Obtaining biogas for use during construction of residential buildings

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Abstract. The present study examines the technical and economic feasibility of a biodigester to generate biogas from organic waste, such as human and food residues, generated during construction projects. Based on existing data and the scaling model selected, the quantity of such waste was estimated on a per-worker basis over a period of 30 days; yielding a daily average of 86 grams of food waste, 250 grams of stool, and 1.5 liters of urine. These estimates are scalable for the calculation of periods of greater or lesser duration. The data, variables, and calculations were analyzed using a technological tool developed for this study, such that other users or parties interested in the use of a biodigester for the management of organic wastes and biogas generation in construction projects can enter the relevant data for their project and generate scaling and cost data as an output. The use of a biodigester for construction projects is based on real-life experience in various sectors, for the most part in rural areas and domestic applications; while factors such as space, maintenance, and safety, among others, have hindered the use of this technology in the construction sector. Nevertheless, its implementation in new construction projects drives positive social, environmental, and economic impacts, as it reduces the volume of organic wastes for disposal, and substitutes for the use of fossil fuels. The latter results in a reduction of pollution, and improves the environment, with corresponding positive effects upon human health and wellbeing. It also represents an opportunity to reduce the cost of gas consumed during the construction process of residential buildings.

1. Introduction
During residential building construction projects, organic waste known as biomass is generated and deposited in landfill sites, generating negative environmental and socioeconomic impacts, such as water pollution and the use of private and public funds for sewage treatment and lost potential energy production [1]. Careful organic waste management on jobsites can reduce the negative impacts to the environment, as well as waste storage and final disposal costs [2]. A biodigester system implemented during residential building construction can be an important part of such management, however, the Colombian business sector does not have access to low-cost tools for an analysis of the technical and financial viability of such a system. Correct analysis should begin with the quantification of the gas consumed by construction activities. Resulting improvements in environmental performance can be of positive economic impact in terms of community recognition of the firm’s commitment to the environment and innovation in environmental management, which may improve its market position and contribute to the added-value of its products [3].

The current study characterizes the type of organic waste generated in situ and analyses the data required to design a biodigester of suitable capacity. The resulting generation of biogas is then estimated
in order to project fixed and variable costs, and determine the net present value of the undertaking. The limitations of biogas generation are also analyzed, in terms of space utilization, process safety considerations, the amount of organic waste available as a function of worker headcount, and the limited number of construction activities that require gas. The methodology used is based on current biogas generation data from databases, and on information gathered through consultations with experts from the construction sector in order to define the consumption and specifications of work performed with the gas. A Microsoft Excel® spreadsheet is used for the management and analysis of the data to calculate the sizing and economic feasibility of a pilot biodigester prototype in civil engineering projects [4].

The present study supports technological development in Colombia, as it allows for the systematic use of existing knowledge concerning biodigesters towards developing models for the improvement of residential construction using sustainable alternatives. The project therefore drives the development of value-added products for consumers and is relevant for national social and environmental policies. The work also supplies the academic and scientific communities with a tool for the quantification of gas consumption during construction projects, establishes the activities which make use of this energy source, and provides a solution to fulfill them using biogas. Finally, it creates an opportunity for greater development of this sustainable environmental strategy by studying its implementation and effects during the construction of residential structures.

2. Methodology

2.1. Gas consumption during residential building construction
Quantification of jobsite gas consumption was carried out through sixty consultations with site experts. Areas of common use had previously been identified as heating of polyvinyl chloride (PVC) between pipe seals, nozzles, fittings, and bends, for electrical installations, and for waterproofing. Quantification of gas consumption was obtained from experts using surveys that requested information about gas-utilizing activities, the volume or type of fuel cylinders used, and the procedure in use for electrical and waterproofing activities.

This consumption is not currently found in existing literature, and published studies do not include it in their fuel consumption figures. These figures are typically given in liters per square meter for the construction activities of foundations, slab, and masonry and structure; with values of 0.25 L/m², 0.13 L/m², and 0.2 L/m², respectively. These consumptions are specified in reduced quantities with respect to electrical energy sources; nevertheless, their environmental impact is higher, given that they represent some 99.97% of emissions. In this manner, the quantification of consumption allows for the creation of controls for its reduction, substituting technologies that do not require the use of this energy, and in this case, by creating alternatives for the use of organic wastes for energy production, while simultaneously reducing the volume of waste to be sent to landfills [5].

2.2. Characterization of organic waste generated during construction
To characterize jobsite organic waste generation, the origin of the waste was first determined, in order to use existing data to accurately determine quantities.

2.2.1. Development of the technological tool. This study developed a technological tool to determine required biodigester volume in relation to the number of workers onsite. The cost of the biodigester was also calculated, taking into account the fixed and variable costs. Lastly, both analyses were combined to examine the proposal financially through the net present value of the investment required and energy savings realizable.

This technological tool was programmed and created on the Excel® platform, where the dimensioning, capacity, costs, and feasibility of implementing the system are calculated, using user-input variables such as worker headcount [6].
3. Results and discussion

3.1. Gas consumption during residential building construction
Gas consumption was quantified through two surveys which requested information about gas-utilizing activities, the volume or type of fuel cylinders currently used in these processes, and construction procedures in the electrical and waterproofing areas.

It was found that gas usage for waterproofing occurs during installation of the asphalt membrane or mantle. Survey respondents differed in their specific methods for this process, specifically in the volume of the gas container used for waterproofing. Some 80% of respondents indicated that the most commonly-used cylinders have a storage capacity of 20, 33, and 40 pounds. Using these figures, a relationship was established of average consumption of 2.135 m³/pound of gas. From surveys directed to experts in the areas of electricity or electrical installations, 100% of respondents (29 individuals) indicated that gas is used to heat PVC parts. Some 89% of respondents used 30-pound cylinders and achieve an average performance per pound of gas of 98.563 tube joints, 92.246 nozzles, 91.896 fittings, or 83.936 curves of ½ inch, ¾ inch, or 1 inch.

3.2. Characterization of organic waste
To calculate the quantity of jobsite food waste per employee, existing data was used which indicates a 2016 Colombian total of 9.76 million tons wasted per year, of which 15.6% (1.52 million tons) occurs during consumption, that is, during a person’s daily meals. This figure was divided by the population (48.8 million in August 2016, per the “Departamento Administrativo Nacional de Estadística (DANE)”, indicating that the average person wastes 86 grams of food per day while eating [7].

On average, a human daily excretes a fecal bolus weighing in the range of 120-400 grams, of which 80% is water and 20% solids (starch, bacteria, muscle fibers, flora, etc.) [8]. On the jobsite, this quantity is taken to be produced only by employees, who compose the population of the site. This waste can be collected in portable or fixed toilets. Human urine is a liquid waste composed of 95% water, 2% mineral salts, and 3% organic substances, including approximately 2 grams of urea per 100 ml. Every day, a normal adult produces between 1 - 2 liters of urine [9].

3.3. Biodigester design in terms of capacity

3.3.1. Sizing. The selection of a horizontal biodigester in the current study corresponds to three design criteria which are critical in the mountainous and seismically-active territory of Colombia; that of the water table, the rocky soil, and soil stability. This proposal is consistent with the analysis undertaken for the design of the Coproctor (horizontal) biodigester, which identified a series of unforeseen difficulties using a Chinese rural type (vertical) biodigester, which complicated the implementation process in human and economic terms. Additionally, this choice takes advantage of lower labor, time, and costs for excavation machinery [10].

The most important variable in the design of a horizontal biodigester is its volume. To calculate this capacity, the nature of its substrate must be taken into account. The biodigester will contain a mixture of organic material (human faces, urine, and food waste) and water in a 1:1 proportion. As indicated in Equation (1), the substrate occupies 75% of the biodigester’s volume, in order to leave sufficient space for the accumulation of biogas resulting from digestion [11].

\[ V_{sustrato} = 0.75 \times V_{total} \]  

(1)

To calculate the volume of waste per worker in any construction projects, Equation (2) was used to obtain the volume of waste per worker (VR) of 0.0021 m³/day/worker. In this equation, L is the volume of urine (L), P is the mass of the stool (Kg), Dh is the density of the stool (Kg/L), A is the mass of the food waste (Kg), and Da is the density of the food waste (Kg/L).
\[ VR = L + P \cdot \frac{1}{D_h} + A \cdot \frac{1}{D_a} \]  

(2)

Equation (3) and Equation (4) assume a standard retention time of 45 days, and the addition of water as required to maintain a 1:1 ratio with the organic material. With \( V_{\text{substrate}} \) as the substrate volume in \( \text{m}^3 \), \( T \) as the number of workers, and \( V_{\text{total}} \) as the volume of the biodigester, then:

\[ V_{\text{substrate}} = T \cdot 2VR \cdot 45 \]  

(3)

\[ V_{\text{total}} = \frac{V_{\text{substrate}}}{0.75} \]  

(4)

To find the width or diameter of the cross section of the biodigester for a given length, Equation (5) yields:

\[ D_{\text{Zanja}} = \sqrt{\frac{4V_{\text{total}}}{\pi L_{\text{Zanja}}}} \]  

(5)

4. Biomass generation

Equation (6) and Equation (7) yield the total amount of input biomass generated, which is a function of the total construction time. Here, \( B_{\text{humana}} \) is the human waste biomass (tons); \( B_{\text{alimentos}} \) is the food waste biomass (tons); \( d_L \) is the density of urine (Kg / L); \( t_{\text{obra}} \) is the total construction time in months; and \( d_{\text{mes}} \) are the number of days worked each month. Normally, 25 business days is the standard figure for \( d_{\text{mes}} \), however, this variable is customizable by the user.

\[ B_{\text{humana}}(\text{ton}) = (T \cdot (P(\text{kg}) + L(\text{litros}) \cdot d_L) \cdot t_{\text{obra}} \cdot d_{\text{mes}})/1000 \]  

(6)

\[ B_{\text{alimentos}}(\text{ton}) = (T \cdot A(\text{kg}) \cdot t_{\text{obra}} \cdot d_{\text{mes}})/1000 \]  

(7)

To estimate total biogas production (\( EG_{\text{production}} \)) in cubic meters, the quantities of food and human waste biomass inputs are multiplied by the ratios of biogas production from each (\( R_{\text{ab}} \) and \( R_{\text{hb}} \), respectively), and summed, as indicated in Equation (8). Research indicates \( R_{\text{ab}} \) and \( R_{\text{hb}} \) to be 135 m³/ton and 18.3 m³/ton, respectively.

\[ EG_{\text{producción}} = B_{\text{alimentos}} \cdot R_{\text{ab}} + B_{\text{humana}} \cdot R_{\text{hb}} \]  

(8)

4.1. Economic analysis of biogas generation using a horizontal biodigester

The cross-sectional area of the biodigester is calculated assuming the 6-meter width of commonly-available 8-gauge tubular polyethylene sheet, which is rolled double to create a 16-gauge tubular assembly. The radius of the unit \( r_B \) is thus calculated using Equation (9). The required length of the biodigester is then found using Equation (10), based on the total volume specified.

\[ r_B = \frac{\text{álumina}}{2\pi} = \frac{6m}{2\pi} \approx 1 \]  

(9)

\[ L_B = \frac{V_{\text{total}}}{\pi r_B^2} \]  

(10)

Additional costs for other material and fittings are fixed; that is, varying the capacity or volume of the reactor does not affect the cost of these components [12].
4.2. Development of the technological tool
An Excel model was built to calculate the cost of building a biodigester based on specific input variables: the required number of PVC bends, fittings, nozzles, and connections; estimated construction time in months; the number of workers and contractors onsite; and the area to be waterproofed in m$^2$, if applicable to the project. This data allows for the estimation of fixed and variable costs, the amount of biomass generated, and the potential for generating biogas from this type of organic waste.

4.3. Environmental impact of the process in the construction sector
According to the results obtained, it is evident that the use of the proposed process would generate a positive environmental impact, as the use of biogas reduces the emission of greenhouse gases such as methane (CH$_4$), whose global warming potential is 21 times greater than that of carbon dioxide (CO$_2$) [13].

5. Conclusions
Gas consumption during the construction of residential buildings in Colombia was found to occur only during the installation of PVC pipe for electrical installations and during the waterproofing or mantle application stage. This usage was quantified through surveys completed by experts in the two areas involved, indicating a consumption rate of one pound of gas for: 2.135 m$^3$ of waterproofing, 98.563 pipe seals, 92.246 nozzles, 91.896 fittings, or 83.936 bends of ½ inch, ¾ inch, and 1 inch.

Characterization of the organic waste produced during construction revealed that each worker generates approximately 1.5 liters of urine, 250 grams of stool, and 87 grams of food waste per day, for a total of 0.0021 m$^3$ daily. Research indicates that one ton of food waste and one ton of human waste can generate up to 135 m$^3$ and 18.27 m$^3$ of biogas, respectively.

The capacity, and therefore the design, of the biodigester was established for a retention and operation period of 45 days, with a total volume dependent on the number of workers on the jobsite. To create an economic analysis, the cost of the biodigester is first estimated, using average material prices for the year 2016. The fixed portion of this cost was found to be USD $277.08, to which the cost of polyethylene must be added. This latter cost depends on the number of workers. For reference, the approximate cost of a month’s labor in Colombia during the same period was USD $210.20.

Loading the Excel tool with a hypothetical jobsite of 100 workers, 24 months of construction, 100 m$^2$ of waterproofed area, and 200 total PVC installations, sufficient surplus gas would remain that, if monetized, would yield a positive net present value (NPV) of USD $228.38.

The proposed implementation of an organic waste biodigester on a residential construction site would reduce the environmental impact of the site, including sewage production. The biodigestion process would generate two environmentally-friendly products, in the form of compost and biogas.

Residential construction sites consume only a small amount of gas, as most of their energy inputs are either electrical or liquid fuels such as gasoline. The cost of building a biodigester system is thus relatively high in comparison to its potential savings, therefore, based on potential savings alone, the proposal is unlikely to be feasible.

On the other hand, if the project generates sufficient surplus gas, monetizing this additional value could make the project feasible. The Excel-based analytical tool developed in this study allows for the calculation of costs for the construction of a biodigester system, and of its potential benefits. It is therefore a dynamic tool that allows interested parties to estimate the potential theoretical feasibility of this type of project.

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