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Final Report

"Removing barriers to Greenhouse Gas mitigation in medium scale agricultural livestock activities within Mexico"

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Productive-Scale Anaerobic Digestion Systems: Four Demonstration Systems

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Executive Summary

Applying the average greenhouse gas (GHG) results of this work to a conservative estimate of 150,000 productive-scale farms in Mexico, anaerobic digestion (AD) systems at medium scale pig and dairy farms in Mexico have the potential to reduce 10 million tCO_2e of GHG per year while producing over 15,000,000 MWh/yr of clean renewable energy. However, current AD technology offerings focus on the industrial agricultural sector or small farmers, leaving productive scale famers within a technology and capacity building gap in the AD sector. This project has shown that domestic AD technology can be scaled-up effectively to provide waste treatment, clean energy production and nutrient recycling in a technically and economically feasible way.

The objectives of the project was to implement clean energy capacity in Mexico, reduce GHG emissions, and demonstrate the feasibility of scaling low-emissions technology in the agricultural sector of Mexico. Through the implementation and use of four demonstration productive-scale AD systems, this project has successfully shown how productive-scale AD systems can achieve these goals through the successful implementation of the four systems, the positive economic results of the investments, the clean energy production, GHG reductions and the waste treatment of the excess effluent not used directly as a soil amendment.

The total project capital costs for implementation of the four projects was MXN$ $1,451,298 for the full AD system, secondary treatment system and biogas uses, including motors and filters. The economic benefits of these systems is calculated based on the value of energy and fertilizer each system will produce, and is estimated at approximately MXN$510,000 per year, providing a simple return on investment of the projects of less than three years. This does not include the reduced risks of fines from the environmental ministry, or improved sanitary and health conditions or increased productivity of the farmers.

The clean energy produced by this project is estimated to be an equivalent of 148,000 kWh per year, and will provide thermal and electrical energy to the farms and the households onsite. Thermal energy uses include cooking, hot water heating and space heating to keep piglets warm at night. The biogas will also be used to produce electricity in adapted gasoline engines ranging from 5.5 – 11 kW. A simple, innovative biogas filter was employed that is reducing H_2S by 98-100%, reducing risk of damaging the motors, a previous barrier to use. By capturing and destroy methane through the production of clean energy, these four projects will reduce over 700 $MTCO_2e$ in GHGs each year, yielding over 7,000 $MTCO_2e$ of GHG in the project lifetime.

This project also succeeded in demonstrating how secondary management of the liquid effluent from the biodigesters—biol—can be managed as either a fertilizer or treated by a secondary system to ensure the farm reduces risk of fines from water contamination. The systems demonstrated between 80-99% reduction in key wastewater indicators, specifically Chemical Oxygen Demand (COD) and Volatile Solids (VS).

The results of this work are still preliminary, as the true impacts of these four systems will be seen over many years. However, the initial technical and economic results show that productive-scale AD system can provide high levels of waste treatment, clean energy production, GHG reduction and economic returns to productive-scale farmers, supporting low carbon development in the agricultural sector of Mexico.

Introduction

Applying the average greenhouse gas (GHG) results of this work to a conservative estimate of 150,000 productive-scale farms in Mexico, anaerobic digestion (AD) systems at medium scale pig and dairy farms in Mexico have the potential to reduce 10 million tCO_2e of GHG per year[1] while producing over 15,000,000 MWh/yr of clean renewable energy[2]. Within the full Mexican agricultural livestock sector, significant additional GHG reductions and clean energy gains could be made at slaughterhouses, cheese production units and other animal production farms. Considering medium scale swine farms, beef production units, dairies and slaughterhouses there is likely the potential for the installation of between 300,000 and 500,000 productive biogas units in Mexico, providing direct economic and health impacts for over three million people. Including domestic farm biodigester systems, this number could reach 3.5 million biodigester installations in Mexico.

However, the potential impact of AD technology within the Mexican agricultural livestock sector has been limited because: (1) The dominant technological and financial offerings are designed for large-scale industrial farms or small domestic farms, excluding a significant cross-section of the Mexican agricultural sector, and; (2) Available anaerobic digestion technology does not treat animal waste to levels that meet national water quality discharge standards, and therefore do not meet the growing needs of farmer to reduce their risk of water quality discharge fines.

To remove these barriers to increasing the use of AD technology in the Mexican agricultural sector, the International Renewable Resources Institute (IRRI), with the Mexico Low Emissions Develop (MLED) program, developed the project *Removing Barriers to Greenhouse Gas Mitigation Opportunities in the Medium Scale Livestock Sector of Mexico*. Central to this program was the implementation of Four Medium-Scale Anaerobic Digester Demonstration Projects at medium-scale farms in key agricultural regions of Mexico in temperate and tropical climates. These projects aim to provide a long-term demonstration of the technical, economic, and social feasibility of applying similar strategies to the more than 500,000 similar farms in the country.

Medium scale livestock producers fall within a technology gap between proven large-scale and domestic-scale biogas technology. These demonstration projects, together with a program of dissemination, have been able to provide needed information and visibility to the "Productive Biogas Sector," as defined by the Global Alliance of Productive Biogas (GAPB). These demonstration systems have shown how to fill this technology gap in Mexico, and provide critical feasibility information for policy makers, farmers, and other stakeholders in the sector.

Specifically, these four demonstration projects have shown that simple, low cost AD technology can be scaled up to provide effective nutrient and energy recovery systems for productive scale farms. The projects show that the technology can be economically accessible and also provide secondary treatment that is specifically designed to treat the waste from medium-scale farms that removes risks of legal fines. This program has shown a technological strategy for synchronizing

[1] Calculation: production of 60 MTCO2e /yr./ farm multiplied by a conservative estimate of 150,000 productive scale farms in Mexico.
[2] Calculation: average production of 16,000 m^3 of biogas / yr. / farm (equivalent to 100 MWh/yr) by a conservative estimate of 150,000 productive scale farms in Mexico

water quality and GHG reduction goals in the agricultural sector in Mexico, removing important barriers for financing and public support.

These projects demonstrate the use of productive-scale anaerobic digesters in dairy and swine farms in tropical and temperate climates in the states of Mexico, Tlaxcala and Morelos. The variety of farm and climate types allows these projects to provide an important reference for a wide range of the current productive-scale operations in Mexico. Critically, they provide an example of the direct economic benefits of providing farmers access to a reliable supply of clean, renewable energy. The economic and efficiency gains can help align market demand for the technology with clean energy, GHG and water pollution goals in Mexico.

Fig. 1 : A farmer of Soyaniquilpan demonstrating his biogas electrical generator using the biogas produced by his productive-scale AD system.

Project Objectives and Key Outcomes

The first objective of this project was to effectively contribute to the MLED goal of "Implementing clean energy interventions" through the installation of four demonstration productive biogas projects in medium-scale swine and dairy farms in temperate and tropical climates. To this end, these projects are currently producing clean energy in the form of methane-rich biogas. The biogas is being used for cooking, heating water, space heating for piglets, and electricity production in the demonstration farms. By treating the organic waste of these farms and displacing fossil fuels, these projects are directly reducing greenhouse gas emissions and water contamination.

The second objective was to contribute to the dissemination of biodigester technology for GHG reduction in medium-scale operations in Mexico. The promotion of the results of these projects will help drive key stakeholders support for the further development of the technology by clearly demonstrating the technical and economic feasibility together with the environmental and health benefits. The demonstration systems themselves are being actively used to familiarize local farmers to the technology and provide them with first-hand experience with the use and benefits of the technology. By familiarizing farmers with the technology, the perceived risk of adopting a new technology is reduced.

This project set out to achieve four specific objectives:

1. Develop detailed case studies and demonstration of the impact of biogas technology within all farm-types and sizes in Mexico, providing examples to follow for future.

2. Identify a consolidated group of stakeholders and actors within the sector in order to identify key areas of collaboration.

3. Generate a clear list of barriers and best practices across the range of project sizes to inform future projects.

4. Define a strategy for promoting GHG reduction platforms, such as NAMAs, within the agricultural biogas sector.

Project Description

This project was composed of the design, installation, start-up and on-going service of four productive scale anaerobic biodigester systems. Sistema Biobolsa, a Mexican company specializing in the installation of domestic scale biodigester systems, was in charge of the installation.

The four projects were***: 1. A tropical swine farm in Coatlán del Rio, Morelos; 2. A tropical dairy farm in Amacuzac, Morelos; A temperate swine farm in Huamantla, Tlaxcala, and; A temperate dairy in Soyaniquilpan, Mexico State.*** Each of these farms received a productive biogas system to receive their different types and amounts of waste. The biogas use for each farm was designed to meet the unique combination of energy needs of each, and the effluent treatment was specialize to best optimize between fertilizer and treatment needs.

Many attempts have been made to scale-down industrial scale biogas designs to suit the "missing middle" of productive-scale farms. The high technical requirements have made medium scale systems economically inaccessible to farmers. This project intended to demonstrate how simple technology used for small farmers could be scaled-up to provide an economically and technically waste to energy project for medium scale farmers.

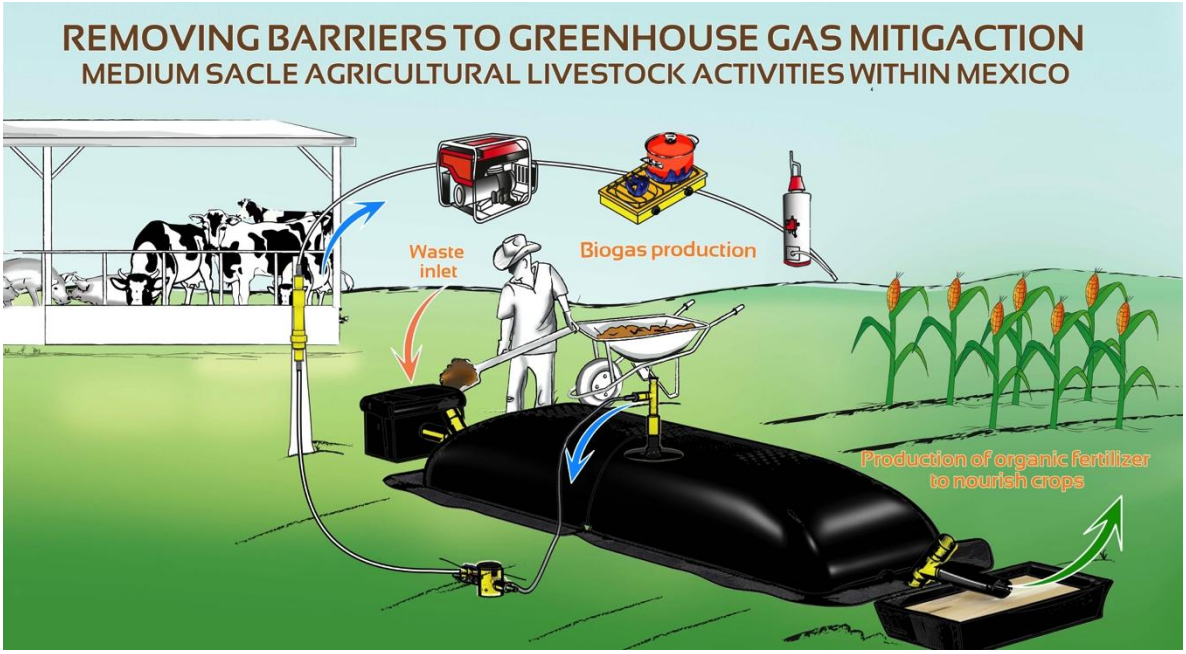

fig. 2: This simple schematic shows the basic principles of a productive-scale AD system. The farmer is adding manure from the animals of his medium scale farm and the biogas is being used for motors, boilers and stoves; the biol can then be reused as a fertilizer for his crops.

The system works by receiving animal waste and water that results from the cleaning of animal barns. A waste receptor receives the raw waste and water and ensures that no inorganic material such as rocks or sand or other large objects enter the system. From this receptor the mixed waste enters the first anaerobic reactor.

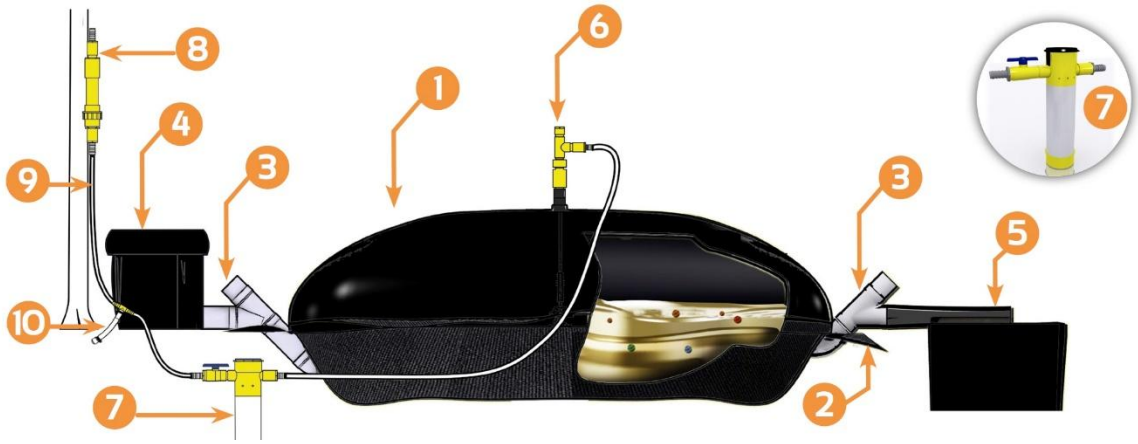

fig. 3: This figure demonstrated the basic components of a simple AD system. 1) Anaerobic Reactor made of 1.5 mm geomembrane 2) Geotextile ground liner 3) PVC connections for inlets and outlets 4) Waste hopper to receive manure and water 5) Biol storage container 6) Biogas exit connections 7) Pressure release valve 8) Biogas filter 9) Gas lines of 1" 60 caliber LLDPE hose 10) condensation traps to drain water from gas lines.

fig. 4: The uses of biogas encountered in this project included (1) space heating for swine maternity areas, (2) cooking on biogas stoves, (3) running biogas generators, and (4) in hot water heaters.

Each of the systems is made up of multiple reactors that can be configured to receive different amounts of waste flows. Within the anaerobic reactors, the waste is broken down in multi-stage biological and chemical process that is driven by anaerobic bacteria. The complex organic molecules of the waste are broken down into its nutrient components. This process has important benefits for the treatment of the waste to legal discharge limits, as discussed in the Waste Treatment Section. Each project consists of a combination (2, 3, 4 and 5) of modular 40 cubic meter anaerobic reactors. The use of multiple reactors allows the system to optimize the treatment phases, and provides additional physical and chemical treatment time. In each reactor, biogas is captured in a 12 cubic meter dome. Biogas hoses run from each system and connect to the main gas line. Each reactor has a pressure relief valve and a biogas filter to remove impurities, water vapor and hydrogen sulfide. The gas line runs directly to stoves, boilers, motors and other gas appliances. The use of the biogas is discussed in detail in the Project Clean Energy Production section.

The waste has an average retention in the anaerobic reactors of 42 days for temperate systems and 30 days for tropical systems. The resulting liquid effluent is called "*biol*" and has had the majority of its volatile solids and over 99% of the pathogens removed. This effluent is a potent organic fertilizer, with the nutrients in the organic waste available for plant uptake. Additional chemical, structural and biologically benefits make it an ideal soil amendment. However, if it is not used immediately as a fertilizer, because of its high nutrient content by law it cannot be discharged into any national waterways or water bodies. This means treatment must be available for farmers where there is an excess of biol.

The secondary treatment systems demonstrated by this project demonstrate a simple strategy that productive farms can take to manage the liquid effluent from AD systems. One farm has extensive fertilizer needs, and captured the biol in a large storage tank where it can then be pumped for application on surrounding agricultural fields. The other farms have more extensive treatment systems. These include a series of small sedimentation tanks that further separate suspended solids from the liquid effluent. The resulting liquid runs through a sub-surface planted aerobic gravel bed and then onto another gravel filter filled with floating aquatic plants. The system leaves room for farmers to use the fertilizer, while receiving effective treatment of the remaining effluent stream. Each of these systems is described in detail in the Organic Waste Treatment section.

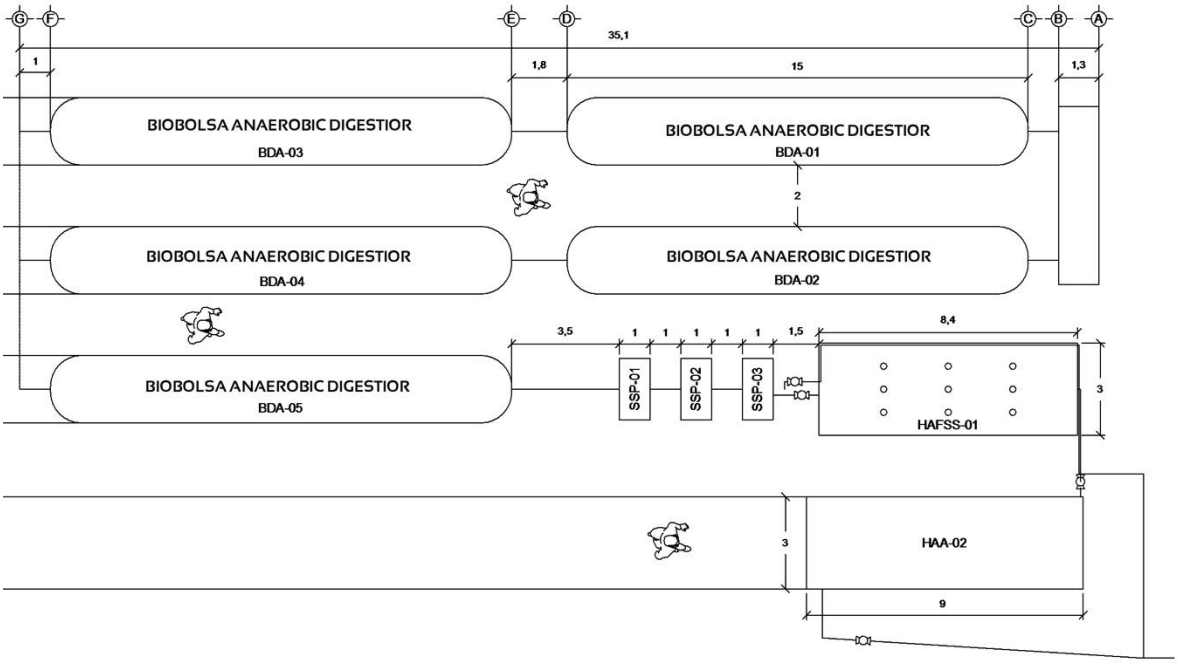

fig. 5: An example payout of a productive-scale AD system with a secondary treatment component. This system is from Coatlán del Rio, and includes five anaerobic reactors, three sedimentation tanks, one subsurface wetland and one wetland.

Each of the projects is a critical piece of farm infrastructure that allows for improved waste management, and the recovery of previously wasted energy and nutrient resources. The economic value to the farmer comes from the provisioning of clean, renewable energy to offset farm energy needs. In some cases, farmers can create added value by adding mechanical, thermal or electrical systems. Chemical fertilizers are also massive cost for agricultural producers, and in rural Mexico, most farm owners also grow forage, grains, and cash crops. The use of the biol to reduce the purchase and use of chemical fertilizers can often be the most significant economic gain of the system. These economic benefits are discussed further in the Project Economic section.

The economic benefits of the AD systems are the main drivers of adoption of the technology; there are also additional environmental benefits that are realized by the project. Federal and state laws regulates the organic wastes from productive scale farms in Mexico because the untreated discharge of the farms is a major contaminant in agricultural watersheds. This discharge has been linked to serious water quality issues in the country. The project achieves a high level of waste treatment and waste management by applying biol to agricultural lands as a fertilizer and ensuring proper treatment of excess effluents.

Also by treating the waste effectively, these projects capture and destroy methane gas, a powerful greenhouse gas (GHG). Methane is naturally released when animal manure is stored in anaerobic conditions, such as in lagoons and storage pits, or when added to water bodies. By capturing this methane, it can be used as an energy source, thereby offsetting the use of other energy sources, specifically fossil fuels. Fossil fuels, such as gasoline, LP gas or the fuels used to produce the electricity release carbon dioxide, also a GHG. Chemical fertilizers also produce GHG emissions

through their production, transport and use. The cumulative GHG reductions are discussed further in the GHG Reductions section.

Each of these projects provides an effective demonstration of the application of productive scale biogas technology. The systems have proven to be technically and economically feasible and have achieved the goals of implanting clean energy projects and demonstrating the use of AD technology in the region.

fig. 6: This is the completed and operational AD system at Coatlan del Rio, Morelos, treating the waste from 600 pigs.

fig. 7: This is the completed functioning system in Huamantla, Tlaxcala, treating the waste from 600 pigs in a temperate climate.

fig. 8: This is the completed functioning system in Soyaniquilpan, Morelos treating the waste from dairy cows in a temperate climate.

fig. 9: This is the completed and functioning system in Amacuzac, Morelos treating dairy waste in a tropical climate.

Project Implementation

The four projects were implemented in parallel, using the same process and workflow: farm selection, site diagnostics, system design, implementation, start-up, and follow-up.

First, the farms were identified through local actors for characteristics that fit the objectives of this work. Specifically, the project called for a swine and a dairy farm in both temperate and tropical climate conditions. The farms were to be located in areas where they could serve as a good public demonstration of the technology, and the farmers would ideally be leaders or active within the agricultural community. Importantly, the farmers were also evaluated by their interest in the system and their ability to pay for the balance of the full system cost and the fixed support provided by the MLED grant.

Once the farms are identified, site diagnostics are conducted. These include a full profile of the farm animal herd, manure production, waste management, energy use, water use, and fertilizer use. During the site diagnostics, the location of the system, any farm modifications, and the work responsibilities of the farmer are also reviewed. This visit allows the technician to confirm that the farmer understands responsibilities, potential risks, and the overall goals of the project.

fig. 10: Site diagnostics register all baseline conditions of the farm, including energy use and waste production.

fig. 10: Site preparations are carried out by the farmers, using designs and measurements from the design phase.

With the final designs completed, the implementation happens in two phases, with the farmer first preparing the site the according to the plans provided for each farm. This may also include simple modifications the surrounding area to improve drainage or the conveyance of waste to the site. Any additional materials from the preparation should be removed, and the sites should be cleaned and leveled.

Once the site has been fully prepped it is inspected and adjusted by the installation technicians as needed. The Sistema Biobolsa technology comes in fully contained packages for ease of transport and installation. The system comes wrapped in a large geotextile ground cover that is installed first to protect the site and the reactor. The reactors are then unrolled and centered in the trenches, and the gas lines and liquid connections are made. Each reactor is filled up initially with a mixture of 20,000 liters of water, 10,000 liters of fresh manure and 1000 liters of anaerobic feedstock. To complete the installation of the digesters, the full biogas line and appliances are installed.

Critically, during this process the end users, owners, and other workers at the farm are trained in the efficient use of the technology. This training is provided based on the User Manual (included as a technical document with this report) as the guide, walking the users through all of the daily use steps and medium and long-term maintenance needs. This training is repeated during the installation and follow-up visits to ensure emphasis is put on key points. A troubleshooting guide, safety warnings, and contacts for technical assistance are also included in the manual, providing farmers with resources to ensure the system works over the long term.

fig. 11: Site Preparations completed in Huamantla.

fig. 12: The AD systems are modular, and come wrapped in the ground liner to protect the geomembrane during transport. This modular aspect of the technology makes accessing sites and installation much easier than on-site construction.

fig. 13: The anaerobic reactors are installed in the sites, filled with water and manure and connected to the gas lines.

The secondary treatment systems are then installed to receive the effluent from the digesters. These were installed in each site using either geomembrane liners or concrete blocks. They can also be made of modular geomembrane containers. Once the secondary treatment is installed, the interconnections are made the gravel filters are filled with different size gravels that have washed and sorted.

Once the systems were fully installed, the farmers began to deposit fresh manure immediately, but at a limited rate. The system required 30-40 days before the first effluent or biogas was produced. From that time on it they have produce biogas and biol each day, with the full amount of the farm manure waste being added. The function, efficiency and production of the systems will continue to stabilize over the first 6 months of use.

After the first 30-40 days, technicians returned to demonstrate the use of the biogas equipment to the farmers. This included the final gas line connections and any adjustment to the energy systems of the farm. In some cases, existing infrastructure was adapted to use biogas and in others new biogas appliances were installed.

fig. 14: Secondary treatment systems installed and functioning in Amacuzac, Morelos.

As a final implementation step, aquatic and wetland plants were added to the secondary treatment system once the flow of liquid had filled each section. The plants often needs to be watched, replanted or maintained according to how each species adapts to the environment. This is done as part of the on-going follow-up of the systems. Other follow up visits included testing the waste treatment, making adjustments to the systems, and conducting further capacity building with the farmers on the use and maintenance of the system. This follow up will continue into the future.

fig. 4: It is critical that there is follow-up and training with the farmers after the installation and as the biodigester begins to function. Here, a technician reviews the gas lines and pressure relief valve.

Projects Economics

As the systems have a short time functioning, true economic impact on each farm cannot yet be determined. The actual baseline costs of each farm have been determined, and the operating specifications of each system together with the initial operating data allows us to provide an accurate estimate as to the potential for the digesters to offset these costs.

During the project design, the maximum economic potential of each system was determined. This calculation provides a view of the maximum potential benefit to the farmers if they maximize the use of the fertilizer and energy resources provided. Taking measurements and collecting data on the actual savings and economic benefits for each farm will continue over the course of the next year.

While these calculations are used to estimate the maximum economic savings to the farmers, they can underestimate the total economic benefit because they exclude opportunities to increase farm incomes. The mechanization and use of thermal energy in some processes may save the farm significant time that can be used for other productive activities. Additional energy may allow the farm to add value to agricultural goods. Biol has been shown to increase yields of forages, grains, and other crops from 20-40%, and increase long-term soil fertility and health[3].

Productive scale farms, particularly swine farms, also face high potential legal fines for not providing adequate waste treatment. These fines have been reported as high as USD$50,000. This financial risk is much higher than the investment in a productive-scale biogas and waste treatment system, and could put many farms out of business.

Farm	Total AD System Cost	Total Secondary Treatment Costs	Biogas Motors	Total System Cost
Huamantla	$235,613.51	$150,000.00	$29,735.00	$415,348.51
Soyaniquilpan	$230,613.51	$54,000.00	$24,800.00	$309,413.51
Coatlán del Rio	$273,410.24	$180,000.00	$61,519	$514,929.24
Amacuzac	$132,806.76	$54,000.00	$24,800.00	$211,606.76
Total	$872,444.02	$438,000.00	$140,854.00	$1,451,298.02

Table 1: The total costs of the project, separated by the four projects, and also by project components.

System	Cap X	LP Gas Value	Biol Value	Total Value	ROI (yrs)
Huamantla	$415,349	$83,255	$250,286	$333,541	1.25
Soyaniquilpan	$309,414	$62,441	$187,714	$250,156	1.24
Coatlán del Rio	$514,929	$104,069	$312,857	$416,926	1.24
Amacuzac	$211,607	$41,628	$125,143	$166,770	1.27
Total	$1,451,298	$291,393	$876,000	$1,167,393	1.25

Table 2: The total capital costs from Table 1 are shown here in comparison the estimated value of the biogas and fertilizer produced by each system. The ROI is shown in years, accounting for the total against the capital cost.

[3] Warnars and Oppenoorth, *Estudio sobre el Biol, sus Usos y Resultados,* HiVOS, 2014.

The project uses the return on investment (ROI) as the key indicator to the financial feasibility of the systems. This considers initial capital expenditure (CapX) and operating costs (OpX) against the economic benefits over time. Tables 2 and 3 show the total CapX and OpX of each project, the estimated economic benefits, and the resulting ROI for each scenario.

These projects included a mixture of funding resources, including the support of MLED, other government programs, and the farmers' own contribution. Table 4 shows the funding mix for each farm. The farmer's contribution was provided as a combination of cash and credit.

These data show that farmers can payback their system in 2-5 years, and that over the lifetime of the system can provide $2-6 USD in return for every dollar invested. The CapX, without additional support is still within the range of credit opportunities available to the farmer, and 2-4 year credit terms would allow farmers to be cash flow positive as they repay the system. Additional funding sources that aim to reduce water contamination, reduce GHG emissions, or improve agricultural productivity can improve the economic returns to the farmer by providing co-financing for the technology. This combination of public and private funds could accelerate the rate of adoption of the technology without providing full subsidies.

System	Cap X	OpX (MXN/yr.)	LP Gas + Electricity Value	Biol Value	Total Value	ROI (yrs)
Huamantla	$415,349	$3,942	$79,843	$150,000	$229,843	1.8
Soyaniquilpan	$309,414	$1,807	$63,576	$50,000	$113,576	2.8
Coatlán del Rio	$514,929	$3,285	$105,080	$7,500	$112,580	4.6
Amacuzac	$211,607	$1,807	$40,449	$15,000	$55,449	3.9

Table 3: Using the current conditions of the farms and the baseline expenses, this table used the CapX of the project to estimate the ROI for each farmer considering their current expenses. This ROI from only savings shows a range of 1.8 to 3.9 years. This value is likely conservative because the farmers have access to the total value of the AD systems shown in Table 2, and therefore will be incentivized to extract more value from the energy and fertilizer.

Farm	Total System Cost	MLED Contribution	%	IRRI	%
Huamantla	$415,348.51	$225,000.00	54%	$190,348.51	46%
Soyaniquilpan	$309,413.51	$130,000.00	42%	$179,413.51	58%
Coatlán del Rio	$514,929.24	$180,000.00	35%	$334,929.24	65%
Amacuzac	$211,606.76	$80,000.00	38%	$131,606.76	62%
Total	$1,451,298.02	$615,000.00	42%	$836,298.02	58%

Table 4: The total costs of the system shown by funding source. MLED supported a total of 42% of the CapX and IRRI supported 58%.

Farm	Total System Cost	Financing Cost	Monthly Payment	Monthly Benefit	Monthly Cash Flow
Huamantla	$415,348.51	$41,535	$19,037	$27,795	$8,758
Soyaniquilpan	$309,413.51	$30,941	$14,181	$20,846	$6,665
Coatlán del Rio	$514,929.24	$51,493	$23,601	$34,744	$11,143
Amacuzac	$211,606.76	$21,161	$9,699	$13,898	$4,199

Table 5: This tables shows a what a financing program for these four system could look like, showing that monthly financing costs could be paid by monthly benefits and provide a cash-flow positive state for the farmer.

Clean Energy Production and Use

The energy production of a biogas system is well understood, and based on the amount and type of the waste being treated and the conversation rate of the AD system. The climate factors and waste types are taken into account when optimizing the AD system to capture that maximum amount of methane. Gaseous bio-methane is a versatile and clean energy source, and can be used for thermal, mechanical, and electrical energy generation through a variety of biogas appliances and equipment. This is a boon to productive farmers than have to deal with a mix of energy sources that are costly and come from external sources.

The actual energy production amount for each farm in this project is not completely certain given that the systems were recently installed and have not full stabilized in their gas production. However, given the amount of waste available according the initial site diagnostics and project design, we can generate a reasonable estimate as to the final biogas production amounts. Given the gas composition of each farm, we can then calculate the energy equivalence and its potential to displace different fuels.

This project succeeded in implementing and demonstrating a clean energy project through these four biogas systems. The project is estimated to generate a total equivalent of 148,000 kWh each year of clean, renewable energy for Mexican farmers.

Energy Type / Source	Equivalence to 1 m^3 of Biogas	Units
Thermal Energy	23	mj
Electricity	2.2	kWh
LP Gas	0.4	kg
Mechanical Energy	2.86	HP

Table 6: This table shows the equivalences of 1 cubic meter of biogas to other types of energy sources[4].

System	AD System Size	Annual Biogas Production	LP Gas Equivalent	Electricity Equivalent	Mechanical Equivalent
Huamantla	160	19,272	6,938	42,398	55,118
Soyaniquilpan	120	14,454	5,203	31,799	41,338
Coatlán del Rio	200	24,090	8,672	52,998	68,897
Amacuzac	80	9,636	3,469	21,199	27,559

Table 7: The table shows the size of the anaerobic digester installed at each farm with the amount of biogas produced at each farm. The biogas energy is shown as equivalent in the other types of energy. The values are shown as the full value of the conversation (not cumulative).

[4] 2006 IPCC Guidelines for National Greenhouse Gas Inventories

By working with the farmers, the most appropriate biogas use or combination of uses was determined. The actual clean energy benefit to the farm comes through productive use, so it is important to optimize the biogas production with the energy demand. Choosing where to use the biogas is also an economic decision, as farmers pay different rates for energy depending on the type and the timing of energy consumption. Table 8 shows the different farm uses of the biogas, and respective fuel displacement.

Thermal Energy Use

Productive-scale farmers have significant thermal energy needs that generally include agricultural and domestic uses as most farmers have households or living quarters on site. The fours farms in the project had expenses in LP Gas between USD$1,500 – $4,600 per year. Domestic uses for biogas includes cooking and water heating, activities that commonly displace LP gas or wood fuel.

On the farm, biogas is of particular importance to swine farmers who require external heat sources for space heating maternity areas of their farmers to keep piglets from freezing to death. The loss of piglets to cold weather is an acute problem for productive-scale farmers that do not have advanced systems for space heating. The loss of piglets to cold can represent significant economic losses and inefficiencies for these farms. Biogas can be used in “heat lamps” that deflect the heat from the biogas flame, or in brick and metal “ovens” that are heated with a biogas flame.

The swine farms in both the tropical and temperate regions of this project have installed biogas heating systems in their farms and have used the systems successfully since the installed. Each system is manually lit, isolated from the animals by a metal shield that radiates the heat directly. The use of the heating system at the temperate farm in Huamantla will likely be most of the year, the tropical system also reported the need for space heating for four to six months of the year.

Other thermal uses for biogas include heating water for cleaning milking equipment. In order to provide an adequate removal of the fats of dairy milk, water of at least 70 degrees Celsius must be used. Otherwise, the equipment will begin to build up quickly with bacteria that impact the quality of the milk. Both dairies have a burner set up for heating water twice per day for cleaning the equipment.

fig. 5 : The thermal energy systems for space heating the maternity spaces to keep piglets warm at night. The top photo shows the burner in an "oven" type heater (with the top removed for the photo) and the bottom photos shows an elevated "heat lamp".

Biogas Motors and Filters

A key proposition of this work was to demonstrate the use of small internal combustion engines adapted to run on biogas to provide a clean mechanical and electrical energy to productive scale farmers in additional to the more simple thermal energy systems. Productive scale farmers consume significant amounts of gasoline to run small motors on their farms from mechanical energy to process grains and forages, pump water, and run dairy equipment. Gasoline and grid-supplied electricity is also consumed to run lights, electric motors, and other domestic and agricultural uses. The farms in this project had grid electricity bills that ranged from USD$1,100 - $2,400 per year, not including expenses for purchasing gasoline to run generators.

The motors used in this project were gasoline internal combustion engines that were sized, adapted and adjusted to the gas production and needs of the different farms. The motors ranges from 5.5 kW to 11 kW, and had adjustments made to the carburetor that allows for a mixture of biogas and oxygen to mix and provide the fuel for the combustion process. The motors can still run on gasoline, and the gasoline flow valve can be turned on or off depending on whether the motor is being run with biogas or gasoline. When there is low biogas pressure the motor can be started with gasoline and then switched over to biogas; when there is positive biogas pressure within the system the motor can start directly on biogas.

fig. 6: A view of the inside of the improved biogas filter, showing the double chambers. The gas flow in this photos goes from right to left. The gas first runs across impregnated coco fiber and then through a bed of activated carbon.

An important factor in the effective use of biogas in internal combustion engines is the removal of the traces of hydrogen sulfide (H_2S) and the humidity from the raw biogas. Humidity must be below 50% and the H_2S should be below 240 ppm in order for the gas to not cause long-term damage to the motor. There are many industrial strategies to remove H_2S from biogas, but all require high capital investments and are energy and / or chemically intensive. Strategies in the domestic biogas sector using a combination of biological and physical removal of H_2S have made recent advancements, and these solutions were scaled up for this pilot to prove the technology at the productive-scale.

The filters are designed to remove both the humidity and the H_2S, utilizing a mixture of impregnated coco fiber and activated carbon. The two larger filters are divided into two separate containers, and the smaller filters are in one large container. The filters have been designed to be economical to maintain, with changes estimated at USD$350 for 3-4 months of filter use. During the early design phase of this project, a series of pilot filters were tested, and the final designs were installed in the demonstration farms. The filters have been extremely successful and recorded consistent measurements of 100% removal of H_2S, and 30-65% reductions in humidity. The most recent biogas concentration measurements are shown in the table below.

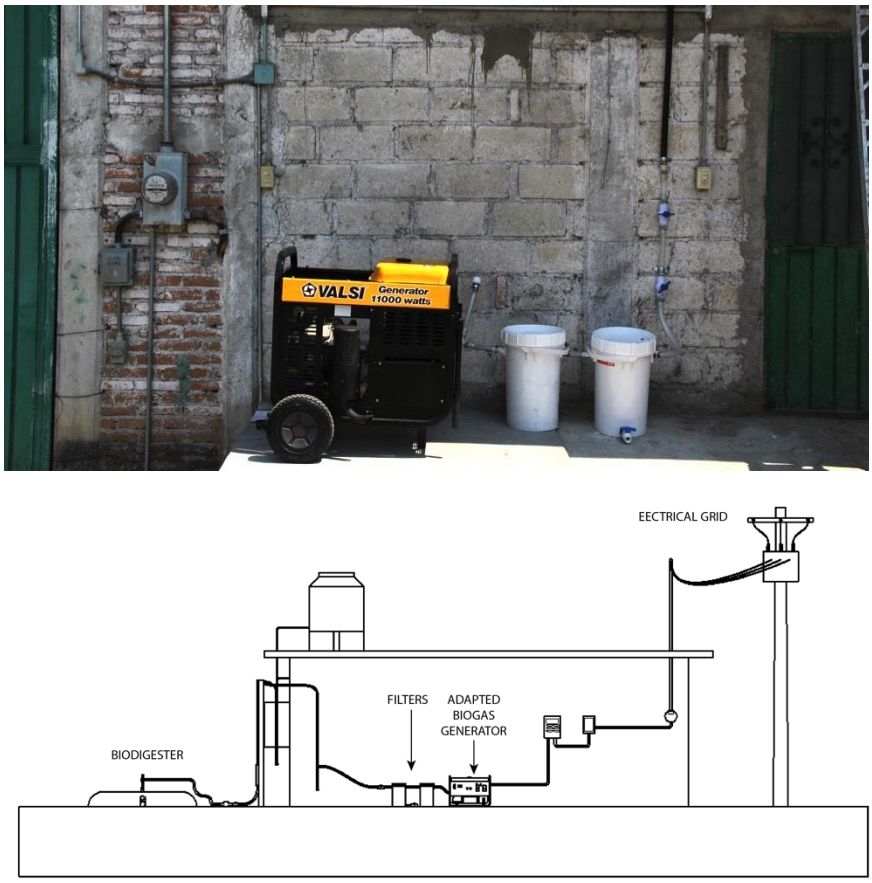

fig. 7: The photo above and the schematic below show the gas line running to the double filter, to the biogas generator and then connecting to the electrical grid. This configuration could improve the viability of the system.

	Soyaniquilpan			Coatlán del Rio			Huamantla			Amacuzac		
Gas Type	Before Filter	After Filter	Reduction (%)	Before Filter	After Filter	Reduction (%)	Before Filter	After Filter	Reduction (%)	Before Filter	After Filter	Reduction (%)
Relative Humidity	74	25	66%	69	31	55%	59	31	47%	62	28	55%
H_2S (ppm)	1325	15	99%	3022	0	100%	1145	0	100%	1240	15	99%
CH_4 (%)	56	58	-4%	61	65	-7%	54	55	-2%	58	66	-14%
CO_2 (%)	29	25	14%	28	23	18%	34	28	18%	28	20	29%
O_2 (%)	15	17	-13%	11	12	-9%	12	17	-42%	14	14	0%

Table 8: This table shows the most recent gas measurements showing the gas composition having stabilized to near-standard values. Importantly, the large reduction in the humidity and H_2S from the filter in all four sites validates the use of a filter to make biogas more suited for use in engines, bringing the value below the recommended 250 ppm.

System	AD System Size	Annual Biogas Production (m3)	LP Gas Equivalent (kg)	Description	Electricity Equivalent (kWh)	Description	Running HRs / day
Huamantla	160	19272	2931	Heating Piglet Pens, boilers, cooking, flaring	26280	Biogas Adapted Gasoline Electrical Generator 12kW	6
Soyaniquilpan	120	14454	3592	Boilers, stoves	12045	Biogas Adapted Gasoline Electrical Generator 5.5kW	6
Coatlán del Rio	200	24090	5654	Heating Piglet Pens, boilers, cooking, flaring	21900	Biogas Adapted Gasoline Electrical Generator Motor 8kW	8
Amacuzac	80	9636	1664	Boilers, stoves	12045	Biogas Adapted Gasoline Electrical Generator 5.5kW	6

Table 9: Here the AD system size is shown as well as the total estimated annual gas production, the energy equivalence in LP gas and the thermal uses; the electrical equivalence and the adapted biogas generator size is also shown. The values for both LP gas and Electricity are cumulative, estimating the split of use of the gas in these systems.

GHG Reductions

The GHG reductions through the use AD systems to capture and use methane is defined by the UNFCCC, and is scientifically well understood. Methane has been identified as a priority gas because of a climate change forcing potential over 21 times that of CO_2. The short residence time of methane in the atmosphere makes projects that reduce methane emissions critical for slowing near-term climate change and its impacts. Destroying methane therefore has direct GHG reductions, and also can provide a low-carbon energy source to displace the use of carbon-emitting biomass and fossil fuels.

The calculation of the baseline methane emissions for each farm is determined during the initial site diagnostics based on the amount of waste produced and the waste management technique. The net methane destruction is based on this baseline, which is expressed as a percentage of the total methane production potential of a waste under common management scenarios.

To ensure the destruction of the methane, and to calculate the displacement of fossil fuels, farmers track biogas use, and the resulting GHG emissions reductions are measured over the course of each year. Because these projects are new, the total displacement of biogas and fossil fuels can not yet be determined, but considering the estimated use we can estimate the potential fuel displacement for each farm.

As mentioned previously, an additional source of GHG emissions from productive scale farmers is the use of chemical fertilizers. These products produce emissions during their production, transport and use. Nitrogen based fertilizers, the most common, are produced using an extremely energy intensive process. They produced in limited areas of the world, and the majority of Mexico's fertilizers are imported, created additional emissions. Finally, according to the UNFCCC methodology AMS-IIIA for offsetting synthetic nitrogen fertilizers, up to 15% of nitrogen fertilizers can volatilize into NO3 during application, a powerful GHG. Using estimates of chemical fertilizer displacement potential, we can determine the potential GHG emissions reductions these projects will achieve.

In total these project have the potential of reduce 735 tCO_2e of GHG emissions each year, with a ten-year total offset of 7,355 tCO_2e. If the farms work effectively to demonstrate the GHG reduction potential, there is potential additional funding streams could help incentivize the installation of AD systems. Using these results and an estimated 150,000 productive farms that could use and AD systems today, the potential in the productive-farm sector to reduce GHG emissions in Mexico are estimated at over 10 million tCO_2e per year.

	GHG Source				
System	**LP Gas**	**Electricity**	**Methane**	**Fertilizer**	**Total**
Huamantla	10.6	61.0	239.0	11.3	322.0
Soyaniquilpan	13.0	28.0	4.0	9.5	54.4
Coatlán del Rio	20.5	50.9	244.0	1.9	317.3
Amacuzac	6.0	28.0	4.0	3.8	41.8
Total	50.2	167.9	491.0	26.5	735.5

Table 10: The GHG reduction for each of the farms and from each of the sources of reductions are shown here. The total estimated GHG reduction from the farm is 735 $MTCO_2e$.

Organic Waste Treatment

Anaerobic digestion breaks down waste through a chemical and biological process that is driven by anaerobic bacteria. Although this process is natural within an AD system, the conditions are optimized to maximize the treatment of the waste stream and the collection of the resulting biogas.

Anaerobic digestion systems are very efficient waste treatment technology. The biogas by-product of this process is often emphasized, but the productive-scale AD systems installed with this project are able to remove 75% to 90% of the overall organic load. While this is a very high treatment rate, for productive-scale swine farmers it is not high enough for their animal waste discharge to meet legal discharge limits. Swine farmers are interested in the renewable energy benefits of AD technology, but they primarily want a treatment system that removes the risk of legal fines.

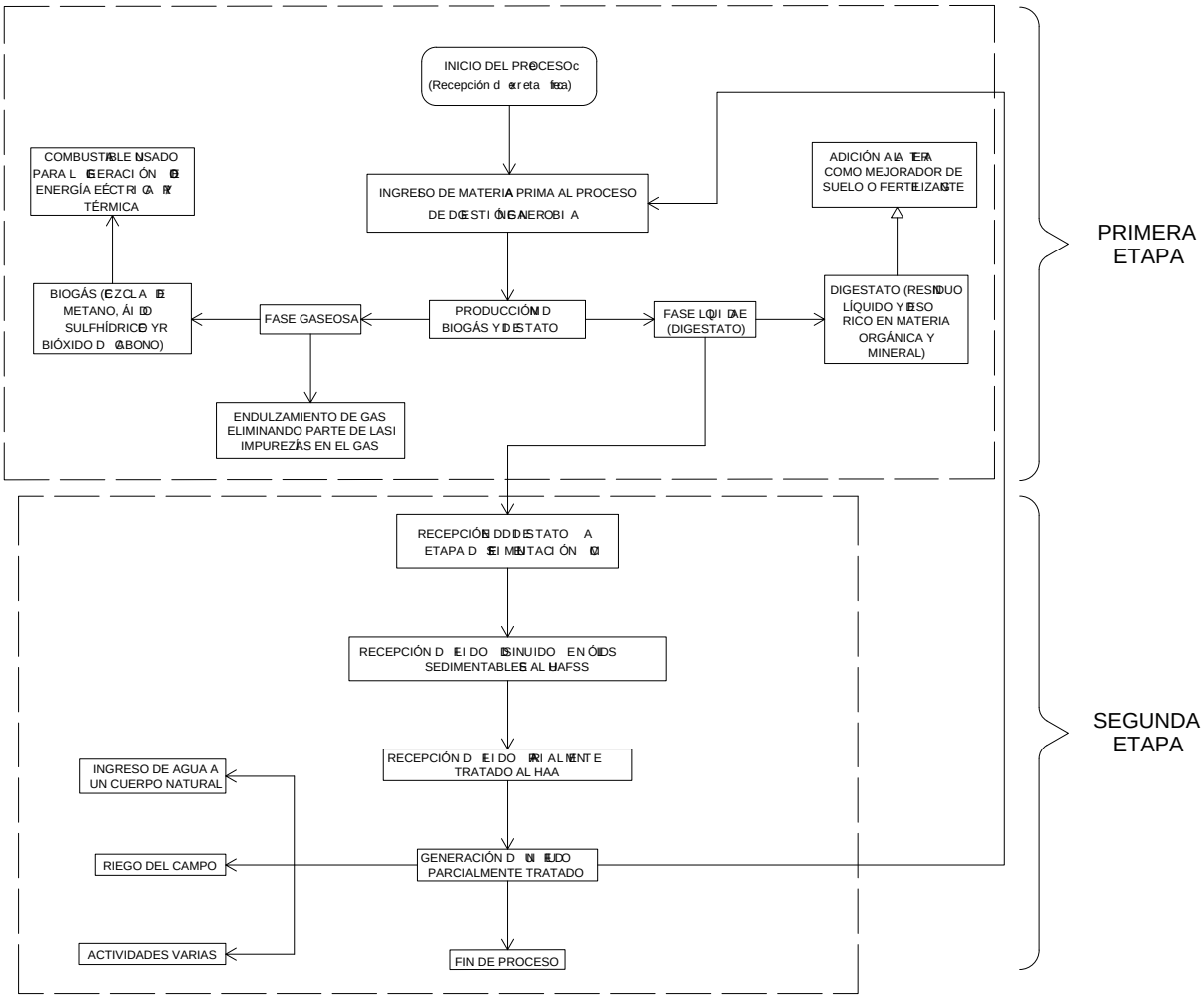

fig. 8: The figure above shows the process flow of the waste treatment provided by the productive-scale AD system and the secondary treatment. Waste flow begins at the center top, and flows through the system. The figure is in Spanish and was used in the program design[5].

[5] Figure 8 is part of the original content developed for this project, which has been documented in Spanish

A central goal of this project was to demonstrate that productive scale AD systems combined with biological secondary treatment could provide effective waste treatment for the biol that is not used directly as a fertilizer. This would remove the risk of fines for farmers, as well as providing the direct economic benefits of the system. The central treatment challenges are measured by the Chemical Oxygen Demand (COD), a proxy for the organic load within a waste stream. In addition, the pH, Total Solids, Volatile Solids, Total Nitrogen and Total Carbon are key indicators that many farmers cannot meet with standard treatment techniques.

This project demonstrated that the waste from productive scale farmers can be managed and treated in such a way that farmers are removed from risk of legal fines. We demonstrated 99% removal of the organic loads of the systems, combining the use of the biol as fertilizer and the secondary treatment of the remaining effluent. Nitrogen in particular had been an element that was hard for productive scale farmers to manage: you want high nitrogen content in your fertilizer, but not in your discharge. The update of the nitrogen from the aquatic plants of the effluent that was not used as fertilizer demonstrated how these two phases work well together.

We are not able to report the exact treatment rates of these systems because the biological treatment process has not had time to completely stabilize, we do have initial treatment data that shows that each of the four systems are completely able to meet the farmers waste treatment needs.

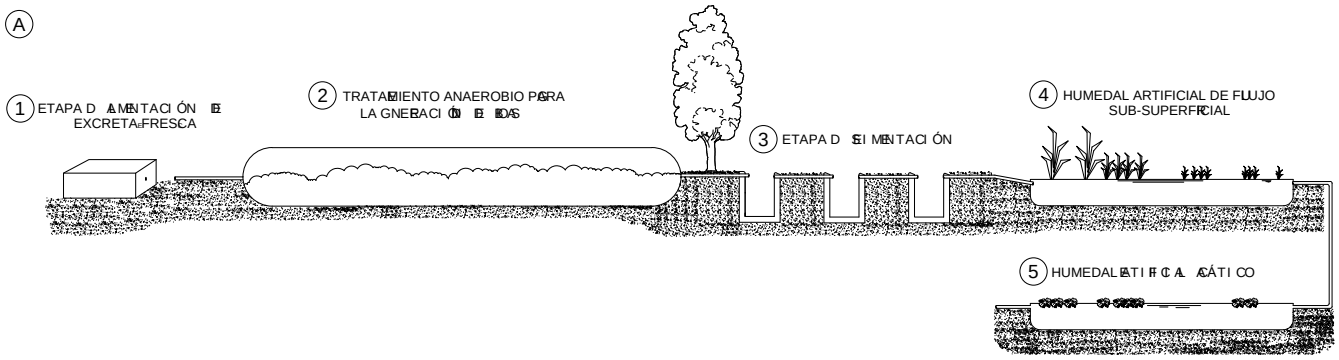

fig. 9: The figure above provides a simplified view of the AD system and secondary treatment. The numbers in the graphic represent sampling points and correspond the graphics below. 1) Manure into Biobolsa (anaerobic reactor) 2) Outflow of Biobolsa 3) Exit of sedimentation 4) Exit from subsurface wetland 5) Exit from wetland.

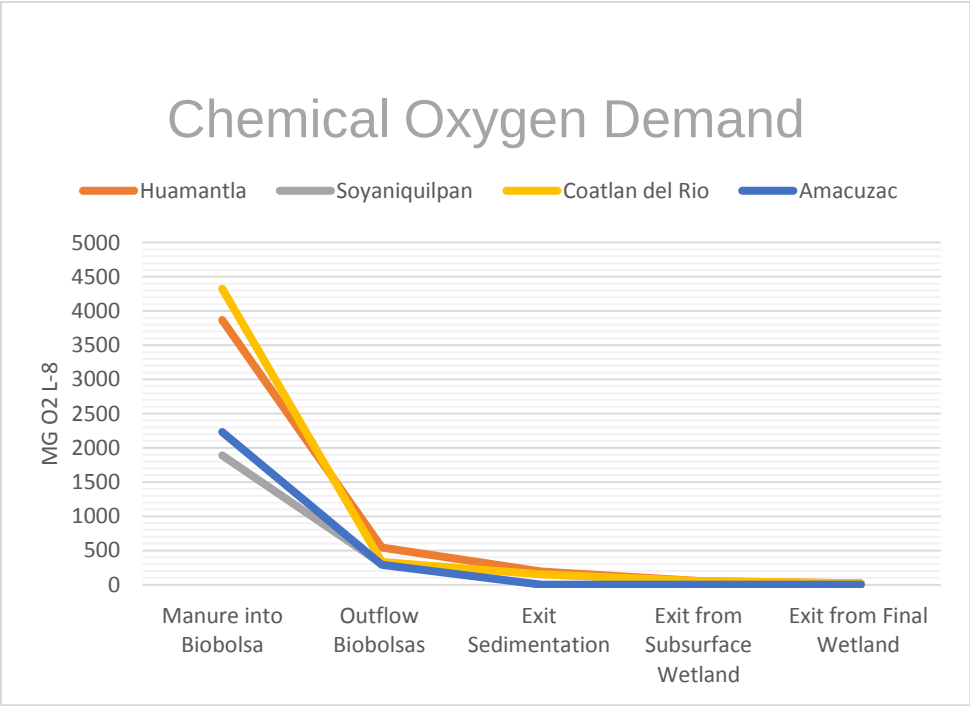

Chart 1: The Chemical Oxygen Demand (COD) is one of the most important indicators for a wastewater treatment process and demonstrated the active organic material that is still available to breakdown. All of the systems were able to reduce the COD to levels of 150 specified by SEMARNAT NOM-001

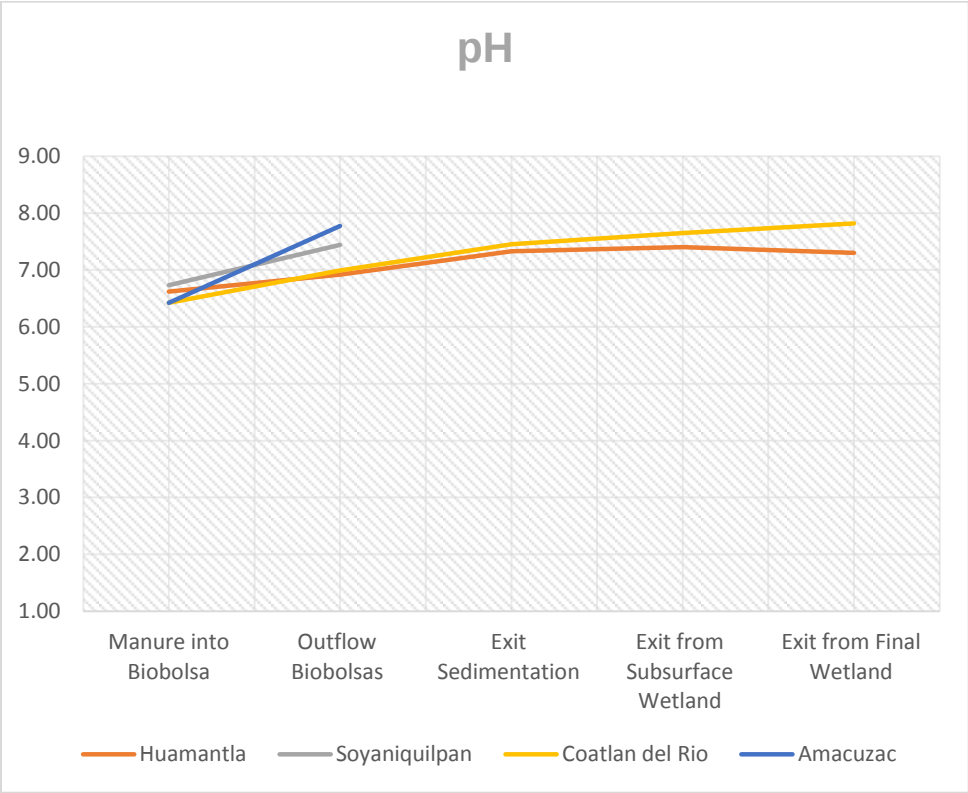

Chart 2: The pH is the measure of the acidity or alkalinity of a substance. All four system show that the waste stream is able to stabilize around 7 (neutral), and all are within legal limits of SEMARNAT NOM-001

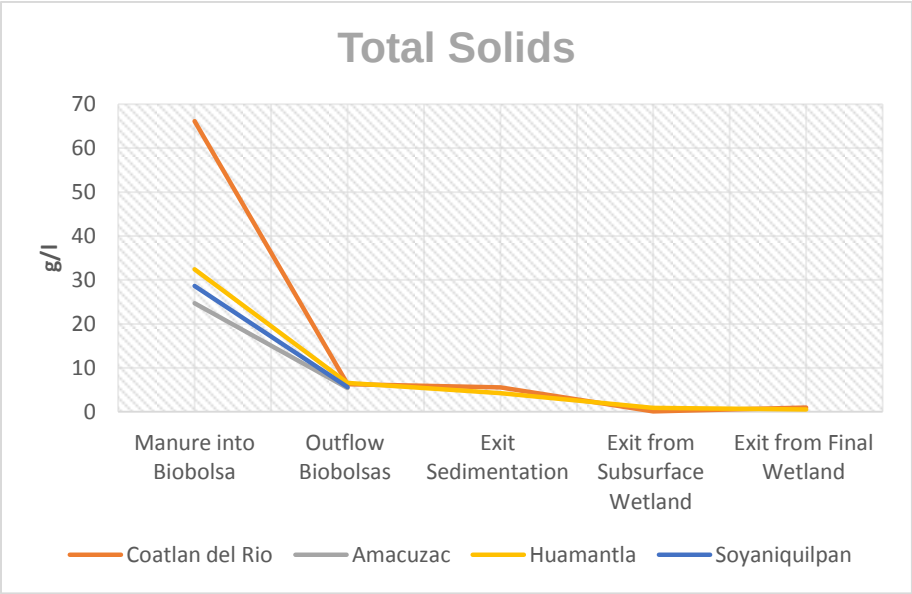

Chart 3: The total solids shown here give a sense of the dilution of the waste before it is added to the system. The high solids content at Coatlán del Rio is due to reduced water use during the time of testing.

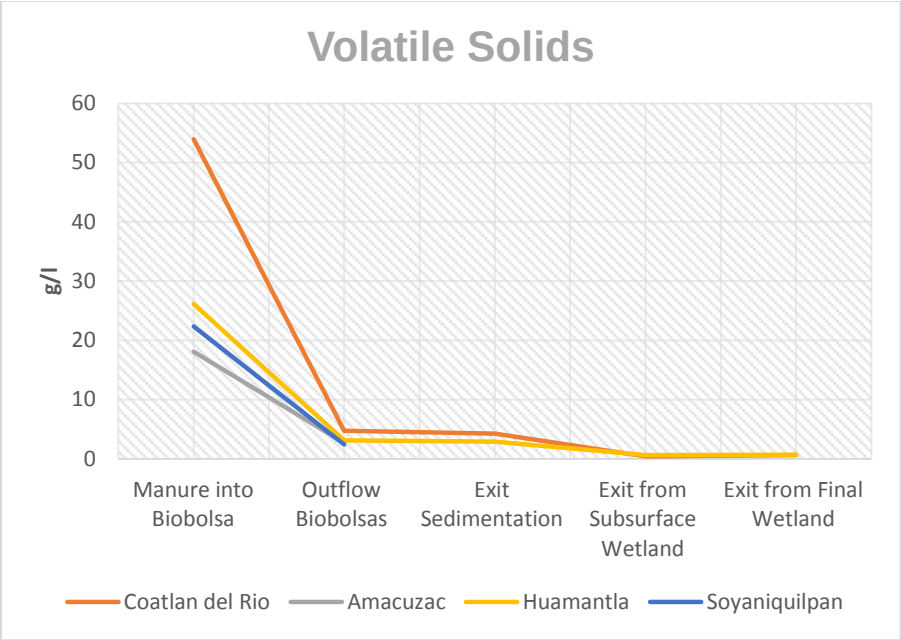

Chart 4: Volatile solids are another very important indicator for the treatment of organic waste. The term "volatile" refers to the amount of the waste that can still react either chemically or biologically. Volatile solids are also linked to the biogas production, and here we can see that the secondary treatment system allows the system to provide a critical further reduction after the large reduction in the AD system.

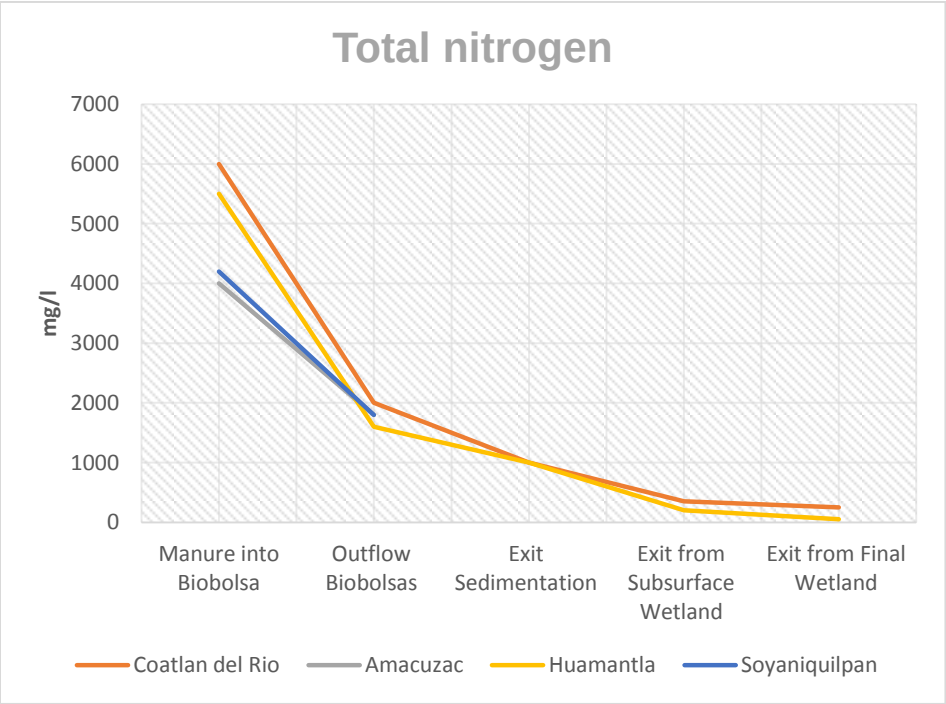

Chart 5: Nitrogen is arguably the most important indicator of the secondary treatment systems because AD system do not remove a significant amount of nitrogen, converting it into a more chemically active form. This makes biol a good fertilizer. Here, we can see the plants in the secondary treatment systems are able to uptake a significant part of the nitrogen, allowing the farmers to achieve the legal treatment levels.

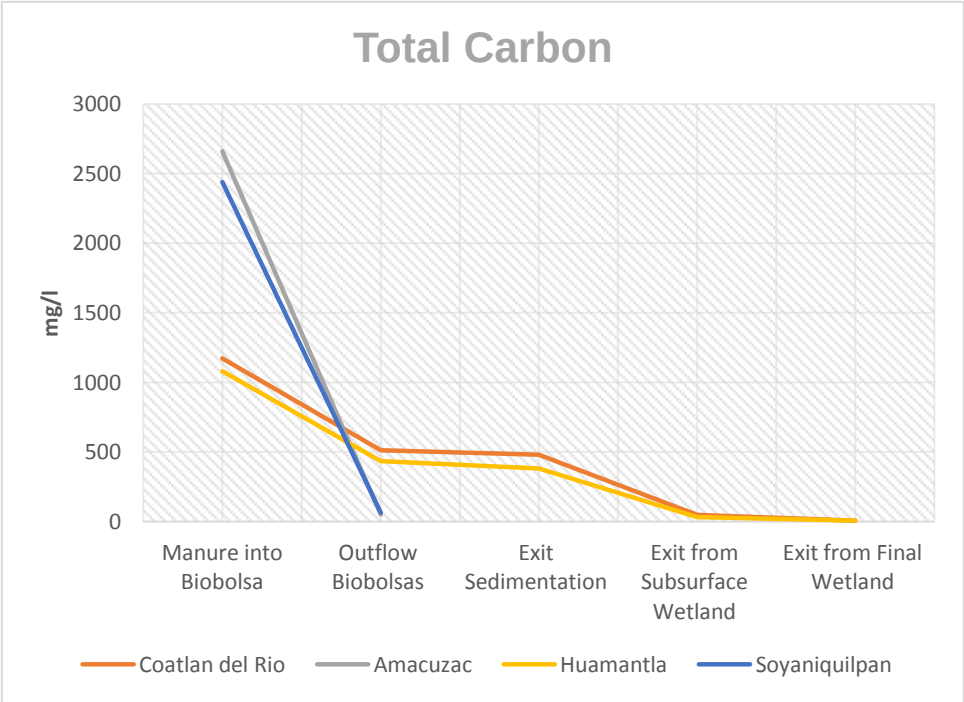

Chart 6: The total carbon is not necessarily a factor for legal limits, but shows the relationship between carbon and nitrogen (an important factor for system health). In this graphic you can see how the two cow systems have elevated carbon levels for the hay and grains in the manure, which is removed quickly in the systems. The swine systems have less carbon, but it takes longer to remove.

Conclusions and Suggested Next Steps

The activities in this project have succeeded in the original objectives of implementing low emissions technology in Mexico and of disseminating the successful use of productive-scale AD systems. The preliminary results show that the strategy is technologically and economically feasible for implementation at medium scale farms in Mexico. While further monitoring will be needed overtime, the initial data has also shown that the technology can produce significantly qualities of clean energy and organic soil amendment to support agricultural activities. Finally, the performance of the projects to date has shown significant potential for the reduction in wastewater contamination and GHG emissions.

It is now critical that these initial results are supplemented by on-going data collection as the systems stabilize and as the farmers integrate the systems as part of their everyday infrastructure. Many of these results are calculations based on the initial results and the operating designs of the systems, and can therefore improve with long term tracking of the actual functionality. A measurement of these results will make the data set and the conclusions of this work more robust.

These results show the incredible potential of simple AD technology adapted to the productive-scale to produce clean energy and reduce GHG emission, but in order for this potential to be realized, there must be coordination between funding key stakeholders. Productive-scale AD technology provides a set of benefits for farmer, that through promotion, capacity building and education, a demand for the technology could be created. The technology provides important environmental, health and economic benefits that are realized by society beyond the benefit direct to the farmer. This should encourage the use of public and international funding support to incentivize the adoption of the technology.

Finally, legal frameworks that encourage the use of productive-scale systems would further help realize the potential of the technology. Streamlined processes for interconnection of small biogas generators to the electrical grid, for example, would help maximize the return of investment for farmers. Water quality regulators that are beginning to tighten monitoring and enforcement of wastewater discharge from medium scale farmers could help build awareness in the technology, suspending fines for farms that move forward with the implementation of productive AD systems to treat their waste.

Finally, synchronization between all of these actors and the private sector to ensure that the farmers get accurate information, high quality products and long term service is of vital importance to ensure the sector is able to grow on the back of successful case studies. In addition to reliable suppliers of equipment, future technology innovation will allow the technology to decrease in price and provide high levels of service and benefits to the farmers. In addition to the technology, rural finance banks and organizations must learn more about the system and its benefits so they can develop financial products to support an active market.