while preserving the nutritive value of the *nixtamal* dough and most importantly, the organoleptic uniqueness of the traditionally-made tortillas.

Keywords: biogas from wastewaters, *nejayote*, wastewater treatment, Mexico, traditional tortilla manufacturing industry.
# List of Abbreviations

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<th>Description</th>
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<tr>
<td>BOD&lt;sub&gt;5&lt;/sub&gt;</td>
<td>Biochemical oxygen demand (5 days at 20°C, mg O&lt;sub&gt;2&lt;/sub&gt;/l)</td>
</tr>
<tr>
<td>CERs</td>
<td>Certified Emission Reduction Credits</td>
</tr>
<tr>
<td>CH&lt;sub&gt;4&lt;/sub&gt;</td>
<td>Methane (mol)</td>
</tr>
<tr>
<td>COD</td>
<td>Chemical oxygen demand (mg O&lt;sub&gt;2&lt;/sub&gt;/l)</td>
</tr>
<tr>
<td>CONASUPO</td>
<td>National Company of Popular Subsistence</td>
</tr>
<tr>
<td>kWh</td>
<td>Kilowatt hour</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied petroleum gas</td>
</tr>
<tr>
<td>MMtCO&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Million tons of carbon dioxide</td>
</tr>
<tr>
<td>MMtCO&lt;sub&gt;2&lt;/sub&gt;e</td>
<td>Million tons of carbon dioxide equivalent</td>
</tr>
<tr>
<td>NAFTA</td>
<td>North American Free Trade Agreement</td>
</tr>
<tr>
<td>NG</td>
<td>Natural gas</td>
</tr>
<tr>
<td>NOMs</td>
<td>Official Mexican Standards</td>
</tr>
<tr>
<td>SS</td>
<td>Suspended solids concentration (kg/m&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>TS</td>
<td>Total solids concentration (kg/m&lt;sup&gt;3&lt;/sup&gt;)</td>
</tr>
<tr>
<td>UNFCCC</td>
<td>United Nations Framework Convention on Climate Change</td>
</tr>
<tr>
<td>VS</td>
<td>Volatile solids (% of TS)</td>
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Maize, and more importantly the tortilla industry was for almost the entire twentieth century an overregulated market where research and development were discouraged by the price controls established by the National Company of Popular Subsistence (CONASUPO) until its disappearance in March 1999 (Puebla Salazar, pers. comm.). The lack of innovation in this industry became highly problematic as the demand for tortilla grew steadily with the demographic revolution of the 1950s and the population tripled in only a couple of decades (Alba, 1984).

By the 1980s extensive research was financed by the Federal Government in collaboration with Mexican and foreign universities to tackle the water pollution caused by the expansion of the tortilla manufacturing sector, comprised by the large cornmeal factories and the traditional corn mills. Although the findings were very promising and economically feasible, namely the aerobic treatment of these industrial wastewaters and the alkaline extrusion of corn, they were never implemented and to date, the problem is persistent and has been aggravated by water scarcity. (Durán de Bazúa, 1985).

On the one hand, the aerobic treatment is a biological process performed by microorganisms to degrade the organic matter in wastewaters in the presence of oxygen (Pescod, 1992). Experimental results from Durán de Bazúa and Harmann (1987) indicate that a protein-rich microbial biomass can be recovered through the aerobic treatment of the wastewaters from the tortilla manufacturing industry – called nejayote – for its use as animal feed. On the other hand, the alkaline extrusion of corn is a physical and chemical process whereby previously ground and moisten corn grains are mixed with slaked lime and cooked into a dough with an extruder (Sánchez Tovar, et al., 1993; Durán Domínguez, 1996). This alternative transformation process does not produce wastewaters and demands less energy and material inputs than the traditional corn-cooking technique known as nixtamalization.

Besides water scarcity, the traditional industry is facing new challenges: a fast-developing biofuels market, the struggle between corn for animal feed and human consumption, a more strict environmental legislation and higher production costs due to a limited and expensive access to water so as to fluctuations in the prices of corn and fossil fuels (Polanco Jaime and Flores Méndez, 2008; Viniegra González, 2009). For example, the frost in February 2011 destroyed about 90 percent of the white corn harvest in the country and

---

1 Mazatec poem to maize (Nijmé) “When the embryo of maize arises, I feel our days lengthen, it is our heart that emerges and grows, it is the pozol, it is the tortilla, it is the world, it is life”.

---
the tortilla manufacturing sector had to produce from imported yellow corn, which is more expensive, generates wastewater with an organic load six times higher than white corn and has lower product yields (Durán de Bazúa and Hartmann, 1987).

To date, the key problem of this industry remains in the untreated discharge of nejayote to the sewer, which has a chemical composition that exceeds the maximum permissible levels of pollutants established in the Official Mexican Standards (NOMs). Furthermore, sanitation is a major challenge faced by local governments in Mexico due to the poor wastewater treatment infrastructure available in the country (CONAGUA, 2007).

In 2006, for example, the 1,593 sanitation plants operating in the country treated 74 m$^3$/s of wastewaters, equivalent to only 36 percent of the 200 m$^3$/s collected in the sewage systems (Loc cit.). Yet, the incipient development of the bioenergy markets in Mexico promoted by the Energy Reform of 2008, has opened the possibility to solve most of these problems in a sustainable way while protecting the traditional tortilla manufacturing industry from disappearing.

**i. i Aim, hypothesis and research questions**

The aim of this thesis is to present an assessment of the availability and quality of biomass from nejayote in a traditional corn mill in Mexico City for biogas production and use of the anaerobic degradation process by-products.

This thesis focuses on the traditional tortilla manufacturing industry for four reasons: first, notwithstanding the diversified traditional uses, the spiritual, symbolic values and even the industrial applications of corn in Mexico, tortillas remain the first and most important source of calories in the diet of Mexicans (Acosta, et al., 1988).

Second, Mexico’s economy is based on the micro, small and medium companies that represent 99 percent of the private sector, employs 78 percent of the economically active population and contributes with 52 percent of the Gross Domestic Product (SE, 2010). The corn industry is not the exception and about 84 percent of the people employed in it works in the traditional manufacture of tortillas, accounting for 125,400 jobs (Loc cit.). However, higher production costs are threatening this economic sector with disappearance; only in a couple of months five thousand of these economic units that employ 5 to 7 workers each went bankrupt due to sudden increases in the price of corn at the end of December 2010 (Pérez, 2011).

Third, the cornmeal industry has been able to adapt and somehow fulfill the legal obligations imposed by the environmental legislation on wastewaters; on the contrary, the traditional sector has mostly failed to comply with its legal obligations due to economic constraints (Ramírez Vives, pers. comm.). This situation has left the businesses that constitute the traditional sector at risk of costly penalties or even closure in case of official control from the Federal Bureau of Environmental Protection (PROFEPA).
Fourth, the industrial cornmeal wastewaters have a different chemical composition compared to their traditional counterparts (cornmeal and dough) due to significant differences in their production processes such as the addition of chemicals to enhance the final product’s shelf life, shorter cooking times, etc. (Buendía González, pers. comm.).

With the given background as base the following hypothesis was formulated: biogas production from the anaerobic degradation in situ of the tortilla manufacturing wastewaters can challenge other treatment options and corn processing techniques for solving the water pollution caused by the untreated discharge of nejayote into the sewer. The alternative options include the alkaline extrusion of corn, the separation of suspended solids by sedimentation and the aerobic treatment of wastewaters.

Four research questions were formulated to achieve this project’s aim and verify or reject the hypothesis:

1. What kind of waste and wastewaters from the traditional tortilla industry in Mexico are available for biogas production?
2. How are those residues and effluents currently used and/or disposed?
3. What are the potential uses of biogas and the anaerobic degradation by-products for this particular industry?
4. What are the advantages and disadvantages of biogas production compared to other wastewater treatments and corn processing techniques?

The thesis is structured in seven parts: the first one describes the methodology on which this research is based; the second provides the theoretical background to biogas and the status quo of its production and uses worldwide. The third part gives a general background of the methane emissions in Mexico, the actions and strategies taken by the Federal Government to mitigate them, and the potentials for methane recovery as an energy carrier in biogas.

The fourth part studies the tortilla manufacturing sector according to the criteria described in the methodology, where current problems and opportunities are discussed. Through a study case, the fifth part analyzes the potential uses of biogas and the anaerobic degradation process by-products at El Michoacano, a traditional corn mill in Mexico City. In this part biogas production is compared to other alternatives like the aerobic treatment of wastewaters, the alkaline extrusion of corn and the separation of suspended solids by sedimentation. The sixth part discusses the results from the case study and to conclude, the seventh part summarizes the main findings of the thesis.
1. Methodology

Notwithstanding the fact that the tortilla manufacturing in Mexico is an activity as old as the origins of the Mesoamerican civilizations, few sources of information with a bioenergy perspective were available for the elaboration of this thesis, as research within the field had mainly an end-of-pipe (EOP) approach to pollution control.

Thence, the main data sources for elaborating the thesis were:

- Published data about the traditional tortilla manufacturing industry so as relevant information to support the general background, the theoretical background and the analytical part. This included technical journals, specialized books, government reports and statistics, legislation and specialized websites.

- Unstructured interviews in the form of personal communications to specialists within the field of wastewater treatment and the traditional tortilla manufacturing industry from the following universities and institutes: National Autonomous University of Mexico (UNAM), Metropolitan Autonomous University (UAM-I), Autonomous University of Chapingo (UACH), and the National Institute of Forests, Agriculture and Livestock Research (INIFAP). The information obtained through these personal communications was useful for many reasons: the first one because in many cases it provided a better understanding of the data collected through other sources and second, because some of this information was not updated or available, as it was the case of some wastewater treatment options studied.

- Field visit to El Michoacano, a corn mill in Mexico City for collecting information to elaborate the study case and verify the data obtained through other sources. The corn mill provided samples of its wastewaters, but no laboratory tests were possible for their analysis.

The study of the traditional tortilla manufacturing industry in Mexico was based in four aspects: the importance of maize as a basic and strategic food, the production volume and geographic location of the traditional manufacturing sector, the current use of resources in the nixtamalization process and the characteristics of the waste and wastewaters produced. These aspects were adapted from other resource assessment reports for methane recovery in the livestock and agricultural sectors (ERG-TetraTech-CySTE; 2010; SEMARNAT-SAGARPA, 2008).

- Basic and strategic foods. These are determined by their importance in the population’s diets and on their economic relevance for the industry and the agriculture sectors. The Law for Rural Sustainable Development has defined eleven: maize, sugar cane, bean, wheat, rice, sorghum, coffee, egg, milk, meat and fish (LDRS, Art.179).

- Production volume and geographic location. Although higher production volumes are preferred, small and medium-scale processing operations located within a certain
geographic proximity (i.e. clusters) allow economies of scale in terms of energy production if the wastes can be handled in a central facility such as a biogas plant.

- **Use of resources in the production process.** Determined by the type and amount of production inputs needed in the transformation processes where biogas and the anaerobic degradation by-products of wastewaters can improve the economic, material and energy efficiency of the agroindustrial activities. In this part, information from the field visit to *El Michoacano* in Mexico City was used to identify the potential uses of biogas and the anaerobic degradation by-products from this corn mill’s wastewaters.

- **Waste profile.** It is defined by the concentration of organic compounds in waste and measured in terms of the biochemical oxygen demand (BOD₅), chemical oxygen demand (COD) and other relevant parameters. This part also includes a brief analysis of the wastewater composition at the corn mill visited in Mexico City in order to further assess its potential for biogas production.

From information of the waste profile and use of resources at *El Michoacano*, four scenarios were formulated to solve the water pollution problem of this corn mill: 1) separate the suspended solids (SS) in *nejayote* by sedimentation for reducing its organic content when discharged to the sewer, 2) aerobically treat these wastewaters in order to recover a protein-rich microbial biomass to be used as animal feed, 3) use the biogas from the anaerobic degradation of *nejayote* to cover part of the energy demand of *El Michoacano*, and 4) switch to the alkaline extrusion of corn as an alternative to the traditional *nixtamalization* technique.

These scenarios were compared based on their processes, end-products and costs. In particular, the use of biogas *in situ* was analyzed for electricity production and as a direct substitute of liquefied petroleum gas (LPG).

This thesis encountered a couple of limitations. The first one was the availability of data about wastewater treatments and alternative transformation techniques in the traditional tortilla manufacturing industry. Most of the studies done in this field were from the early 80s and only a few included a bioenergy perspective. This can be explained because at that time the production inputs (i.e. water, maize, LPG, electricity, etc.) were subsidized, and the research aimed to tackle the water pollution problem of this industry rather than producing energy from waste.

The second one was that no laboratory work was possible to analyze the *nejayote* samples provided by the corn mill visited in Mexico City. The actual composition of *El Michoacano* wastewaters would have provided a more accurate assessment of the potentials of biogas production compared to other wastewater treatment options. However, sending the samples to Sweden was not possible due to constraints with permits, costs and time. Laboratory-made samples were not considered since the materials needed, such as white corn, cannot be found in Sweden; this would have given samples with a different chemical composition to the ones taken on site. Therefore, the assessment of biogas production from the *nejayote* at *El Michoacano* was done with information available from the literature and the data gathered during the field visit.
Biogas is produced through the anaerobic degradation of organic matter, commonly from industrial organic wastes (i.e. slaughter houses, residues from the food industry, etc.), agricultural wastes, sludge from wastewater treatment plants, biofuel production by-products (i.e. glycerine, stillage, etc.) and when separated, household organic wastes (Deublein and Steinhauser, 2010). The anaerobic degradation process consists of four phases (Fig.1):

1) **Hydrolysis**: non-soluble biopolymers (proteins, carbohydrates and lipids) are broken down to soluble organic compounds by hydrolytic bacteria,

2) **Acidogenesis**: the soluble organic compounds (amino acids, sugars, long chain fatty acids and glycerol) are decomposed into volatile fatty acids (VFAs) and carbon dioxide (CO$_2$) by acidogenic bacteria,

3) **Acetogenesis**: acetogenic bacteria convert VFAs into acetic acid (CH$_3$COOH) or hydrogen (H$_2$) and carbon dioxide,

4) **Methanation**: methanogens use these intermediate products for producing biogas – also called raw gas –, a mix that contains 55-75% methane, 25-45% carbon dioxide and a small percentage of trace gases like hydrogen sulfide, hydrogen, nitrogen, ammonia, siloxanes, halides, oxygen, water vapour and carbon monoxide (Aranzabe and Ciria, 2004; de Mes, et al., 2003).

**FIGURE 1.** Simplified representation of the anaerobic degradation process (de Mes, et al., 2003).
This biological process is strongly influenced by parameters such as temperature, pH, hydrogen partial pressure, mixing, light, nutrients (C:N:P ratio), etc. (Deublein and Steinhauser, 2010). For a stable anaerobic degradation it is fundamental that various biological conversions remain sufficiently coupled. For example, molecular hydrogen is formed during different stages of the process and it is consumed by the microbial consortia that exchange electrons through what is called interspecies electron transfer (Appels, et al., 2008). Assuming that the microorganisms that produce and consume hydrogen are well balanced, an organic overloading will increase the hydrogen partial pressure, causing an accumulation of volatile fatty acids (VFAs) and in consequence a decrease in the pH under which the methanation can be inhibited (Pind, et al., 2003).

Biogas is mainly used for heating, cooking and in the co-generation of heat and electricity, but depending on the quality requirements for certain applications, it can be upgraded to high purity standards like compressed biogas (CBG) which contains 97 percent methane or liquid biogas (LBG) which contains 100 percent methane to be used as biofuels for transport. Carbon dioxide can also be recovered and used as a cooling gas, for feeding greenhouses, etc., while the hydrogen sulfide can be precipitated in order to utilize the recovered sulfur as a fertilizer (Deublein and Steinhauser, 2010).

Among the by-products of biogas production, the effluents of the process – called digestate– can be used as bio-fertilizers depending on the substrate, material for soils amendment, converted to energy pellets or burnt in combined heat and power (CHP) plants (Martin, 2010).

Biogas production at a small scale has existed for centuries, for example, it was first used in Assyria (today Iraq) for heating baths around the year 10 BC and to date, many developing countries like China, India, Nepal and some African countries produce biogas for cooking, heating and providing electricity (Achten, et al., 2010; Deublein and Steinhauser, 2010). At the industrial scale, there are approximately 9,200 biogas plants in the world with a total electric power capacity of 31,378 MW; from those, 8,536 plants are located in Europe, 600 in the U.S., 19 in Asia, 18 in Australia, 15 in Canada, 8 in South America – mainly in Argentina, Brazil and Chile –and 4 in Africa (Deublein and Steinhauser, 2010).

In other developing countries the construction and implementation of biogas plants are small and simple (with digester volumes of 2-10m³); most of them have been financed through Clean Development Mechanism (CDM) projects for the mitigation of greenhouse gases from agriculture and the livestock sector rather than for electricity production, as in the case of Mexico (SAGARPA-FIRCO, 2007).
Pollution was recognized as a serious problem long ago but it was not until the 1960s that it became an international concern that culminated in 1983 with the World Commission on Environment and Development (WCED) and the publication in 1987 of the Brundtland report *Our Common Future*, placing the concept of sustainable development into the center of the global environmental and development debate (Selin and Linnér, 2005).

With the environmental crisis of the sixties and the United Nations conferences that followed the Brundtland report as the background, there was a paradigm shift regarding pollution control within the industrial realm. Also known as *cradle-to-grave*, the old paradigm essentially followed a linear flow of resources: extraction of raw materials, manufacture of products, use and eventual disposal (Braungart, et al., 2007).

Because in natural ecosystems true waste products are rare, during the 1990s a new approach gained acceptance. It aimed at reducing and preferably eliminating industrial wastes so as the use of materials that cannot be naturally degraded or consumed as fuels (Manahan, 1999). The new field of Industrial Ecology (IE) focused on integrating the production and consumption aspects of the entire life cycle of materials and energy with the purpose of “minimizing their environmental impacts while optimizing the utilization of resources, energy and capital” (*Loc cit.*).

Also called “the science of sustainability” (Allenby, 1990), the Industrial Ecology approach is based on the *cradle-to-cradle* principle by which the traditional linear flows of energy and materials are closed into loops by means of transforming them into useful production inputs for the same or other industrial processes (Ayres and Ayres, 1996). This can be achieved through material substitution, dematerialization, material cascading and recycling (Ayres and Ayres, 1996; Manahan, 1999).

Much like natural ecosystems, the concept and strategies of IE can be applied for optimization of industrial processes on three different levels: the global, the inter-firm and the firm level (Chertow, 2000) and can be driven by the development of new technologies, economics or by government regulation (Manahan, 1999).

In particular, awareness of the environmental impacts associated to climate change from anthropogenic activities and the global concerns about rapidly decreasing known fossil fuel reserves have fostered the implementation of IE strategies at all levels towards the achievement of energy security in a sustainable way, as it has been the case of biogas production from organic waste, a type of material cascading.

### 3.1 Current situation in Mexico

The strategies and actions for adapting to climate change in Mexico are circumscribed within two main international directives: the United Nations Framework Convention on Climate Change (1995) and the Kyoto Protocol (1997). Climate change mitigation and adaptation are
guiding principles of the National Development Plan 2007-2012 for the achievement of two Sustainable Development goals: the first one proposes the reduction of greenhouse gases (GHGs) through schemes of energy efficiency and the use of renewable sources, in particular biomass from waste, and the second one aims to foster strategies that strengthen the adaptive capacity to climate change.

Although carbon dioxide emissions remain the largest national source of greenhouse gases to the atmosphere with 492.8 million tons (MMtCO₂), methane emissions almost doubled in the last couple of decades from 5.1 to 8.8 million tons of carbon dioxide equivalent (MMtCO₂e) in 1990 and 2006 respectively (SEMARNAT-INE, 2009). Furthermore, methane emissions from waste had a three-fold increase from 1.5 to 4.6 MMtCO₂e for the same years (Arvizu, 2008). This can be explained due to a rise in the methane emission sources without the means to avoid or mitigate these emissions; the sources include municipal and industrial wastewaters so as the organic fraction of the municipal solid waste (OFMSW) that decomposes in landfills (Loc cit.).

Also, there have been important changes in the methane contribution by category: in 1990 the organic fraction of the municipal solid waste contributed with 54% of the total, the municipal wastewaters with 29% and the industrial wastewaters with 17%. For the year 2006 the methane emissions from the OFMSW slightly decreased to 52%, those from municipal wastewaters decreased to 14% but the methane from industrial wastewaters doubled to 34% (SEMARNAT-INE, 2009; Arvizu, 2008).

Particularly for the industrial wastewaters, the expansion of the industrial sector has not been accompanied by a similar capacity to treat the wastewaters from its processes; only 15% of the industrial wastewaters are treated in compliance with the Mexican Official Standards (NOMs) for other uses (i.e. treated water for industrial, commercial and residential services) and the other 85% are discharged to the environment mostly without any treatment (Arvizu, 2008) as it is the case of the tortilla manufacturing industry. For example, in 2006 the National Commission of Water (CONAGUA) reported that approximately 70% of the wastewater treatment plants within the industrial sector were not in use or did not comply with the water discharge standards of the NOMs (Loc cit.).

Methane emissions from industrial wastewaters from 1990 to 2006 in Mexico are shown in Figure 2. The data was calculated with the 1996’s Good Practice Guidance and Uncertainty Management Methodology from the Intergovernmental Panel on Climate Change (IPCC) and it includes wastewaters from the following industries: iron and steel, non-ferrous metals, fertilizers, food & beverage, paper & pulp, petroleum refining, rubber and others (not specified in Arvizu, 2008).

Regarding the organic fraction of the industrial wastes, only manure from swine operations and to a lesser extent the residues from dairy farms and slaughterhouses have been used to recover methane through Clean Development Mechanism projects in the country (www.globalmethane.org, visited 26th April 2011). Mexico has the eight largest swine population in the world with over 15.2 million pigs (Loc cit.) that produce approximately 5.7 million tons of manure with a biogas potential of 4,050 million cubic meters per year.
(SAGARPA-FIRCO, 2008). The carbon dioxide emission reduction from the anaerobic degradation of swine manure has been estimated in 36.6 million tons per year (Loc cit.).

**FIGURE 2.** Methane emissions from industrial wastewaters in Mexico 1990-2006 (MtCO$_2$e). Based on Arvizu, 2008.

Given the previous estimations, the Global Methane Initiative reported that in 2010 there were approximately 170 anaerobic digesters in operation based on the National Technical Standards for the Design and Construction of Biodigesters developed by the Mexican Federal Government for the mitigation of methane from the agricultural and livestock sectors (ERG-Tetra Tech-CySTE, 2010; SEMARNAT-SAGARPA, 2008).

The installed digesters are covered anaerobic lagoons and the most common biogas applications are electricity production, heating, and cooking (ERG-Tetra Tech-CySTE, 2010). The projects are joint-ventures between the farm owners who contribute with two thirds of the total investments and the Federal Government that contributes with the other third (Bonilla, 2010). These projects are also eligible for fiscal incentives in the form of tax deductions and credits (SEMARNAT-FIRCO, 2008).

Waste and wastewaters from agroindustrial activities are an important source of methane as an energy carrier that has not been fully harnessed; instead it has mainly remained as a greenhouse gas whose emissions have not been avoided or mitigated (Arvizu, 2008; Paredes, *et al.*, 1991). Currently, the traditional tortilla manufacturing industry discharges about 13 to 16 million cubic meters of untreated wastewaters to the sewer that could otherwise be used for energy production, as it will be analyzed in the next part of the thesis.
All agroindustrial activities consist of the conditioning, transformation, conservation and commercialization of products from agriculture, livestock, forestry and fishing into value-added goods for consumption (ASERCA, 2008). Therefore, the agroindustry has the task of fulfilling the population’s alimentary demands by meeting high safety and quality standards with a sustainable use of natural resources.

In Mexico, the manufacture of tortillas relies on two types of industry: the large cornmeal factories and the traditional corn mills. This activity is one amongst eleven others that integrate the Food and Beverage Manufacturing Industry and it is a fundamental link in the vertical integration of the value chain of maize-tortilla (Loc cit.), as it is analyzed below following the criteria previously defined in the methodology.

4.1 Maize: a basic and strategic food.

The first archaeological evidence of the use of corn in Mesoamerica is about 6,250 years old and it has over 600 uses profoundly rooted in the cultures of Mexico, Belize, Guatemala, El Salvador, Honduras, Nicaragua and Costa Rica (Piperno and Flannery, 2001). Furthermore, corn has a much widely diversified use compared to other cereals: as food for human consumption and feed for animals, for the production of starch, glucose, dextrose, fructose, oils, snacks, ethanol, etc., and as raw material in the manufacture of alcoholic beverages and other products within the textile, electronic, mining and pharmaceutical industry (Polanco Jaime and Flores Méndez, 2008).

In addition to these applications, in Mexico the root, stalks, silk, ears and husk – the last ones traditionally called olote and totomoxtle respectively –, have many other uses. For example, the root and stalks are utilized as fuel for cooking and house heating; the olote and the silk are used in traditional medicine as infusions for treating diarrhea and malaria respectively, and the olote one can also be burnt to scare mosquitoes away. The totomoxtle is a common material for the manufacture of handicrafts and to wrap tamales (Flores Valdez, et al., 2007).

Corn (Zea mays) is also a staple ingredient used for preparing tortillas, atole, tamales, sopes and other traditional dishes considered basic in the diet of the majority of the Mexican population as it is their main source of calories (Acosta, et al., 1988). The consumption of 8 to 10 tortillas (286gr) provides 47 percent of the daily calories in an average Mexican diet that also includes bread, sugar, oils, dairy products, bean, pasta and others (Tron de la Concha, 2004; Polanco Jaime and Flores Méndez, 2008) and it is the source of up to 46 percent of the proteins consumed by the poorest decile (Gálvez, 2007). Tortillas are also a source of calcium, iron, thiamin, niacin, riboflavin and amino acids like leucine, threonine, valine, etc. (Flores Valdez, et al., 2007).

For this, it is considered the most important food of the eleven defined in the Law for Rural Sustainable Development: maize, sugar cane, bean, wheat, rice, sorghum, coffee, egg,
milk, meat and fish (LDRS, Art.179). This law regulates the agricultural production, industrialization and commercialization of food in order to assure the country’s alimentary sovereignty and security.

Maize has a unique genetic diversity that can be found all over the territory despite the differences in climate and altitude within it (Salinas Moreno, pers. comm.); it is also the most important crop in terms of the economy and above all, of the culture, as it conveys symbolic and spiritual values that are absent in other large corn-producing countries such as France or United States (Fournier, 1996).

As reported by the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA), 10 million tons of white corn are consumed in Mexico in the form of tortillas every year. Despite the negative impacts of the economic liberalization in the maize industry during the eighties, the annual average tortilla consumption has remained relatively stable over time with 105 kg per capita (SAGARPA, 2007).

On average, Mexican families devote 7 percent of their monthly income in buying tortillas\(^2\); however, when compared to other cereals, the expenditure is much larger as it represents 24 percent of the total expenses in corn-based products\(^3\). The other 76 percent is used in the acquisition of grain, flour, dough, tostaditas and snacks (Polanco Jaime and Flores Méndez, 2008).

Maize is also a staple ingredient in the elaboration of feed for the livestock sector, thus increases in the international market price of yellow corn have altered the national price and availability of white corn for human consumption towards its use as animal feed (Loc cit.). Among the reasons to explain this situation is that Mexico imports from the U.S. approximately 30 percent of the total yellow corn consumed nationally, being currently the fourth largest importer after Japan, Korea and Taiwan (Loc cit.).

Furthermore, worldwide production of white corn is limited and geographically dispersed\(^4\) (Flores Valdez, et al., 2007), thence higher prices are likely to affect the traditional tortilla manufacturing industry for two reasons: the first one is that the production costs rely on and vary with the international prices of white corn because the subsidies to this grain were eliminated in 2008 with the North American Free Trade Agreement (NAFTA).

The second one is because yellow corn is not a direct substitute of white corn for the manufacture of tortillas. In Mexico white corn is preferred over the yellow one for its taste and because the last one has a brittle nature derived from the artificial drying processes used in the U.S. This makes yellow corn unsuitable for nixtamalization since the losses of organic

\(^2\) The average monthly income of a Mexican family of 4 members is 11,670 pesos (ca. US 870) (ENIGH, 2010).
\(^3\) Mexican families spend circa 33 percent of their monthly income in food (incl. meat, dairy products, fruits and vegetables, etc.), beverages and tobacco (ENIGH, 2010). From this, 52 percent is spent in corn-based products (Flores Valdez, et al., 2007).
\(^4\) Mexico leads the white corn production with 19 million tons every year, followed by South Africa with 5.7 million tons, Egypt with 5.6 million tons, Nigeria with 4.4 million tons and the U.S. with 3.2 million tons of white corn (Flores Valdez, et al., 2007).
matter into *nejayote* are six times higher than those from white corn, reducing the overall productivity of this type of corn and increasing the total production costs of corn mills (Sánchez Tovar, *et al.*, 1993; Durán de Bazúa and Hartmann, 1987).

According to Durán de Bazúa (1985), if agricultural and industrial wastes were “reprocessed and conditioned to be used in feeds, and with a lesser cost, cereals would be fully used for human consumption”. As it will be further analyzed in the fifth part of the thesis – *Biogas and by-products utilization* –, the treatment of wastewaters in the traditional tortilla manufacturing industry is also an opportunity for competitiveness if corn mills are able to produce high-quality products at lower energy costs.

**4.2 Production volume and geographic location.**

Maize production in Mexico is comprised by 92 percent of white corn, 7 percent of yellow corn and 1 percent of other types (Flores Valdez, *et al.*, 2007). In 2006 the official value of maize production was 44,440 million pesos (ca. US 3.7 million) representing nearly 13 percent of the agricultural gross domestic product (CNPAMM, 2007), however, these numbers are usually underestimated as they do not include the economic value of corn production for subsistence and the market value of maize by-products traded with other industries (i.e. livestock sector).

The agroindustrial chain of value of maize comprehends a primary and a secondary sector. The primary sector relies on production and harvest of white and yellow corn and represented 36 percent (nearly 33 thousand million pesos or 2,700 million USD) of the total chain value in 2006; the secondary sector, constituted by the corn-processing industries for food, animal feed and other applications, corresponded to the other 64 percent of the chain of value of maize equivalent to 58 thousand million pesos or 4,700 million USD (Flores Valdez, *et al.*, 2007 with data from SAGARPA, 2007).

Within the secondary sector, the traditional tortilla manufacturing industry is worth over 32 thousand million pesos (ca. US 2,600 million) or 1 percent of the national gross domestic product (SAGARPA, 2007), accounting for 55 percent of the total sector’s value; the cornmeal industry, the cereals and snacks industry and other corn-based industries represent altogether the remaining 45 percent of the secondary sector’s value (*Loc cit.*).

Albeit the economic relevance of the traditional tortilla manufacturing sector within the agroindustrial chain of value of maize, the production volumes of corn mills and their geographic location are reliant on local consumption patterns and income (Villaseñor Flores, 2009). For example, in the North of Mexico wheat tortillas are usually consumed for breakfast and dinner and only corn tortillas are consumed for lunch; in Central Mexico corn tortillas are preferred over their wheat counterparts but a lot of families also eat white bread (French baguette, *bolillo*, *teleera*, etc.). In the South and Southeastern regions corn tortillas are considered basic in the people’s diets and they accompany all their daily meals (*Loc cit.*).

Even though it can be assumed that production volumes in the Central, South and Southeastern regions of Mexico are larger than in the North, with the extinction of the
National Company of Popular Subsistence (CONASUPO) in March 1999, the exact characteristics and geographic distribution of the traditional tortilla manufacturing industry can no longer be known since this government agency was in charge of the authorization and registry of all the corn mills and tortillerías\(^5\) in the country (Maximiliano Martínez, et al., 2011). CONASUPO was also responsible for the acquisition, storage, transport, commercialization, supply of grain and in general, for the market regulation of the maize and tortilla industry that currently operates under the schemes derived from the economic liberalization of the 1980s, the NAFTA and the large multinationals that control most of the activities of the extinct CONASUPO (Loc cit.).

Estimations of the Ministry of Agriculture, Livestock, Rural Development, Fisheries and Food (SAGARPA) indicate that in 2008 there were between ten and twelve thousand corn mills operating in the country and circa 78,830 tortillerías, the last ones representing 55 percent of all the economic units within the food industry (INEGI, 2009). Traditional corn mills process and transform 32 percent of the white corn produced every year in order to manufacture 54 percent of the total amount of tortillas that are commercialized in Mexico; the other 46 percent is supplied to the market by the cornmeal industry, which demands 35 percent of the white corn produced annually. The remaining 33 percent of white corn is used by the rural population in the elaboration of tortillas for subsistence and to feed their animals (Polanco Jaime and Flores Méndez, 2008 with data from SAGARPA, 2007).

Ambriz García and Paredes Rubio identified three types of traditional corn mills by production volume of nixtamal dough per day: small (3,000 kg/day), medium (5,000 kg/day) and large (10,000-12,000 kg/day). These economic units typically have a tortillería where they sell to the public approximately 10 percent of the nixtamal dough in the form of tortillas and a few more kilos fresh. The other 90 percent of their daily nixtamal dough production is distributed to local tortillerías, restaurants and small businesses (Ambriz García and Paredes Rubio, 2009).

The traditional tortilla manufacturing industry is very fragmented, geographically dispersed and organizationally disintegrated (Ramírez Vives, pers. comm.). In most cases, traditional corn mills lack the economic capacity to comply with their legal obligations (environmental, sanitary, occupational safety, etc.) at the risk of costly penalties or even closure in case of official control (Hernández Franco y de Teresa Ochoa, 2009; Villaseñor Flores, 2009).

This traditional industry follows a resource intensive transformation process that has remained virtually unchanged (Ramírez Romero and León Sánchez, 2009). The lack of innovation in the technologies used by corn mills and tortillerías has put them at risk of disappearing as the price of their products (nixtamal dough and tortillas) cannot be increased at the same rate as the prices of the production inputs have had over the last decade (maize, water, gaseous and liquid fuels and electricity). In the following section the transformation process of traditional corn mills will be studied based on the use of material and energy inputs. The aim is to identify the potential uses of biogas and the anaerobic degradation by-\h

\(^5\) A tortillería is the physical place, a store, where tortillas are cooked and sold to the public.
products of *nejayote* in the improvement of the economic and resource efficiency of these economic units.

### 4.3 Use of resources in the tortilla manufacturing industry.

In Mexico, corn processing in the traditional tortilla industry follows an ancient technique known as *nixtamalization* (from the Nahuatl language *nextli*: slaked lime ashes and *tamalli*: cooked corn dough), a water, time and energy intensive process (Fig. 3).

Nowadays the *nixtamalization* process is more or less standardized, consisting in a slaked lime solution at boiling temperature where corn is cooked for about 30 minutes to 1 hour; then the *nixtamal* (cooked corn) is left to repose overnight up to approximately 15 hours to facilitate the grinding for preparing the dough (Robles de la Torre, 1986). Although the traditional technique includes a rinsing step (Fig.3), in some corn mills it has been eliminated in order to reduce the overall process time, the water consumption and the costs (Puebla Salazar, pers. comm.).

![Flowchart of the traditional nixtamalization process](image-url)

**FIGURE 3.** Traditional nixtamalization technique.
Modified from Durán de Bazúa and Hartmann, 1987.

After three decades the environmental problems of the traditional *nixtamalization* technique are persistent and have been aggravated by a more strict environmental legislation and higher production costs due to the limited and more expensive access to water, fluctuations in the price of corn and the market volatility of the fossil fuels. The typical cost structure of processing one ton of white corn at *El Michoacano* corn mill in Mexico City is shown in Table 1 with data for September 2011.
From Table 1 it is possible to identify that after the cost of maize, the energy expenses are the second most important and represent 24 percent of the production cost per ton of corn processed. The nixtamalization process mainly consumes thermal energy from gas, which is used to heat the water of the mixing tank where the corn is cooked with the calcium hydroxide. Either liquefied petroleum gas (LPG) or natural gas (NG) can be used.

Although the unitary price of NG is lower than that of LPG, most corn mills use LPG because the installation and distribution costs are much lower, LPG has a higher energy density per unit volume than the NG (94 MJ/m$^3$ and 38 MJ/m$^3$ respectively), and most importantly, the cost of NG varies with the international price of this fossil fuel and the exchange rate of the U.S. dollar, while LPG is subsidized by the government. Electricity is used to power the engines of the mills, the conveyor belts, the water pumps and it is also used for the lighting system (Ambriz García and Paredes Rubio, 2009).

The following table shows the energy demand of El Michoacano per ton of white corn processed:

**TABLE 2.** Energy demand per ton of corn processed at El Michoacano.

<table>
<thead>
<tr>
<th>Concept</th>
<th>Amount per ton of corn</th>
<th>Equivalent in MJ*</th>
<th>Percentage of total energy demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPG</td>
<td>36 liters</td>
<td>846</td>
<td>77%</td>
</tr>
<tr>
<td>Electricity</td>
<td>70 kWh</td>
<td>252</td>
<td>23%</td>
</tr>
</tbody>
</table>

*The conversion factor for LPG is 0.250 m$^3$ per liter, and 94 MJ/m$^3$. For electricity is 3.6 MJ per kWh. Based on data from El Michoacano (Puebla Salazar, pers. comm.).
Despite the electricity consumption is much lower than the gas per ton of corn processed, the unitary cost per kWh of electricity is higher than that of the liquefied petroleum gas (LPG) which is 2.80 pesos for electricity and 0.70 pesos for LPG (the cost per liter of LPG is 4.50 pesos and the conversion factor is 6.5 kWh per liter). The electricity represents 55 percent of the total cost of energy – 360 pesos – and LPG accounts for the other 45 percent (Table 1). Thus, it can be inferred that a variation in the price of electricity can strongly affect the cost structure of *El Michoacano* and the same situation would apply to the traditional corn mills that have a similar structure of their energy demand and costs.

According to the *National Strategy of Energy 2010-2024*, the variations in the international markets of fossil fuels have been reflected in higher electricity prices, which have mainly affected the commercial sector – that includes the traditional corn mills – and the large industries because their electricity fees are not subsidized (SENER 2008, 2010).

The figure below (Fig.4) shows the changes in the average price of electricity for the two types of fees that apply to traditional corn mills based on their energy demands.

![Figure 4: Average price of electricity per type of fee (pesos/kWh).](image)

Made with data from the Ministry of Energy. Prices include a value added tax (VAT) of 15% from 2004 to 2009 and a VAT of 16% for 2010 and 2011. Information available since 2004.

The final price of electricity paid by a corn mill will depend on the type of fee contracted with the Federal Commission of Electricity (CFE) and it is comprised by the voltage, the energy consumed, the value of maximum demand and the power factor. In Figure 4, the fee on top applies to small establishments with a maximum energy demand of 25kW and the one below applies to establishments that require 120-440 volts for operating their machinery and that have an energy demand above 25kW (SENER, 2008), as in the case of *El Michoacano* corn mill.

In both types of fee, the final price will vary with the cost of electricity production, affecting the cost structure of corn mills. Therefore, biogas can be potentially used to cut

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down the cost of electricity by partially – or entirely if possible – substituting it through the anaerobic treatment of the corn mills’ wastewaters.

4.4 Waste profile: nejayote.

Food processing in general requires large volumes of water that are converted into wastewaters (Navarrete and Osorio, 1991). As described above, the water requirements by the traditional nixtamalization technique are in the order of 6 to one (water:grain ratio) and the effluent or nejayote (from the Nahuatl language nextli: slaked lime ashes, ayoh: broth and atl: water) is usually in a ratio of about four to five times the amount of corn processed (Orozco, et al., 2008; Durán de Bazúa and Hartmann, 1987).

Since traditional corn mills annually process and transform 3.2 million tons of white corn for the manufacture of tortillas, about 13 to 16 million cubic meters of nejayote are being produced and discharged untreated to the sewage systems every year. When disposed, the nejayote has an elevated temperature (40-70°C), pH (10-14) and contains high organic loads in the form of suspended and dissolved solids (Table 3).

**Table 3. Average composition of nejayote.**

<table>
<thead>
<tr>
<th>Parameter (mg/l)</th>
<th>Nejayote</th>
<th>NOMs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids concentration (SS)</td>
<td>2.4-4.6 kg/m³</td>
<td>150</td>
</tr>
<tr>
<td>Biochemical oxygen demand (BOD₅)</td>
<td>1.5-3.0 kg/m³</td>
<td>150</td>
</tr>
<tr>
<td>Chemical oxygen demand (COD)</td>
<td>7.5-11.0 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Dissolved organic carbon (DOC)</td>
<td>3.0-5.0 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen (TKN)</td>
<td>0.08-0.27 kg/m³</td>
<td></td>
</tr>
<tr>
<td>Phosphorus (PO₄³⁻)</td>
<td>0.007-0.018 kg/m³</td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>10-14</td>
<td></td>
</tr>
</tbody>
</table>

Durán de Bazúa and Hartmann, 1987.

Compared to the Official Mexican Standards (NOMs) that establish the maximum permissible levels of pollutants in wastewater discharges into national water receiving bodies and municipal sewage systems, the composition of nejayote surpasses most of the parameters:

**Table 4. Nejayote composition vs. limits imposed by the Official Mexican Standards (NOMs) NOM-001-SEMARNAT-1996 and NOM-002-SEMARNAT-1996.**

<table>
<thead>
<tr>
<th>Parameter (mg/l)</th>
<th>Nejayote</th>
<th>NOMs*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended solids</td>
<td>2,400-4,600</td>
<td>150</td>
</tr>
<tr>
<td>Biochemical oxygen</td>
<td>1,500-3,000</td>
<td>150</td>
</tr>
<tr>
<td>Total Kjeldahl Nitrogen</td>
<td>80-270</td>
<td>40</td>
</tr>
<tr>
<td>Phosphorus (PO₄³⁻)</td>
<td>7-18</td>
<td>20</td>
</tr>
<tr>
<td>pH</td>
<td>10-14</td>
<td>5.5-10</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>40-70</td>
<td>40</td>
</tr>
</tbody>
</table>

*The NOMs do not include the chemical oxygen demand (COD) as a parameter.

The untreated nejayote complies with the maximum limits established by the NOMs regarding phosphorus concentration, pH and temperature, but all the other parameters are
surpassed; by 16 to 30 times in the case of the suspended solids (SS), by 10 to 20 times for the biochemical oxygen demand (BODs) and by 2 to 7 times in the case of nitrogen (TKN).

In *El Michoacano* 4 tons of white corn are transformed to 7.7 tons of *nixtamal* dough every day. The corn is processed in 6 batches of 650 kilograms, each mixed with 1.1 cubic meters of water, 6.5 kilos of calcium hydroxide and 400 grams of natural gums (Xanthan and Guar); this mix produces 1,250 kilos of *nixtamal* dough and 500 liters of *nejayote* per batch. Thence, the daily *nejayote* production can be estimated in 770 liters per ton of corn processed and 3080 liters per day.

Compared to the theory, the amount of *nejayote* produced at *El Michoacano* is 77 percent of the amount of corn processed rather than 4 to 5 times more. This is due to the low water requirements of the *nixtamalization* process at this corn mill, where 1.7 liters of water are used per kilogram of corn processed instead of 6 liters. Furthermore, the addition of the Xantan and Guar gums allows the grain to absorb water up to 90 percent of the corn’s dry weight instead of the standard 75 to 80 percent when the gums are not added. This is done to prevent the tortillas to get too dry and break when they are reheated.

Based on the average composition of *nejayote* (Table 3), every day *El Michoacano* discharges 3.08 cubic meters of wastewaters with a total suspended solids (SS) content of 7.5 to 14 kilograms; however, this value – so as the COD and BOD₃ – could be higher due to the low water demand per kilogram of corn processed at this corn mill. As reported by Durán de Bazúa and Hartmann (1987), the *nejayote* composition from an urban corn mill with a similar water demand to *El Michoacano* resulted in a COD value of 21 kg/m³, a BOD₃ of 8 kg/m³ and 20 kg/m³ of SS; all of them being much higher than those presented in Table 3.

A scenario like this suggests a larger amount of organic matter per cubic meter of *nejayote* that could be anaerobically degraded to methane for energy production *in situ*. Even though speculative, the implications for biogas production at *El Michoacano* based on the observations from Durán de Bazúa and Hartmann (1987) will be discussed in the sixth chapter of this thesis.

In regard to the kind and amount of solid waste from corn mills, the grain bought to the suppliers usually contains up to 0.3% of impurities like broken grains and corn sand—called *granza* and *tamo* respectively – that are recovered during the sifting step (Puebla Salazar, pers. comm.). From every 650 kilograms-batch of corn between 1.5 to 2 kilos of *tamo* and *granza* are recovered, yielding from 9 to 12 kilograms per day. Currently, these residues are used for animal feed and packaged in recycled sacs from the corn storage. Because the *tamo* and *granza* are sold *in situ*, *El Michoacano* does not incur in delivery expenses but profits from the 2.40 pesos per kilo of these corn residues.
5. Biogas compared to other wastewater treatments and corn processing techniques

The nixtamalization process at El Michoacano starts by sifting 650 kilos of white corn per batch with a 3/16 inches mesh where the tamo and granza are recovered (Fig.5). Then the clean grain is lifted up with a bucket elevator to a mixing tank where it is cooked in 1,100 liters of water with 6.5 kilos of slaked lime and 400 grams of Xantan and Guar gums for 15 to 20 minutes at a boiling temperature of 93°C. Afterwards the nixtamal (cooked corn) is transferred, by gravity, to another tank – six tanks in total – where is left to repose overnight.

The next day the nixtamal from each rest tank is moved to a deposit where it is drained and briefly washed; in this step the nejayote is discharged directly to the sewer. Then the nixtamal descends by gravity to the top of a mill – two mills in total – where it is grinded with 20 to 22 liters of fresh water per batch (Puebla Salazar, pers. comm.). The nixtamal dough produced is weighted in 50 kilogram units called maletas that are wrapped in light blankets to be delivered to tortillerías located within a ratio of 8 to 10 kilometers from the corn mill. Every day from 5:00 to 16:00 hours, 150 to 153 maletas are produced from the 4 tons of white corn transformed into 7.7 tons of nixtamal dough.

![Figure 5](image.png)

**Figure 5.** Nixtamalization process at El Michoacano (field visit, June 29th 2011).

Every day, El Michoacano discharges 3.08 cubic meters of nejayote with an approximate suspended solids content of 2.4 to 4.6 kilograms per cubic meter (Table 3). Even though the low water demand per kilogram of corn processed at this corn mill could have given higher COD, BOD$_5$ and SS values, no laboratory work was possible to analyze the nejayote samples provided during the field visit. Thence, the values presented in Table 3 were used for calculating the biogas potential from its anaerobic degradation in situ.
Based on the above data, four scenarios were formulated to solve the water pollution problem of this corn mill: 1) separate the suspended solids (SS) in nejayote by sedimentation for reducing its organic content when discharged to the sewer, 2) aerobically treat these wastewaters in order to recover a protein-rich microbial biomass to be used as animal feed, 3) use the biogas from the anaerobic degradation of nejayote to cover part of the energy demand of El Michoacano, and 4) switch to the alkaline extrusion of corn as an alternative to the traditional nixtamalization technique.

These scenarios were compared based on their processes, end-products and costs in order to provide an alternative to the current modus operandi or business as usual at El Michoacano. In the business as usual, the environmental burden of nejayote to the sewage system is unchanged and the corn mill continues operations without treating its wastewaters. Although this option does not involve any costs, the non compliance with the Official Mexican Standards (NOMs) leaves this corn mill at risk of costly penalties or even closure in case of official control from the Federal Bureau of Environmental Protection (PROFEPA).

5.1 Separation of suspended solids.

In the first scenario the suspended matter in nejayote can be separated by sedimentation in order to reduce its organic content when discharged to the sewer. This primary treatment will allow a BOD$_5$ reduction of 25 to 55 percent and a suspended solids (SS) removal of 50 to 70 percent (Ramírez Romero, et al., 2011; Pescod, 1992). Still, the primary effluents would not comply with the NOMs since a minimum BOD$_5$ of 750 mg/l exceeds the maximum permissible of 150 mg/l (Cf. Table 4), but the sedimentation time will allow to have a lower temperature in these waters when discharged to the sewer.

Given the characteristics and daily amount of nejayote at El Michoacano (Cf. Table 3), two information requests were sent to companies specialized in waste handling and wastewater treatment: Tekniska Verken i Linköping AB and Envac Scandinavia AB. In both cases a low-cost sedimentation tank made of fiberglass and with a capacity of 3m$^3$ was sized based on a residence time of approximately one hour (Ramírez Romero, et al., 2011; Ekendahl, pers. comm.; Barrling, pers. comm.). The estimated cost of the tank is 80,000 pesos (ca. US 5,800).

After separation, the suspended solids would be screw pressed with a Volute ES-051ST to lower their water content to 20-25% (Lorenz, pers. comm.) in order to be sold as animal feed, as it is currently done in El Michoacano with the tamo and granza at 2.40 pesos per kilo. According to EcoAzur S.A. de C.V., a third wastewater company consulted, the screw press has a processing capacity of 1.5 kg/h of solids (dry basis) and an electricity consumption of 0.2 kWh (Loc cit.).

The effluents from the primary sedimentation and the screw pressing can be neutralized to a pH of 7-7.5 with CO$_2$ in order to comply with the NOMs (Ramírez Romero, et al., 2011). Although the content of calcium hydroxide in these waters is unknown, in order to prevent fouling in piping from limescale buildup (Navarrete and Osorio, 1991), the
addition of carbon dioxide can also be used to precipitate it in the form of calcium carbonate according to the following chemical equation:

\[ \text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \]

As reported by Velasco Martínez and his colleagues (1997), the recovered carbonate could be used as an additional source of calcium in animal diets by mixing it with the tamo and granza. Assuming a 70 percent removal of the suspended solids in nejayote, about 10 kg of solids can be recovered per day according to the following calculation:

\[
(4.6 \text{ kg/m}^3 \times 3.08 \text{ m}^3)(0.70)
\]

Approximately 70 kg of suspended matter can be recovered every week; even so, the cost of the press is 530,000 pesos or ca. US 40,000 (Lorenz, pers. comm.), giving a total investment cost of 610,000 pesos. Even if 910 kilograms of solids (25% moisture) can be recovered per year and sold at 2.40 pesos per kilo, an annual profit of 2,180 pesos would be too small compared to the investments costs; on these grounds, this scenario is rejected as a viable option for the wastewater treatment at El Michoacano.

### 5.2 Aerobic treatment for the recovery of protein-rich microbial biomass.

The second scenario is based on the laboratory results of Durán de Bazúa and Hartmann (1987) where the suspended matter in the nejayote is also separated by sedimentation and the dissolved organics are precipitated by aerobically transforming them into microbial biomass with rotating biological reactors (RBRs).

The RBRs process, also known as rotating biological contactors (RBCs), is a secondary treatment consisting of a series of corrugated plastic discs attached to a common shaft. The discs are partially submerged in the wastewater and slowly rotate in a concrete tank (see Fig.6). Microorganisms in the wastewater attach and multiply in the rotating discs forming a biological fixed film or a thin layer of biomass. During rotation, the active microorganism populations in the film degrade the organic matter in wastewater in the presence of oxygen taken from the air (Pescod, 1992; Taicheong and Stenstrom, 1979).

![Figure 6. Typical design of a rotating biological reactor (RBR). Based on Durán de Bazúa and Hartmann, 1987.](image-url)
The excess biomass that shears off during rotation can be separated by sedimentation and mixed with the primary suspended solids, the *tamo* and *granza*. This mix can be dried by different methods (i.e. freeze-drying, spray-drying or conventional oven-drying at 60°C) and pelletized to produce high quality animal feed with a microbial protein content up to 40 percent on a dry basis to be used in fish and shrimp diets (Durán de Bazúa and Hartmann, 1987).

According to these authors, 11 to 12 tons of white corn will produce enough nejayote to recover the protein-rich microbial biomass equivalent to one ton of feeding corn (*Loc cit.*) with similar quality to the Food and Agriculture Organization (FAO) standards (Pedreza and Durán, 1985). The evaluation of the biomass as a feed supplement was performed *in vivo* with mono and poly-gastric animals where a particular study using as test animal carps (*Cyprinus carpio*) showed that “[…] it can be successfully used in the formulation of a diet […] up to 40% of the protein source without deleterious effects in weight gain and assimilation efficiency” (Paredes, *et al*., 1991).

Typically, the aerobic treatment of wastewaters with RBRs has a BOD₅ removal efficiency between 85 to 95 percent (Pescod, 1992; Taicheong and Stenstrom, 1979) and the process can also be designed to lessen the amount of nitrogen reaching the sewer that cause eutrophication (McNeill, 2000). This can be done through the oxidation of nitrogen from ammonia to nitrate (nitrification), followed by the reduction of nitrate to nitrogen gas by denitrification (*Loc cit.*).

Because the water demand of the traditional *nixtamalization* technique is usually six times the amount of corn processed, ideally the effluents from the aerobic treatment could be tertiary treated in order to recirculate this water into the process (*Loc cit.*). The tertiary or advanced treatments include disinfection with ozone, chlorine, ultraviolet light or sodium hypochlorite (Pescod, 1992); however, the current cost of water in Mexico City (50 pesos per cubic meter) is not high enough to make the tertiary treatment a feasible alternative. Calcium compounds should also be removed from the water to prevent fouling in piping from limescale buildup (Navarrete and Osorio, 1991).

A preliminary economical assessment of this scenario was performed by Durán Domínguez (1996) based on the amount of dissolved organic carbon (DOC) in nejayote. DOC refers to the amount of organic matter that bacteria can metabolize to assimilate nitrogen and produce energy (Durán de Bazúa, pers. comm.). The following variables were considered for a corn mill processing one ton of corn per day and producing 3 m³ of nejayote:

- An organic load of 5 kg/m³ or 5,000 mg/l dissolved organic carbon,
- A yield of 0.5 mg biomass (dry basis) per mg DOC,
- Protein content of 0.4 mg/mg biomass (dry basis),
- Protein price of 1,800 pesos per kilogram of protein (wet basis with 10% moisture),
- One working year equivalent to 300 days.

The total invested capital (including the variable and fixed costs) was estimated in 9.35 million pesos (ca. US 675,000) while the gross annual sales from one ton of the
pelletized biomass were estimated in 1.8 million pesos (ca. US 130,000), both at current prices of 2010 (Loc cit.). The costs include the machinery and equipment, freight, accessories, installations, maintenance, labour and other services (not specified in Durán Domínguez, 1996). Because the machinery and equipment acquired have an approximate lifespan of 15 years, after the fifth year the capital investments would be fully recovered and the corn mill would be able to profit from the gross annual sales for the remaining 10 years.

Despite the high profitability of this option, the preliminary economic assessment from Durán Domínguez does not give insights of the market structure and situation to actually analyze the sales potential of the protein-rich microbial biomass as animal feed. This can be a serious disadvantage in the sense that El Michoacano would need to engage in new activities for the production and commercialization of a new product within a different market. These activities will demand a new human, technical and financial infrastructure to successfully penetrate the market, which can make this scenario unattractive regardless of the estimated revenue.

5.3 Biogas for energy production.

In the third scenario biogas is produced through the anaerobic degradation in situ of nejayote to cover part of the energy demand of El Michoacano corn mill. In this scenario, biogas can be used for electricity production or as a direct substitute of the liquefied petroleum gas (LPG). In order to calculate the biogas yield, a mass balance was made:

**Table 5. Mass balance for El Michoacano.**

<table>
<thead>
<tr>
<th>Mass flow</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>tons/day</td>
</tr>
<tr>
<td>Maize</td>
<td>4</td>
</tr>
<tr>
<td>Water*</td>
<td>6.8</td>
</tr>
<tr>
<td>Nixtamal dough</td>
<td>7.7</td>
</tr>
<tr>
<td>Nejayote*</td>
<td>3.1</td>
</tr>
</tbody>
</table>

*Volume to weight ratio based on water’s density. Data from Puebla Salazar, pers. comm.

The organic matter in nejayote, measured as the chemical oxygen demand (COD) was used to calculate the potential biogas yield, where the consumption of 1 kg$_{\text{COD}}$ of oxygen relates to about 0.35Nm$^3$ of methane according to the following chemical equation (Deublein and Steinhauser, 2010):

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Based on the theoretical values of Table 3, nejayote contains 7.5 to 11 kg$_{\text{COD}}$ per cubic meter, thus 3.08 m$^3$ of nejayote will produce between of 8 to 12 m$^3$ of methane on a daily basis assuming a 70% COD removal. The methane yields were calculated as follows:

$$Q_{\text{CH}_4} = (7.5kg_{\text{COD}} \times 3.08m^3)(0.35Nm^3) = 8m^3$$

$$Q_{\text{CH}_4} = (11kg_{\text{COD}} \times 3.08m^3)(0.35Nm^3) = 12m^3$$
Based on a methane yield of 8 m$^3$/d, about 2.5 m$^3$ of methane can be produced per cubic meter of *nejayote*. This estimate is similar to the one reported by Durán de Bazúa and Hartmann (1987) in laboratory experiments with an anaerobic fixed film sequential reactor system, also called a fixed film reactor cascade. The sequential system consisted of five identical reactors made from plexiglass with a total working volume of 125 liters of laboratory-made *nejayote*. An organic load of 6.5 kg$_{COD}$/m$^3$ reported a yield of 2.5 m$^3$ methane per cubic meter of *nejayote* and 4 m$^3$ biogas with a 60:40 methane to carbon dioxide ratio (Durán de Bazúa and Hartmann, 1987).

Yet, the results from Durán de Bazúa and Hartmann (1987) imply a higher COD removal efficiency than the one calculated for *El Michoacano* corn mill, as in both cases a methane yield of 2.5 m$^3$ per cubic meter of *nejayote* was obtained from different organic loads (6.5 kg$_{COD}$/m$^3$ and 7.5 kg$_{COD}$/m$^3$, respectively).

Anaerobic degradation systems usually have a COD removal efficiency of 60 to 80 percent (Deublein and Steinhauser, 2010) and in both cases the presence of calcium hydroxide in *nejayote* enhanced the biodegradability of the organic matter. This is because calcium hydroxide acts as a hydrolyzing agent that increases the solubility of organic material and thus, the COD removal efficiency (López Torres and Espinosa Lloréns, 2008). However the dry matter (DM) content of the laboratory-made *nejayote* used by Durán de Bazúa and Hartmann (1987), and of the *nejayote* from *El Michoacano* is unknown. Therefore, the differences in the DM content of the two wastewaters can possibly explain why an organic load of 6.5 kg$_{COD}$/m$^3$ would yield the same amount of methane (2.5 m$^3$/m$^3$ of *nejayote*) than an organic load of 7.5 kg$_{COD}$/m$^3$.

A digester with a classical European design (Fig.7) was sized for the degradation of *nejayote* with a capacity of 17 m$^3$ and an estimated working volume of 15 m$^3$. The digester would be made in polyethylene (PE) since plastic polymers are lightweight, good thermal insulators, easy to fabricate and install, and PE in particular is a very low-cost polymer (Perry, R., 2008). Although the average temperature in Mexico City is 18°C (de Buen Rodríguez, 2008), a dark insulation layer is needed to prevent the light entering the reactor and to maintain mesophilic temperatures inside it, particularly during the winter season when the temperature can be as low as -2°C (Loc cit.).

![Figure 7](image_url)
Due to the low organic content in the *nejayote*, the residence time was calculated to 5 days despite it is the shortest time recommended for achieving a stable digestion process (Appels, *et al.*, 2008). This value was obtained by dividing the digester’s working volume (15m$^3$) between the *nejayote* produced per day (3.08m$^3$). With a 5-days residence time, the organic loading rate will be 0.5 kgVS/m$^3$d to 1 kgVS/m$^3$d given that the volatile solids (VS) represent 98 percent of the total solids (TS) in maize. The organic loading rate (ORL) was calculated by dividing the amount of suspended solids (SS) in *nejayote* per day, between the working volume of the anaerobic reactor:

$$SS_1 = 2.4kg/m^3 \times 3.08m^3 = 7.4kg/d$$
$$SS_2 = 4.6kg/m^3 \times 3.08m^3 = 14.2kg/d$$

$$ORL_1 = \frac{7.4kg/d}{15m^3} \approx 0.5kgVS/m^3d$$
$$ORL_2 = \frac{14.2kg/d}{15m^3} \approx 1kgVS/m^3d$$

The system is a high-rate continuous process (Pind, *et al.*, 2003) where the *nejayote* will be fed to the reactor in six batches of 500 liters at 40°C every two hours from 5:00 to 15:00 hours (within working hours). In total, 3080 liters of *nejayote* will be fed on a daily basis. For the start up, the digester will be inoculated with active biogas sludge from a nearby wastewater treatment plant in Mexico City. The anaerobic degradation process will take place under absolute darkness conditions in order to prevent methanation inhibition due to light (Deublein and Steinhauser, 2010).

During working hours when the reactor is not mixed, the digested *nejayote* will leave the reactor via overflow. The liquid inside the reactor will be recirculated with a centrifugal pump during part of the afternoon and night in order to thoroughly mix the sludge. A couple of hours before five in the morning the digester mixing will be stopped to allow the reactor’s liquid to sediment. This running protocol allows the enrichment of the microbes able in *nejayote* digestion by increasing the contact between them and the substrate (Ejlertsson, pers. comm.; Ward, *et al.*, 2008). As reported by Gómez and his colleagues (2006), a similar running protocol for the co-digestion of primary sludge with fruit and vegetable waste yielded higher biogas values under partial mixing conditions than under continuous mixing and static conditions.

As mentioned earlier in this section, the presence of calcium hydroxide as an alkali pretreatment agent in *nejayote* will allow a BOD$_5$ removal of 85-90% and a COD removal of 70-80% (López Torres and Espinosa Lloréns, 2008). Still, the nitrogen content in the effluent from the anaerobic degradation will reach the sewer with a concentration above the maximum permissible according to the NOMs (*Cf.* Table 4) since this nutrient is conserved during the process (Topper, *et al.*, 2006; Marchaim, 1992). The same applies to phosphorus (*Loc cit.*), although the concentration in the effluent will remain within the limits established by the NOMs.

With a daily biogas production of 14 to 20 m$^3$, the raw gas would be stored in a low-pressure bag with a capacity of 30 m$^3$ made of PVC-coated plastic foil (Deublein and
Steinhauser, 2010) that would feed either a water boiler or a gas engine for electricity production. The amount of biogas per day was calculated based on a 60:40 methane to carbon dioxide gas composition with the following equations:

\[ Q_{CO_2} = Q_{CH_4} \times \frac{\%CO_2}{\%CH_4} \]  \hspace{1cm} (Eq.1)  
\[ Q_{biogas} = Q_{CH_4} + Q_{CO_2} \]  \hspace{1cm} (Eq.2)

About 4,920 to 7,210 m³ of biogas will be produced per year. Given these values two options are possible: O1) biogas can be used for electricity production or O2) as a direct substitute of LPG. For the first option Table 6 shows the estimated gross and net electricity production with combustion engines that operate with natural gas. Although biogas can be upgraded to high levels of methane content, most internal combustion engines require a minimum of 80 percent methane to operate; for that reason the biogas yield was recalculated to a 80:20 percent ratio with Eq.1 and Eq.2 (see above).

**TABLE 6.** Estimated annual gross and net electricity production (O1) with a gas combustion engine MG105 with capacity of 65kWe and 35% electric efficiency.

<table>
<thead>
<tr>
<th>Enriched biogas 80%CH₄ (m³/year)</th>
<th>Gross electricity production* (kWh/year)</th>
<th>Net electricity production** (kWh/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,690-5,410</td>
<td>10,440-15,320</td>
<td>9,400-13,790</td>
</tr>
</tbody>
</table>

*The conversion factor is 8kWh/m³ of enriched biogas (SAGARPA-FIRCO, 2007; Clementson, 2007).  
**The net electricity production is calculated as the gross electricity production minus 10% due to the energy consumed by the biogas process. Based on Ambar Electroingeniería’s catalogue on gas combustion engines available at [http://www.ambarelectro.com.mx](http://www.ambarelectro.com.mx).

Transforming 1,460 tons of corn per year at *El Michoacano* (Cf. Table 5) with an electricity demand of 70kWh per ton of corn processed (Cf. Table 2), requires 102,200 kWh of electricity every year. Biogas could cover about 9 to 14 percent of this demand; yet the amount of enriched biogas produced per day (ca. 15 m³) is insufficient to run the gas engine in continuous. Thence, the enriched biogas should be accumulated for at least two days to run the MG105 every second day during one hour and twenty minutes based on a consumption of 23 m³/h of gas. This would yield a net electricity production of 76 kWh given a conversion factor of 8kWh/m³ biogas and an electric efficiency of 35% from the MG105; enough electricity for transforming 1.1 tons of corn every second day at *El Michoacano*.

Before including the capital investment for this option, electricity from biogas would report annual savings of 5 to 8 percent of the total energy costs at this corn mill (Table 7). These costs comprise the annual cost of electricity (286,160 pesos) plus the annual cost of LPG (237,570 pesos), giving a total of 523,730 pesos. The annual cost of electricity was calculated by multiplying the energy demand per year (102,200 kWh) times the price per kWh (2.80 pesos). The annual cost of LPG was calculated based on a unitary cost of 4.50
pesos per liter of liquefied petroleum gas, where 52,560 liters are needed for processing 1,460 tons of corn every year at \textit{El Michoacano} (\textit{Cf.} Table 2).

\begin{table}[h]
\centering
\caption{Electricity cost structure for \textit{El Michoacano} (\textit{O1}).}
\begin{tabular}{|c|c|c|}
\hline
Cost of electricity (pesos/year) & Cost of electricity with biogas production (pesos/year) & Total energy savings* (percentage) \\
\hline
286,160 & 260,400-246,100 & 5-8\% \\
\hline
\end{tabular}
\end{table}

*The total energy costs include the annual cost of LPG plus the annual cost of electricity.

If the biogas is used as a direct substitute of the LPG (\textit{O2}), then the demand covered would be as follows:

\begin{table}[h]
\centering
\caption{LPG demand covered by biogas at \textit{El Michoacano} (\textit{O2}).}
\begin{tabular}{|c|c|c|}
\hline
LPG demand (kWh/year)* & Raw biogas 60\%CH\textsubscript{4} (kWh/year)* & Demand covered (percentage) \\
\hline
341,640 & 29,500-43,280 & 9-13\% \\
\hline
\end{tabular}
\end{table}

*The conversion factor is 6.5 kWh per liter of LPG and 6 kWh per cubic meter of 60\% methane biogas (SAGARPA-FIRCO, 2007).

With an annual cost of 237,570 pesos for LPG, direct substitution with biogas (\textit{O2}) would report savings of 4 to 6 percent of the total energy costs at \textit{El Michoacano}, equivalent to 20,950 and 31,420 pesos respectively. As with the electricity from biogas (\textit{O1}), these calculations have not yet included the capital investments of the anaerobic degradation system.

For either option (\textit{O1} or \textit{O2}) an additional source of income can be obtained through the issuance of Certified Emission Reduction Credits (CERs). According to the European Climate Exchange (ECX), the price per ton of carbon dioxide avoided on August 17\textsuperscript{th} 2011 was 8.8 Euro, equivalent to 162.5 Mexican pesos at an exchange rate of 18.5 pesos per Euro (\url{www.europeanclimateexchange.com} and \url{www.xe.com/ucc/}, visited on August 17\textsuperscript{th} 2011).

The issuance of CERs for biogas production and utilization in options one and two are based on five UNFCCC methodologies for small scale projects:

i. AMS-I.A. Electricity generation by the user,
ii. AMS-I.C. Thermal energy production with or without electricity,
iii. AMS-I.I. Biogas/biomass thermal applications for small users,
iv. AMS-III.H. Methane recovery in wastewater treatment,
v. AMS-III.AO. Methane recovery through controlled anaerobic digestion.

The potential carbon dioxide (CO\textsubscript{2}) emission reductions of electricity from biogas (\textit{O1}) are shown in Table 9 and those from the direct substitution of LPG (\textit{O2}) are shown in Table 10:
TABLE 9. Annual CO₂ emission reductions from biogas for electricity.

<table>
<thead>
<tr>
<th>Gross electricity production (kWh/year)</th>
<th>CO₂ from combustion of coal* (tons/year)</th>
<th>CO₂ from combustion of methane** (tons/year)</th>
<th>CO₂ emission reductions (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10,440-15,320</td>
<td>10-15</td>
<td>4-6</td>
<td>6-9</td>
</tr>
</tbody>
</table>

*The conversion factor for coal is 940 gCO₂/kWh (IEA, 2010) but can be lower depending on the fuel mix for electricity production. **The conversion factor for natural gas is 370 gCO₂/kWh (Loc cit.). Based on Table 6.

TABLE 10. Annual CO₂ emission reductions from biogas for LPG substitution.

<table>
<thead>
<tr>
<th>Demand of LPG covered by biogas 60%CH₄ (kWh/year)</th>
<th>CO₂ from combustion of LPG* (tons/year)</th>
<th>CO₂ from combustion of methane* (tons/year)</th>
<th>CO₂ emission reductions (tons/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>29,500-43,280</td>
<td>19-28</td>
<td>11-16</td>
<td>8-12</td>
</tr>
</tbody>
</table>

*The conversion factor for LPG is 650 gCO₂/kWh (IEA, 2010) and for natural gas is 370 gCO₂/kWh (Loc cit.). Elaborated with data from Table 8.

The results from Table 9 and 10 indicate that the direct substitution of LPG with biogas (O₂) allows a larger carbon dioxide emissions reduction compared to the electricity production from biogas (O₁).

From the data calculated at this point, a preliminary economic assessment was done. The capital costs for the biogas system were estimated in 110,000 pesos (ca. US 8,200) including the reactor, valves, a centrifugal pump, a biogas bag and other installation costs (Perry, 2008). For electricity production the biogas enrichment cost should also be considered, so as an additional of 2.5 million pesos (ca. US 186,000) for the acquisition of the gas combustion engine MG105 (http://www.ambarelectro.com.mx, visited on September 21st 2011). On these grounds, electricity production from biogas (O₁) can be rejected as a viable option since the estimated energy savings, equivalent to 26,190 to 40,900 pesos per year, are too small compared to the investment costs that exceed the 2.6 million pesos.

The direct LPG substitution with biogas (O₂) would be equivalent to 18 liters per day from 20 m³ of raw gas; on a yearly basis this would report annual savings for 29,700 pesos in LPG (6,570 liters at 4.50 pesos each). An additional income of 1,950 pesos per year from the issuance of Certified Emission Reduction Credits (CERs) could be earned from the 12 tons of CO₂ avoided through the anaerobic degradation of nejayote.

The biogas system will demand energy for operating the 0.37kW centrifugal pump for mixing the sludge; this would require 3kWh/day and 1080 kWh/year from 8 hours of work per day. With a cost per kWh of 2.80 pesos, the annual operation costs of the system will be 3,020 pesos and thence, the total annual savings for the corn mill will be 28,630 pesos. The lifespan of this low-cost biogas system is 10 to 15 years and the total investment will be recovered after four years.
5.4 Alkaline extrusion of corn.

The fourth scenario proposes a radical change by switching from the traditional nixtamalization technique to the alkaline extrusion of corn. To extrude means to shape a material by forcing it through a specially designed opening (Rauwendaal, 1998). In the alkaline extrusion process (Fig. 8), the previously ground and moisten corn grains are mixed with slaked lime and fed to an extruder (Sánchez Tovar, et al., 1993; Durán Domínguez, 1996), where a rotating screw conveys this mix forward through an electrically heated barrel. As the mix is pushed forward the screw the channel depth decreases; the combination of the screw rotation and the compression causes friction and more heat that will cook the grain mix. By the time it reaches the end of the screw, the cooked mix will come out through the die as dough (Rauwendaal, 1998).

![Figure 8. Alkaline extrusion technique. Modified from Durán Domínguez, 1996.](image)

Over two decades ago alkaline extrusion was proposed to substitute traditional slaked lime-cooking of corn (nixtamalization) for manufacturing tortillas. In a set of experiments by Sánchez Tovar and his colleagues (1993) this alternative technique was tested to produce either fresh dough or precooked cornmeal; the results demonstrated that the extruded products had a rheological behavior “similar to that of the traditionally slaked lime-cooked doughs and the tortillas were not significantly different from its traditionally-made counterparts”. Additionally, the flavor, mastication and rolling characteristics of the extruded tortillas were preferred over the traditionally-made ones (Loc cit.).

From the environmental perspective, alkaline extrusion does not produce wastewaters (nejayote) and demands considerably less time and lower energy consumption compared to the nixtamalization technique (Table 11) while keeping the nutritive value of tortillas (Loc cit.). In this matter, other technological innovations have been developed in the last decade but none of them has achieved the technical and economic breakthrough in the industry; namely, the partition method, nixtamalization through high pressure and the use of microwaves (Sánchez Sinencio, 2009).
**TABLE 11.** Traditional *nixtamalization* versus alkaline extrusion.

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Nixtamalization</th>
<th>Alkaline extrusion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process time (hours)</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Water consumption (water:grain ratio*)</td>
<td>6:1</td>
<td>1:1</td>
</tr>
<tr>
<td>Wastewater (<em>nejayote</em>:grain ratio*)</td>
<td>5:1</td>
<td>None</td>
</tr>
<tr>
<td>Energy consumption based on <em>nixtamalization</em></td>
<td>1</td>
<td>0.3</td>
</tr>
</tbody>
</table>


The alkaline extrusion in Mexico was patented by Durán de Bazúa and Sánchez Tovar in the late-seventies. Even though several studies demonstrated the economic feasibility and environmental benefits of this technology at that time (Sánchez Tovar, *et al.*, 1993; Durán Domínguez, 1996; Hernández Morales, 2005), the aggressive economic liberalization of the 1980s impeded its implementation (Ramírez Romero and Durán Domínguez, pers. comm.).

Specifically, when the government privatized the tortilla manufacturing industry, all the undergoing projects and research were stopped. The idea was that eventually the *invisible hand* of the free market would make this industry fully competitive, but the deregulation process also eliminated all the subsidies (maize and production inputs such as water, electricity and fuels) so as the legal, technical and human infrastructure and the assistance needed for the transition. In consequence, the traditional tortilla manufacturing industry became completely reliant on the large multinational trading companies that control the acquisition, storage, transport, commercialization, supply of grain and most importantly, the price of corn, former activities of the extinct CONASUPO (Maximiliano Martínez, *et al.*, 2011: Villaseñor Flores, 2009).
This thesis presented an assessment of the availability and quality of biomass from the wastewaters in a traditional tortilla manufacturing corn mill in Mexico City for biogas production. The results of this technical and economic evaluation indicate that the anaerobic treatment in situ of nejayote cannot challenge other treatment options or corn processing technologies to tackle the water pollution problem from its untreated discharge to the sewer.

The biogas yield was limited by two factors: first, the amount of organic matter in nejayote is only 6 percent compared to the 94 percent of water content, which gave an organic loading rate of only 0.5kgVS/m³d to 1kgVS/m³d. This is because during nixtamalization, approximately 5 percent of the corn (dry weight basis) is lost into nejayote, where 3 percent is suspended matter and 2 percent remains soluble (Durán de Bazúa and Hartmann, 1987; Orozco, et al., 2008).

Second, the organic matter in nejayote is mainly comprised by carbohydrates (Velasco Martínez, et al., 1997), which have a lower methane yield per unit VS than lipids and proteins; thus, co-digestion with protein and lipid-rich organic residues (i.e. cooking oil, meat products, etc.) from nearby commercial establishments to El Michoacano would increase the overall biogas yield. Even though the assessment of this option is beyond the aim of this thesis, it should be considered for future research given the fact that no previous studies have analyzed this possibility.

With an estimated biogas production of 14 to 20 m³ per day, electricity production from biogas was discarded as a viable biogas application since the estimated savings, equivalent to 26,190 to 40,900 pesos per year, are too small compared to the investment costs that exceed the 2.6 million pesos. The direct substitution of LPG with biogas proved economically feasible, yet the estimated annual savings are not large enough to be attractive despite the environmental benefits of the anaerobic treatment of nejayote.

Only a sudden increase in the price of LPG would make this option more realistic, an unlikely scenario under the current scheme of price control and regulation from the government (SENER, 2010b). This occurs because LPG is the most important energy carrier in the residential, commercial and small industry sectors due to the versatility of its applications (i.e. heating, cooking, etc.), which discards it as an economic driver for the implementation of the anaerobic treatment of nejayote.

Based on the previous results, economies of scale were considered as an alternative to the anaerobic treatment in situ of nejayote. El Michoacano is one of the thirteen corn mills owned by Industria del Maíz Puebla S.A. de C.V. (IMPSA) where they manufacture nixtamal dough to be sold in tortillerías within Mexico City and its metropolitan area. Although the corn processing volumes vary among them, in total they process circa 1,200 tons of white corn per month, with an average of 85 tons per corn mill (Puebla Salazar, pers. comm.).

That amounts to approximately 40 tons of corn and 30.8 cubic meters of nejayote per day that could be transported to a biogas facility. All the corn mills from IMPSA are located...
within a radio of 8 to 10 km distance between them (*Loc cit.*) which would allow to maintain the substrate’s temperature by the time it’s fed into the reactor. Given the high transportation costs within the Metropolitan Area of Mexico City, also known as Greater Mexico City, a preliminary economic assessment was made based on the daily savings from the direct substitution of LPG with biogas.

Assuming a direct substitution of 18 liters per day and corn mill, about 1,058 pesos per day could be saved (234 liters of LPG in total at 4.50 pesos each); yet, the average price of transportation is 93 pesos per cubic meter of *nejayote* regardless of the distance within the city (Ramírez, pers. comm.). Thence, the cost of transporting 30.8 m³ of *nejayote* per day to a biogas facility would be 2,790 pesos, an amount that at least doubles the savings from the biogas production.

It is important to remember that the assessment of the availability and quality of the *nejayote* at *El Michoacano* was done with information from the literature since no laboratory work was possible for analyzing the samples provided during the field visit. The actual composition of these wastewaters would have provided a more accurate assessment of their biogas production potential, perhaps throwing more positive results towards the anaerobic degradation *in situ* of *nejayote* as a solution to the water pollution from its untreated discharge to the sewage system.

As reported by Durán de Bazúa and Hartmann (1987), the *nejayote* composition from an urban corn mill with a similar water demand to *El Michoacano* had a COD value of 21 kg/m³, a BOD₅ of 8 kg/m³ and 20 kg/m³ of SS; all of them being higher than the theoretical values presented in Table 3. These characteristics imply a larger amount of organic matter per cubic meter of *nejayote* that could be anaerobically degraded to methane for energy production *in situ*. With an expected BOD₅ removal of 85-90% from the anaerobic treatment of *nejayote* (López Torres and Espinosa Lloréns, 2008), the effluents would still exceed the limit of 150 mg O₂/l (*Cf.* Table 4). Even so, this biological treatment would greatly reduce the environmental burden of the untreated *nejayote* that reaches the sewer.

Using the same calculation method as in part 5.3 *Biogas for energy production*, a COD value of 21 kg/m³ would yield 7 m³ CH₄ and 5 m³ CO₂ per cubic meter of *nejayote* with a total biogas production of 37 m³/d from 3.08 cubic meters of *nejayote*. Given a conversion factor of 6 kWh per cubic meter of biogas and 6.5 kWh per liter of LPG, this daily amount of biogas is equivalent to 35 liters of LPG; thus, 13,500 m³ of biogas per year would substitute approximately 12,770 liters of this fuel.

Analyzed in the previous chapter, 52,560 liters of LPG are needed for processing 1,460 tons of corn every year at *El Michoacano*. In terms of the annual energy demand, direct substitution of LPG with biogas would cover 24 percent of this demand; in economic terms, biogas would allow annual savings of circa 57,740 pesos based on a unitary cost of 4.50 pesos per liter of liquefied petroleum gas. An additional income of 3,900 pesos per year from the issuance of Certified Emission Reduction Credits (CERs) could be earned from the 24 tons of CO₂ avoided through the anaerobic degradation process. The annual operation costs of the biogas system would be the same as those previously calculated (3,020 pesos) and thence, the
total annual savings at *El Michoacano* would amount to 58,620 pesos. With a lifespan of 10 to 15 years for this low-cost biogas system, the total investment would be recovered after two years.

Electricity production from biogas with a COD value of 21 kg/m³ would cover 26 percent of the corn mill’s annual electricity demand equal to 102,200 kWh. The enriched biogas was calculated with Eq.1 and Eq.2 (Cf. part 5.3 Biogas for energy production) giving a yield of 28 m³ per day and 10,310 m³ per year. The MG105 gas engine would run during one hour and 10 minutes every day based on a consumption of 23 m³/h. This would result in a net electricity production of 70 kWh/d, the amount currently demanded for processing one ton of corn at *El Michoacano* (Table 2). Despite this option would report annual savings of 73,580 pesos, equal to 14 percent of the total energy costs at the corn mill, the investment costs of 2.6 million pesos remain too high to consider electricity production a feasible biogas application.

In either case, the scenarios based on the data from Durán de Bazúa and Hartmann (1987) for the urban corn mill with a similar water demand to *El Michoacano* are just speculative. As mentioned before, the laboratory analysis of *nejayote* at *El Michoacano* would have provided a more accurate assessment about the anaerobic degradation *in situ* as a solution to the water pollution problem caused by its untreated discharge to the sewer.

Neither for the treatment *in situ* of these wastewaters or in a biogas facility, the co-digestion of *tamo* and *granza* was considered for three reasons: first, the aim of the biogas process is not to displace these residues from their current use as animal feed because they cannot be used for human consumption. Second, *El Michoacano* would be losing the profit from selling these residues, and third, co-digesting the *tamo* and *granza* would also mean adding more organic matter to the wastewaters *ergo* to the sewer even after the anaerobic degradation process, which is the key environmental issue of this thesis.

Notwithstanding that the aerobic treatment of *nejayote* for the recovery of protein-rich microbial biomass is economically feasible as reported in the literature, it would demand on behalf of *El Michoacano* to engage in new activities for the production and commercialization of a new product within a different market. These activities will demand a new human, technical and financial infrastructure to successfully penetrate the market, which according to the CEO at *El Michoacano*, makes this scenario unattractive regardless of the estimated profit (Puebla Salazar, pers. comm.).

Regarding the separation of suspended solids, this option was rejected on the grounds that the estimated profit per year (2,180 pesos) is too small compared to the investment costs of 610,000 pesos. This is mainly because the price of the screw press is too high; however other dehydration options could be considered, such as centrifugation of the separated solids followed by other drying methods (i.e. freeze-dry, spray-dry, oven-dry, etc.).

Another alternative is to do only the sedimentation step, where the recovered organic matter would be taken to a wastewater treatment plant instead of being screw pressed. As a measure to reduce the BODs and COD values of the untreated *nejayote*, the local government could encourage the implementation of this option by taking responsibility of transporting the
separated solids to a wastewater treatment plant within Mexico City. Based on this, the investment from *El Michoacano* would be approximately 80,000 pesos, and despite the effluents from the sedimentation process would still exceed the maximum permissible values established in the NOMs, the burden to the sewer would be lessened.

Furthermore, the effluents from sedimentation will have a lower temperature when they reach the sewer and carbon dioxide can be added to neutralize their pH. The addition of carbon dioxide will also prevent fouling in piping from limescale buildup (Navarrete and Osorio, 1991), and although the content of calcium hydroxide in these waters is unknown, the precipitated carbonate could be used as an additional source of calcium in animal diets by mixing it with the *tamo* and *granza* (Velasco Martínez, *et al.*, 1997). Because sanitation remains a major problem in Mexico (CONAGUA, 2007), the main challenge this alternative scenario will face is the government’s capacity to successfully get involved.

6.1 To wrap up…

None of the scenarios analyzed in chapter five offer the economic incentives to change the *modus operandi* of the traditional tortilla manufacturing industry in regard to the untreated discharge of *nejayote* to the sewer. Yet, during the field visit to *El Michoacano* and the informal conversations with Tomás Puebla Salazar, the CEO of *Industria del Maíz Puebla S.A. de C.V. (IMPSA)*, the environmental awareness of the water pollution problem caused by *nejayote* was not only acknowledged but there was an explicit interest for wastewater treatment options that would help the thirteen corn mills owned by IMPSA to comply with the NOMs. In itself, this is the most important driver to change the business as usual at these corn mills.

To date, Mexico City has nine wastewater treatment plants with capacities of 25 up to 2,000 liters per second; from those, only six are currently in operation at an average of 80 percent of their installed capacities (CONAGUA, 2007). Despite the changes to the applicable legislation in 2004 and the availability of financial resources to improve the wastewater treatment infrastructure (*Loc cit.*), the local government has not been able to cope with the water pollution problem from the traditional tortilla manufacturing industry. Thus, the combination of the anaerobic treatment of *nejayote* and the alkaline extrusion of corn as a two-stage technological package may provide the economic incentives to *El Michoacano* for complying with the NOMs.

As mentioned in section 5.4 *Alkaline extrusion of corn*, this transformation process preserves the nutritive value of the *nixtamal* dough and most importantly, the organoleptic characteristics of the traditionally-made tortillas. The organoleptic uniqueness is of particular relevance because the traditional industry owes its permanence to the flavour, smell, mastication and rolling characteristics of an ancient technique that has remained virtually unchanged over time. This is also the reason why the cornmeal industry has not been able to displace the traditional sector, as the flour-based tortillas do not share the “freshly-made” tortillas’ organoleptic uniqueness.
Since the direct conversion from the traditional *nixtamalization* technique to the alkaline extrusion of corn is very expensive, *El Michoacano* could benefit from two government programs operating in benefit of the traditional tortilla manufacturing industry. The first one is the Support Program for the Corn-milling Industry (PROMASA) consisting of a temporary subsidy of up to 0.50 pesos per kilogram of *nixtamal* dough (Criterios de operación PROMASA, 2010), and the second one is the Program *Mi Tortilla*, consisting of credits for the maintenance and updating of machinery and equipment in corn mills (http://www.microempresas.org.mx/ visited on September 9th 2011).

The price of an extruder to transform the 4 tons of corn currently processed at *El Michoacano* starts in 205,500 pesos if bought directly from the retailer; the technical specifications of the Bronto extruders (E-500, E-1000 and E-1500) can be found in their website (http://www.bronto.ua/en, visited in September 22nd 2011). Since the maximum credit of the Program *Mi Tortilla* (150,000 pesos) is not enough to buy a corn extruder to change the overall tortilla manufacture process at once, the anaerobic treatment of *nejayote* could be financed with the support of this government program as a *first stage* of the technological package proposed.

The investments of a biogas system for the direct substitution of LPG will be recovered after four years, and the total savings from the fifth to the fifteenth year (estimated lifespan of the system) will be around 314,900 pesos. These savings will suffice to pay for the technology transition to the alkaline extrusion process as a *second stage* of this technological package. Because the alkaline extrusion of corn does not produce wastewaters, the anaerobic system at *El Michoacano* will no longer be needed; even so, the equipment could be installed in another corn mill of IMPSA for treating its *nejayote*.

Even though the lack of information about the alkaline extrusion of corn within the traditional industry has hindered its implementation, the window of opportunity given by IMPSA’s interest – more than the need itself – for an option that allows *El Michoacano* to comply with the NOMs should not be wasted. A technological combination like the one proposed is environmentally desirable, economically feasible and profitable in the long run since the alkaline extrusion will demand considerably less time, water and energy than the *nixtamalization* technique and above all, it will permanently solve the water pollution problem caused by *nejayote*. 
7. CONCLUSIONS

The major findings of this thesis are:

1. The anaerobic degradation *in situ* of *nejayote* at *El Michoacano* can yield 14 to 20 m$^3$ of biogas per day, a rather low amount to make electricity production a viable biogas application due to the high investment costs. Yet, about 18 liters of LPG per day can be directly substituted with the same amount of biogas.

2. Biogas production in a central facility is not economically feasible because the transportation costs within Greater Mexico City are much higher than the estimated savings from the anaerobic treatment of 30.8 m$^3$ per day of *nejayote*.

3. Although profitable, the recovery of protein-rich microbial biomass through the aerobic treatment of *nejayote* is also costly and involves taking care of a new product within a different market, making this scenario unattractive regardless of the estimated revenue.

4. To a certain extent, the separation of suspended solids by sedimentation can taper off the water pollution problem of *nejayote* but it does not offer the economic incentives for implementation.

5. The alkaline extrusion of corn is currently expensive and the lack of information about this technology within the industry has hindered its usage. Even so, a combination of the anaerobic treatment of *nejayote* and the alkaline extrusion of corn in a two-stage technological package is economically feasible, environmentally desirable and profitable in the long run.
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PERSONAL COMMUNICATIONS:

- PhD. Yolanda Salinas Moreno, National Institute of Forests, Agriculture and Livestock Research (INIFAP), June 14th 2011.
- MSc. Ofelia Buendía González, Autonomous University of Chapingo (UACH), June 14th 2011.
- PhD. Gerardo Ramírez Romero, Autonomous Metropolitan University in Iztapalapa (UAM-I), June 15th 2011.
- PhD. Florina Ramírez Vives, Autonomous Metropolitan University in Iztapalapa (UAM-I), June 16th 2011.
- Tomás Puebla Salazar, CEO Industria del Maíz Puebla S.A. de C.V. (IMPSA), June 29th and September 13th 2011.
- PhD. María del Carmen Durán Domínguez de Bazúa, National Autonomous University of Mexico (UNAM), July 26th 2011.
- Vicente Ramírez, Employee at Transportes Especializados Zepeda S.A. de C.V. (TEZ), October 3rd 2011.
- PhD. Jörgen Ejlertsson, Linköpings Universitet, October 7th 2011.
- Marco Lorenz, General Manager of EcoAzur S.A. de C.V., October 10th 2011.
- Peder Barrling, Business Area Manager at Tekniska Verken i Linköping AB, October 10th 2011.
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