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Biogas in Cajamarca: A Comprehensive Approach to Solid Waste Management and Sustainable Development

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ABSTRACT

The study analyzes the integrated management of solid waste after the approval of the "Plan de Valorización de Residuos Orgánicos e Inorgánicos 2022" (Organic and Inorganic Waste Valorization Plan 2022). It studies the decomposition phases of organic waste considering factors such as landfill age, waste characteristics, presence of oxygen and temperature. To evaluate the biogas potential of solid waste, the "EPA Model" and the "Mexican Biogas Model 2.0" are proposed, underlining the importance of choosing appropriate methods. A connection is made with a study in Iquitos, Peru, which highlights solid waste management in the tropical rainforest, suggesting the generation of compost and highlighting methane (CH4) as the main component of biogas, with opportunities for the energy industry. The use of precise measurement instruments is recommended, considering the economic limitations, and the exploration of other mathematical models to evaluate medium or long term projections.

Key words: Biogas, Solid waste, Estimation, EPA model.

Biogás en Cajamarca: Un Enfoque Integral para la Gestión de Residuos Sólidos y el Desarrollo Sostenible

RESUMEN

El estudio analiza la gestión integral de residuos sólidos tras la aprobación del "Plan de Valorización de Residuos Orgánicos e Inorgánicos 2022". Estudia las fases de descomposición de residuos orgánicos considerando factores como la edad del vertedero, las características del residuo, la presencia de oxígeno y la temperatura. Para evaluar el potencial de biogás en los residuos sólidos, se proponen el "Modelo EPA" y el "Modelo Mexicano de Biogás 2.0", subrayando la importancia de elegir métodos adecuados. Se establece una conexión con un estudio en Iquitos, Perú, que resalta la gestión de residuos sólidos en el bosque húme-

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do tropical, sugiriendo la generación de compost y destacando el metano (CH_4) como componente principal del biogás, con oportunidades para la industria energética. Se recomienda el uso de instrumentos de medición precisos, considerando las limitaciones económicas, y la exploración de otros modelos matemáticos para evaluar proyecciones a medio o largo plazo.

Palabras clave: Biogás, residuos sólidos, estimación, modelo EPA.

Introduction

This research work addresses the crucial issue of solid waste management and the estimation of the biogas generation potential in the city of Jaén, located in the Cajamarca region, during the year 2023. Reference is made to the "Plan de Valorización de Residuos Orgánicos e Inorgánicos 2022" (Municipalidad Provincial de Jaén, 2022), approved in 2022 by the Provincial Municipality of Jaén. The main objective of this plan is to encourage the reduction of solid waste generation and convert the waste generated into inputs for other productive processes through recycling, thus promoting the circular economy. It is evident that inadequate solid waste management has had negative environmental consequences, aggravated by population growth, industrial processes and consumption practices. In this context, research and methodologies are being carried out worldwide to estimate the potential of biogas generated from solid waste as a technically and economically viable alternative energy source.

The objective of this study is to determine the energy potential of solid waste for biogas generation, in order to optimize its use. To achieve this purpose, two recognized methodologies and previous studies were used, specifically the "EPA MODEL" and the "MEXICAN BIOGAS MODEL 2.0". These methodologies were selected in order to establish an adequate framework for our research and accurately determine the biogas potential of solid waste in the city of Jaén.

1. Background

The study conducted by (Guerra, 2008) focuses on solid waste management in rainforest cities, specifically in Iquitos, Peru. The research highlights the importance of solid waste management to reduce pollution and improve the living and working conditions of the population. The conditions and results of solid waste degradation in Iquitos were analyzed to understand its contribution to the resource stock in the rainforest. The results revealed that the soil of the landfill receiving the solid waste lacks nutrients, but several ways of treating this waste to generate compost and increase the amount of raw material were identified. In addition, biogas generation, especially methane (CH_4), was observed during solid waste degradation. The calculation of methane volume was performed according to the Mexican scheme, and the potential of methane as a resource for the energy industry in the area was highlighted.

The study proposes a process for the production of compost from solid waste, which could improve the management of this waste. It also suggests the implementation of actions to take advantage of the biogas produced in the landfill. In summary, there are recommended options and processes to generate compost from solid waste, which benefits productivity, employment and environmental preservation in the Amazon (Guerra, 2008).

2. Methodology

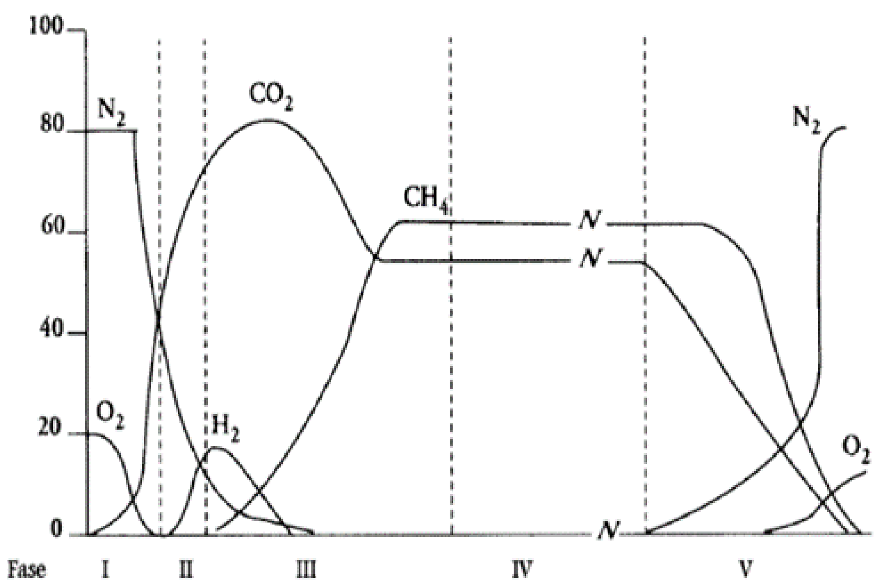
2.1. Organic waste decomposition process

The organic waste decomposition process, according to (Camargo and Vélez, 2009), is a complex process with several phases influenced by environmental factors such as the age of the landfill, the characteristics of the waste, the presence of oxygen and the temperature. Five stages can be distinguished in this process. The first stage, called "Aerobic", begins immediately after the disposal of solid waste in the landfill, where biodegradable substances decompose easily in the presence of oxygen, generating water, carbon dioxide (CO2) and partially decomposed matter, with a temperature ranging from 35 to 40 °C.

In the second stage, known as "Aerobic with Development of Anaerobic Conditions", the fermentation process takes place, with the participation of facultative organisms that generate organic acids and reduce the pH, creating conditions conducive to the generation of CO2 and the release of metals into the water. The third stage, called "Anaerobic", results from the action of organisms that generate methane (CH4), with a significant decrease in CO2 production under appropriate conditions. In the fourth stage (the "Stable Methanogenic" stage), there is a high generation of methane (CH4), with a percentage range between 40% and 60% by volume.

Finally, the fifth stage, known as "Stabilization", is characterized by a decrease in CH4 generation, with the introduction of atmospheric air that favors aerobic conditions in the system.

Figure 1. More optimal composition of biogas in a landfill cell



Source: Vélez & Camargo (2009).

The stages of the organic waste decomposition process have a direct impact on the biogas composition, and the duration of each stage is influenced by climatic conditions and operational factors at the landfill. The first two stages, which refer to initial decomposition, can last from several weeks to two years or more. High compaction, high ambient temperatures and disposal of waste in thin layers and small cells are factors that favor biodegradation and minimize the time between these stages. Stages 3 and 4, related to methane generation, usually last approximately 5 years. The operability of the landfill and the amount of moisture in the solid waste influence this stage. Higher moisture accelerates biological reactions, reducing the time between these stages and increasing biogas production over time. The last stage, the stabilization stage, can extend over several decades or even centuries, depending on the actions taken during the landfill operation period to increase its useful life (Camargo and Vélez, 2009). Regarding the composition of the biogas, especially the ratio of CH4 and CO2, it is observed that, at maximum production, they have a ratio of 1.2:1, as detailed in Table 1.

Table 1. Range of biogas composition generated in landfills

Parameter	Unit	Range of variation
Methane	$\%CH_4$	30 - 65
Carbon dioxide	$\%CO_2$	20 - 40
Nitrogen	$\%N_2$	5 - 40
Hydrogen	$\%H_2$	1 - 3
Oxigen	$\%O_2$	0 - 5
Argón	%Ar	0 - 0.04
Hydrogen sulfide	$\%H_2S$	0 - 0.01
Total sulfate	%S	0 - 0.01
Total chloride	%Cl	0.005
Temperature	% C	10 - 40
Moisture content	% humedad relativa	0 - 100
Mass	Kg/m^3	1,1 - 1,28
Minimum eneergy level	MJ/Nm^3	10,8 - 23,3

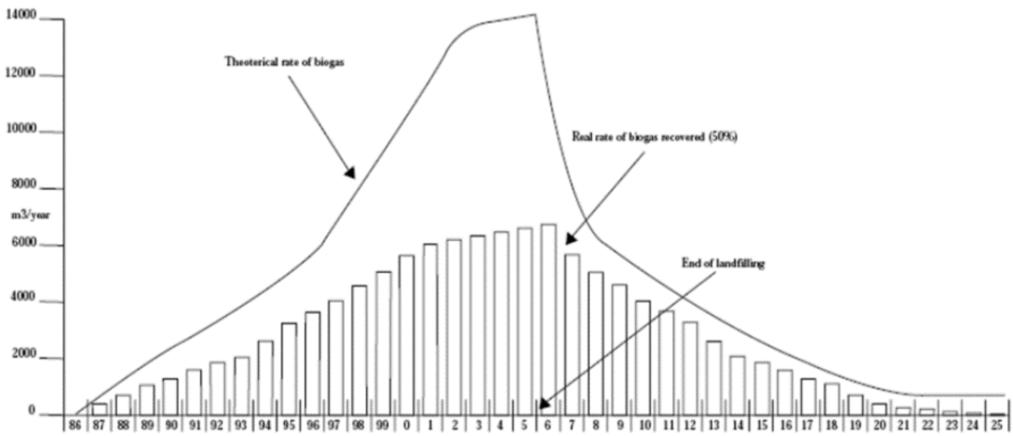
Source: Vélez and Camargo (2009), in "Biogas emissions produced in landfills"

2.2. Models for biogas generation

Currently, several methods and mathematical models have been developed to facilitate the estimation and projection of biogas generation potential. A prominent example is the IPCC, which recommends two methods for biogas calculation and projection, with the main objective of establishing national greenhouse gas inventories. The first method, known as the default methodology (Bingemer and Crutzen, 1987). This simpler approach assumes that all potential methane generation is released in the same year in which the solid waste is deposited. However, this approach does not always reflect reality, as illustrated in Figure

2. It is recommended for use in areas where detailed information on solid waste is limited, and estimates and projections are needed, considering factors such as degradable organic carbon content and the quality of landfill management. This methodology is suitable for the calculation, estimation and projection of emissions at regional and national levels.

Figure 2. Fate of biogas generation sustained over time.



Source: Vélez and Camargo (2009), in "Biogas emissions produced in landfills".

In contrast, the second, more complex method, known as the "first order" or "Scholl-Canyon" kinetic methodology, is more suitable for projecting and estimating emissions at individual landfills. This methodology uses very specific input data to predict biogas production over the lifetime of the landfill. Research in places like Nigeria has used these models, with results suggesting methane (CH_4) emissions from solid waste of less than 100 Gg in 1994, increasing to 231 Gg in 2004. The projection indicated that by 2010, CH_4 production would be approximately 450 Gg, and was expected to increase steadily to 610 Gg by 2020. This illustrates how the CH_4 generation rate can be projected by various mathematical models for biogas production.

In conjunction with the Environmental Protection Agency's (EPA) Landfill Gas Emission Model (LandGEM), this methodology stands out as a valuable tool for calculating emission rates at sites such as landfills. Based on a "decomposition equation with first-order kinetics," LandGEM quantifies emissions from the decomposition of biodegradable solid waste. In addition, it is useful for estimating total gas emission rates, including CH_4, CO_2, air pollutants and volatile organic compounds associated with decomposition.

2.3. EPA Model

Some authors such as Rodriguez and Urrego (2016), recommend that in order to make use of the present mathematical model, it is necessary to previously know "the average annual rate of disposed waste", the number of years the landfill was in operation, as well as the number of years closed, the "potential of disposed waste", to generate methane and the "methane generation rate".

In addition to the above, the author recommends the use of the following mathematical expression:

LFG: Refers to the figure representing "total gas generated" (cubic feet).

Lo: Refers to the "total methane generation potential of the waste" (cubic feet/lb).

R: Refers to "Average annual waste disposed during active life" ("pounds").

k: Refers to the "annual methane generation rate" (1/year).

T: Refers to the "time since opening" of the landfill (years).

C: Refers to the "time since closure" of the landfill (years), if not yet closed C = 0.

Table 2. Valores estándar de k y L0

Model parameter	Value
k	0,050 per year
Lo	170 m^3/ton

Source: Stege G. User's Manual: Mexican Biogas Model (2009).

3. Results

3.1. Result of Population Growth:

As for the population prediction in the province of Jaen until 2064, it was obtained from the comparison of the "urban population of the district" in the 2007 and 2017 censuses, in which an annual population growth rate of 1.61% was obtained, as evidenced in Table 3.

Table 3. Solid Waste Generation (Tn/year), by 2021

Year	Population (hab.)	RR.SS Gene-ratión (ton/year)	Per-Capita con-sumption
2018	186322	28775.35	0.423
2019	187216	18216.00	0.267
2020	188115	18091.70	0.263
2021	189018	29755.88	0.431
AVE-RAGE		23709.73	0.346

Source: Development and elaborated, based on SIAR (2020) and Census 2007-2017

In order to calculate the per-capita generation, it is necessary to know the total production of the province of Jaén, dividing the amount of solid waste by the number of inhabitants, from which the following was obtained:

The information obtained with the development of this study was considered as an initial milestone, it was verified that the "per capita generation" of D.S.W., in which the socioeconomic stratum and the "corresponding number of inhabitants" were considered. In terms of "per capita" production in the province of Jaén, "0.346 kg/inhab/day" was obtained, which indicates that each citizen of the district produces "346 grams" of SRs per day in the province of Jaén.

Having already established the per capita generation, we proceeded to estimate the projection of solid waste generation.

3.2. Results of Solid Waste Generation.

After defining and establishing the per-capita generation, we proceeded with the estimation and projection using the MATHEMATICAL MODEL - EPA, as shown in Table 6 below, whose projection goes from 2018 to 2065 (approximately 47 years of projection):

Table 4. Solid Waste Generation (Tn/day and Tn/year), for the time period from 2018, to 2065.

Year	Total solid waste generation (Tn/day)	Total generation of solid waste (Tn/year)	ACCUMULATED	Year	Total non-household waste generation (Tn/day)	Total generation of solid waste (Tn/year)	ACCUMULATED
2018	78.22	28548.77	28548.77	2042	108.94	39762.20	846483.50
2019	79.30	28945.60	57494.37	2043	110.45	40314.89	886798.39
2020	80.41	29347.94	86842.32	2044	111.99	40875.27	927673.66
2021	81.52	29755.88	116598.20	2045	113.54	41443.44	969117.10
2022	82.66	30169.49	146767.68	2046	115.12	42019.50	1011136.60
2023	83.81	30588.84	177356.52	2047	116.72	42603.57	1053740.17
2024	84.97	31014.03	208370.55	2048	118.34	43195.76	1096935.93
2025	86.15	31445.12	239815.67	2049	119.99	43796.18	1140732.11
2026	87.35	31882.21	271697.88	2050	121.66	44404.95	1185137.06
2027	88.56	32325.37	304023.26	2051	123.35	45022.18	1230159.23
2028	89.79	32774.70	336797.95	2052	125.06	45647.99	1275807.22
2029	91.04	33230.26	370028.22	2053	126.80	46282.49	1322089.71
2030	92.31	33692.16	403720.38	2054	128.56	46925.82	1369015.53
2031	93.59	34160.49	437880.86	2055	130.35	47578.09	1416593.62
2032	94.89	34635.32	472516.18	2056	132.16	48239.42	1464833.04
2033	96.21	35116.75	507632.93	2057	134.00	48909.95	1513742.99
2034	97.55	35604.87	543237.80	2058	135.86	49589.80	1563332.79
2035	98.90	36099.78	579337.57	2059	137.75	50279.10	1613611.89
2036	100.28	36601.56	615939.14	2060	139.67	50977.98	1664589.87
2037	101.67	37110.33	653049.46	2061	141.61	51686.57	1716276.44
2038	103.09	37626.16	690675.62	2062	143.58	52405.01	1768681.45
2039	104.52	38149.16	728824.79	2063	145.57	53133.44	1821814.90
2040	105.97	38679.44	767504.22	2064	147.59	53872.00	1875686.89
2041	107.44	39217.08	806721.30	2065	149.65	54620.82	1930307.71

Source: SIAR (2020) and Census 2007-2017

According to Table 4, it was possible to project up to the year 2065, with the maximum value of solid waste generation being 54620.82 Tn/year, which suggests a generation of 149.65 Tn/day for the same year.

3.3. Biogas Generation Result: Estimation using the EPA Model.

Next, the estimation and/or projection of BIOGAS generation was made according to the mathematical model "EPA MODEL", based on the following:

LFG: Refers to the figure representing "total gas generated" (cubic feet)

Lo: Refers to the "total methane generation potential of the waste" (cubic feet/lb)

R: Refers to "Average annual waste disposed during active life" ("pounds")

k: Refers to the "annual methane generation rate" (1/year)

T: Refers to the "time since opening" of the landfill (years)

C: Refers to the "time since closure" of the landfill (years), if it is not yet closed C = 0

For the value of k, it will be 0.050 1/year, and for the value of Lo it will be 170 m3/ton, once these values were defined, we proceeded with the estimation and projection using Excel software.

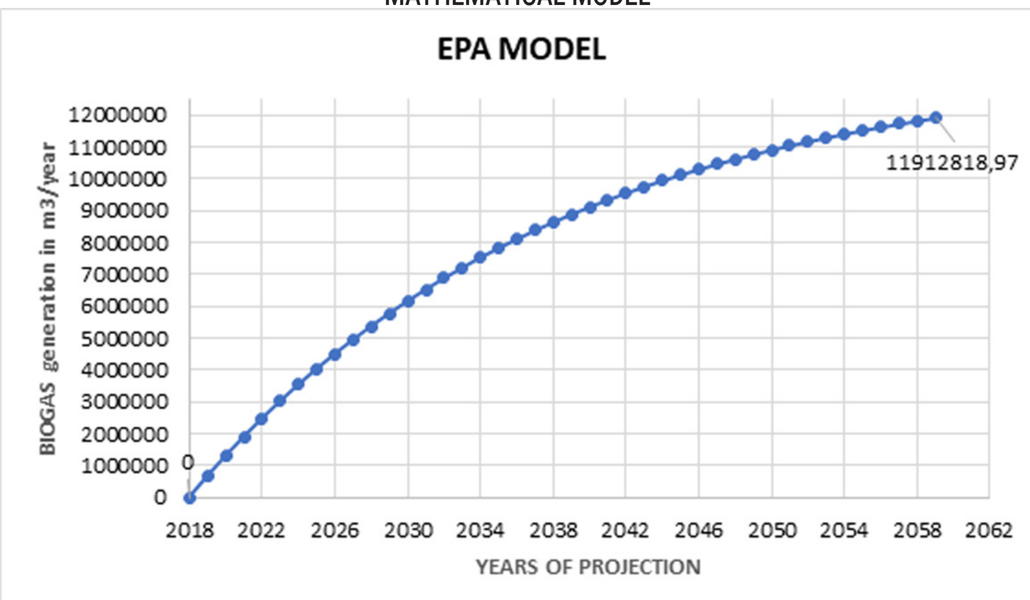
Table 5. Biogas generation (m3/year and m3/h), for the time period from 2018, to 2065 - "EPA MATHEMATICAL MODEL".

Year	Provision T/year	EPA MODEL		Year	Provision T/year	EPA MODEL	
		m3/year	m3/h			m3/year	m3/h
2 018	28 548.77	0.00	0.00	2 042	39 762.20	9 554 780.61	1 090.73
2 019	28 945.60	666 840.71	76.12	2 043	40 314.89	9 755 629.17	1 113.66
2 020	29 347.94	1 301 159.22	148.53	2 044	40 875.27	9 946 682.23	1 135.47
2 021	29 755.88	1 904 541.65	217.41	2 045	41 443.44	10 128 417.53	1 156.21
2 022	30 169.49	2 478 496.77	282.93	2 046	42 019.50	10 301 289.49	1 175.95
2 023	30 588.84	3 024 459.76	345.26	2 047	42 603.57	10 465 730.38	1 194.72
2 024	31 014.03	3 543 795.83	404.54	2 048	43 195.76	10 622 151.40	1 212.57
2 025	31 445.12	4 037 803.58	460.94	2 049	43 796.18	10 770 943.68	1 229.56
2 026	31 882.21	4 507 718.29	514.58	2 050	44 404.95	10 912 479.27	1 245.72
2 027	32 325.37	4 954 714.99	565.61	2 051	45 022.18	11 047 112.08	1 261.09
2 028	32 774.70	5 379 911.40	614.15	2 052	45 647.99	11 175 178.78	1 275.71
2 029	33 230.26	5 784 370.73	660.32	2 053	46 282.49	11 296 999.59	1 289.61
2 030	33 692.16	6 169 104.36	704.24	2 054	46 925.82	11 412 879.13	1 302.84
2 031	34 160.49	6 535 074.30	746.01	2 055	47 578.09	11 523 107.16	1 315.42
2 032	34 635.32	6 883 195.67	785.75	2 056	48 239.42	11 627 959.31	1 327.39
2 033	35 116.75	7 214 338.97	823.55	2 057	48 909.95	11 727 697.75	1 338.78
2 034	35 604.87	7 529 332.22	859.51	2 058	49 589.80	11 822 571.89	1 349.61
2 035	36 099.78	7 828 963.07	893.72	2 059	50 279.10	11 912 818.97	1 359.91
2 036	36 601.56	8 113 980.74	926.25	2 060	50 977.98	11 998 664.65	1 369.71

Year	Provision T/year	EPA MODEL		Year	Provision T/year	EPA MODEL	
		m3/year	m3/h			m3/year	m3/h
2 037	37 110.33	8 385 097.95	957.20	2 061	51 686.57	12 080 323.58	1 379.03
2 038	37 626.16	8 642 992.60	986.64	2 062	52 405.01	12 157 999.96	1 387.90
2 039	38 149.16	8 888 309.59	1 014.65	2 063	53 133.44	12 231 888.01	1 396.33
2 040	38 679.44	9 121 662.33	1 041.29	2 064	53 872.00	12 302 172.51	1 404.36
2 041	39 217.08	9 343 634.32	1 066.62	2 065	54 620.82	12 369 029.19	1 411.99
TOTAL	1 930 307.71	Rprom	40 214.74	TOTAL	1 930 307.71	Rprom	40 214.74

Source: SIAR (2020)

Figure 3. Biogas generation (m3/year and m3/h), for the time period from 2018, to 2065 - "EPA MATHEMATICAL MODEL"



In accordance with Table 7 and Figure 4, it was verified that the amount of BIOGAS produced based on the generation of solid waste, obtained maximum values such as 12 369 029.19 m3/year (for the year 2065), or its equivalent in m3/h units whose maximum value was 1 411.99 m3/h (for the year 2065), for the opposite case, i.e. for the minimum values, were obtained: 666 840. 71 m3/year (for the year 2019), or its equivalent in m3/h, whose minimum value was 76.12 m3/h (for the year 2019); Finally, an average generation of solid waste of 40 214.74 T/year or Mg/year was obtained, and as a total, 1 930 307. g/year or T/year was obtained, for the period from the year 2018, until 2065.

3.4. Biogas Generation Performance: Estimation using the Mexican Model 2.0

According to the authors Rodriguez & Urrego, (2016), mentioned that this model, assumes that the time span corresponds to one year, counting from the beginning of the waste deposit and is where biogas production begins, also after one year has passed, biogas production decreases exponentially in each unit of waste, while the organic fraction of the waste is consumed (Rodriguez Miranda & Urrego Martinez, 2016).

It is supported by a first-order decreasing equation

$$Q_{LFG} = \sum_{t=1}^{n} \sum_{j=0,1}^{1} 2kLo[Mi/10](e^{-ktij})(MCF)(F)$$

Where:

QLFG: Refers to the expected maximum value biogas flow rate("m3/year")

i: This is the increase in time in periods of "1 year"

n: Is the difference between the "Year of calculation" - "the year of waste disposal start"

j: This is the increase over time in periods of 0.1 year

Mi: This is the mass of waste disposed of in a given year i, whose units are Mg (Megagrams)

tij: Refers to the "age of section j" of the "mass of RR.SS. My disposition in year i" ("decimal years")

MCF: Corresponds to the "methane correction factor", this figure will depend on the depth of the wells and the type of landfill.

F: Refers to the "fire adjustment factor", in this model it is assumed that the biogas is composed of 50% methane and carbon dioxide, with less than 1% percentage of other constituents.

k: Refers to the "methane generation rate" expressed in "1/year", this value will depend on the availability of nutrients, moisture, acidity, and "temperature" in the landfill.

Lo: Potential methane production, whose units are m3/Mg, this model assigns values to k and L0, but always depending on the climatic factors of the area in which the site is located and the speed of degradation of the SRs (Stege and Davila, 2009).

Table 6: "CH4 Potential Indices, L0 values from the Mexican Model"

Annual precipitation (mm/year)	K (Per year)
0 - 249	60
250 - 499	80
≥ 500	84

Source: Stege G. (2009) - "User's Manual: Mexican Biogas Model".

Table 7: "Methane Production Indexes (K)", k-values of the "Mexican Model".

Annual precipitation (mm/year)	K (per year)
0 - 249	0.04
250 - 499	0.05
500 - 999	0.065
≥ 1000	0.08

Source: Stege G. (2009) - "User's Manual: Mexican Biogas Model".

After defining and establishing the values for the MEXICAN MATHEMATICAL MODELING v. 2.0. This period of time was considered because this mathematical postulate stated that methane (CH4) and CO2 gases begin to appear from the year of decomposition in the silo or landfill, therefore, the year 2018 would be considered as year 0.

Table 8: Biogas generation (m3/year and m3/h), for the time period from 2018 to 2065 - "MEXICAN MATHEMATICAL MODEL 2.0".

Year	Provision T/year	MEXICAN MODEL METHANE generation		MEXICAN MODEL CO2 generation		LADGEM-TOTAL BIOGAS MODEL	
		m3/year	m3/h	m3/year	m3/h	m3/year	m3/h
0	28 548.77	0.00	0.00	0.00	0.00	0.00	0.00
2019	28 945.60	474 580.09	54.18	474 580.09	54.18	949 160.17	108.35
2020	29 347.94	932 611.29	106.46	932 611.29	106.46	1 865 222.58	212.92
2021	29 755.88	1 374 992.41	156.96	1 374 992.41	156.96	2 749 984.82	313.93
2022	30 169.49	1 802 579.67	205.77	1 802 579.67	205.77	3 605 159.34	411.55
2023	30 588.84	2 216 188.84	252.99	2 216 188.84	252.99	4 432 377.67	505.98
2024	31 014.03	2 616 597.20	298.70	2 616 597.20	298.70	5 233 194.41	597.40
2025	31 445.12	3 004 545.48	342.98	3 004 545.48	342.98	6 009 090.96	685.97
2026	31 882.21	3 380 739.60	385.93	3 380 739.60	385.93	6 761 479.19	771.86
2027	32 325.37	3 745 852.42	427.61	3 745 852.42	427.61	7 491 704.84	855.22
2028	32 774.70	4 100 525.39	468.10	4 100 525.39	468.10	8 201 050.79	936.19
2029	33 230.26	4 445 370.07	507.46	4 445 370.07	507.46	8 890 740.14	1 014.92
2030	33 692.16	4 780 969.60	545.77	4 780 969.60	545.77	9 561 939.21	1 091.55
2031	34 160.49	5 107 880.15	583.09	5 107 880.15	583.09	10 215 760.31	1 166.18
2032	34 635.32	5 426 632.22	619.48	5 426 632.22	619.48	10 853 264.44	1 238.96
2033	35 116.75	5 737 731.90	654.99	5 737 731.90	654.99	11 475 463.80	1 309.98
2034	35 604.87	6 041 662.13	689.69	6 041 662.13	689.69	12 083 324.27	1 379.37
2035	36 099.78	6 338 883.82	723.62	6 338 883.82	723.62	12 677 767.63	1 447.23
2036	36 601.56	6 629 836.92	756.83	6 629 836.92	756.83	13 259 673.83	1 513.66

Year	Provision T/year	MEXICAN MODEL METHANE generation		MEXICAN MODEL CO2 generation		LADGEM-TOTAL BIOGAS MODEL	
		m3/year	m3/h	m3/year	m3/h	m3/year	m3/h
2037	37 110.33	6 914 941.51	789.38	6 914 941.51	789.38	13 829 883.03	1 578.75
2038	37 626.16	7 194 598.79	821.30	7 194 598.79	821.30	14 389 197.58	1 642.60
2039	38 149.16	7 469 191.97	852.65	7 469 191.97	852.65	14 938 383.94	1 705.29
2040	38 679.44	7 739 087.22	883.46	7 739 087.22	883.46	15 478 174.45	1 766.91
2041	39 217.08	8 004 634.52	913.77	8 004 634.52	913.77	16 009 269.05	1 827.54
2042	39 762.20	8 266 168.45	943.63	8 266 168.45	943.63	16 532 336.90	1 887.25
2043	40 314.89	8 524 008.97	973.06	8 524 008.97	973.06	17 048 017.93	1 946.12
2044	40 875.27	8 778 462.16	1 002.11	8 778 462.16	1 002.11	17 556 924.32	2 004.22
2045	41 443.44	9 029 820.95	1 030.80	9 029 820.95	1 030.80	18 059 641.90	2 061.60
2046	42 019.50	9 278 365.72	1 059.17	9 278 365.72	1 059.17	18 556 731.45	2 118.35
2047	42 603.57	9 524 365.02	1 087.26	9 524 365.02	1 087.26	19 048 730.03	2 174.51
2048	43 195.76	9 768 076.08	1 115.08	9 768 076.08	1 115.08	19 536 152.15	2 230.15
2049	43 796.18	10 009 745.47	1 142.67	10 009 745.47	1 142.67	20 019 490.93	2 285.33
2050	44 404.95	10 249 609.59	1 170.05	10 249 609.59	1 170.05	20 499 219.18	2 340.09
2051	45 022.18	10 487 895.23	1 197.25	10 487 895.23	1 197.25	20 975 790.46	2 394.50
2052	45 647.99	10 724 820.03	1 224.29	10 724 820.03	1 224.29	21 449 640.07	2 448.59
2053	46 282.49	10 960 593.00	1 251.21	10 960 593.00	1 251.21	21 921 185.99	2 502.42
2054	46 925.82	11 195 414.89	1 278.02	11 195 414.89	1 278.02	22 390 829.78	2 556.03
2055	47 578.09	11 429 478.72	1 304.74	11 429 478.72	1 304.74	22 858 957.44	2 609.47
2056	48 239.42	11 662 970.10	1 331.39	11 662 970.10	1 331.39	23 325 940.20	2 662.78
2057	48 909.95	11 896 067.67	1 358.00	11 896 067.67	1 358.00	23 792 135.35	2 716.00
2058	49 589.80	12 128 943.46	1 384.58	12 128 943.46	1 384.58	24 257 886.91	2 769.17
2059	50 279.10	12 361 763.20	1 411.16	12 361 763.20	1 411.16	24 723 526.40	2 822.32
2060	50 977.98	12 594 686.73	1 437.75	12 594 686.73	1 437.75	25 189 373.46	2 875.50
2061	51 686.57	12 827 868.26	1 464.37	12 827 868.26	1 464.37	25 655 736.52	2 928.74
2062	52 405.01	13 061 456.69	1 491.03	13 061 456.69	1 491.03	26 122 913.38	2 982.07
2063	53 133.44	13 295 595.91	1 517.76	13 295 595.91	1 517.76	26 591 191.82	3 035.52
2064	53 872.00	13 530 425.06	1 544.57	13 530 425.06	1 544.57	27 060 850.13	3 089.14
2065	54 620.82	13 766 078.82	1 571.47	13 766 078.82	1 571.47	27 532 157.65	3 142.94
2066	0.00	14 002 687.62	1 598.48	14 002 687.62	1 598.48	28 005 375.25	3 196.96
TOTAL	1 930 307.71	384 836 001.01	39 394.03	TOTAL	1 930 307.71	R prom	39 394.03
TOTAL METHANE GENERATION m3/año			384 836 001.01	TOTAL METHANE GENERATION m3/h			43 931.05
TOTAL BIOGAS GENERATION m3/h			769 672 002.02	TOTAL BIOGAS GENERATION m3/h			87 862.10

Source: SIAR (2020) and Census 2007-2017

Figure 4. Biogas generation (m3/year), for the time period from 2018 to 2065 - "MEXICAN MATHEMATICAL MODEL 2.0"

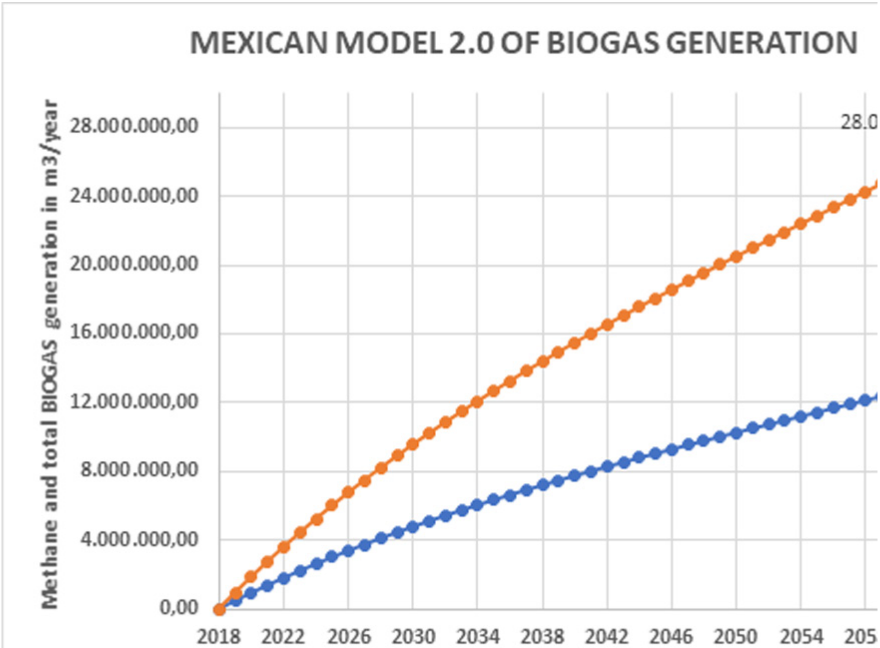
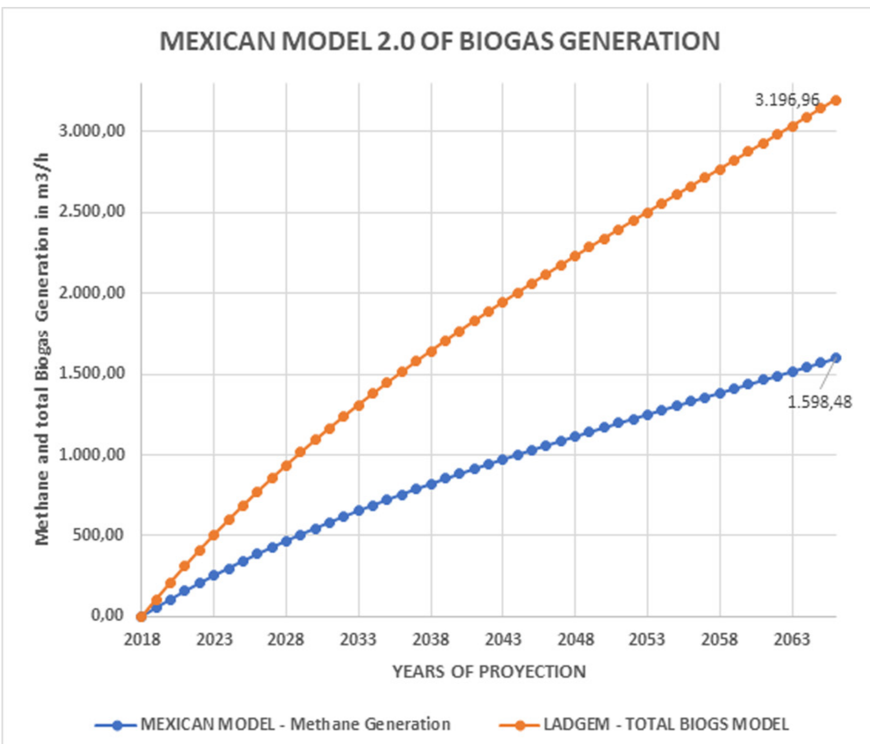


Figure 5. Biogas generation (m3/h), for the time period from 2018 to 2065 - "MEXICAN MATHEMATIC MODEL 2.0".



According to Table 8, it was possible to project up to the year 2065, with the maximum value of solid waste generation being 54620.82 Tn/year, which suggests a generation of 149.65 Tn/day for the same year. In accordance with Table 8 and Figures 5 and 6, it was verified that the amount of biogas produced based on the generation of solid waste, obtained maximum values such as 14 002 687.62 m3/year with respect to the generation of methane (for the year 2066), corresponding to a value of 28 005 375.25 m3/year (of total Biogas generated, including Methane and Carbon Dioxide), or its equivalent in the units m3/h whose maximum value was 1 598. 48 m3/h and 3 196.96 m3/h respectively to the mentioned data (for the year 2066), for the opposite case, i.e. for the minimum values, we obtained: 474 580.09 m3/year regarding methane generation (for the year 2019), or its equivalent in m3/h, whose minimum value was 54. 18 m3/h (for the year 2019) and for the total biogas generation (i.e. Methane + Carbon Dioxide), the values were 949 160.17 m3/year or its equivalent 108.35 m3/h; Finally an average solid waste generation of 54 620.82 T/year or Mg/year in the year 2065 was obtained, and finally as a total 1 930 307.71 Mg/year or T/year was obtained, for the period from the year 2018, until 2065.

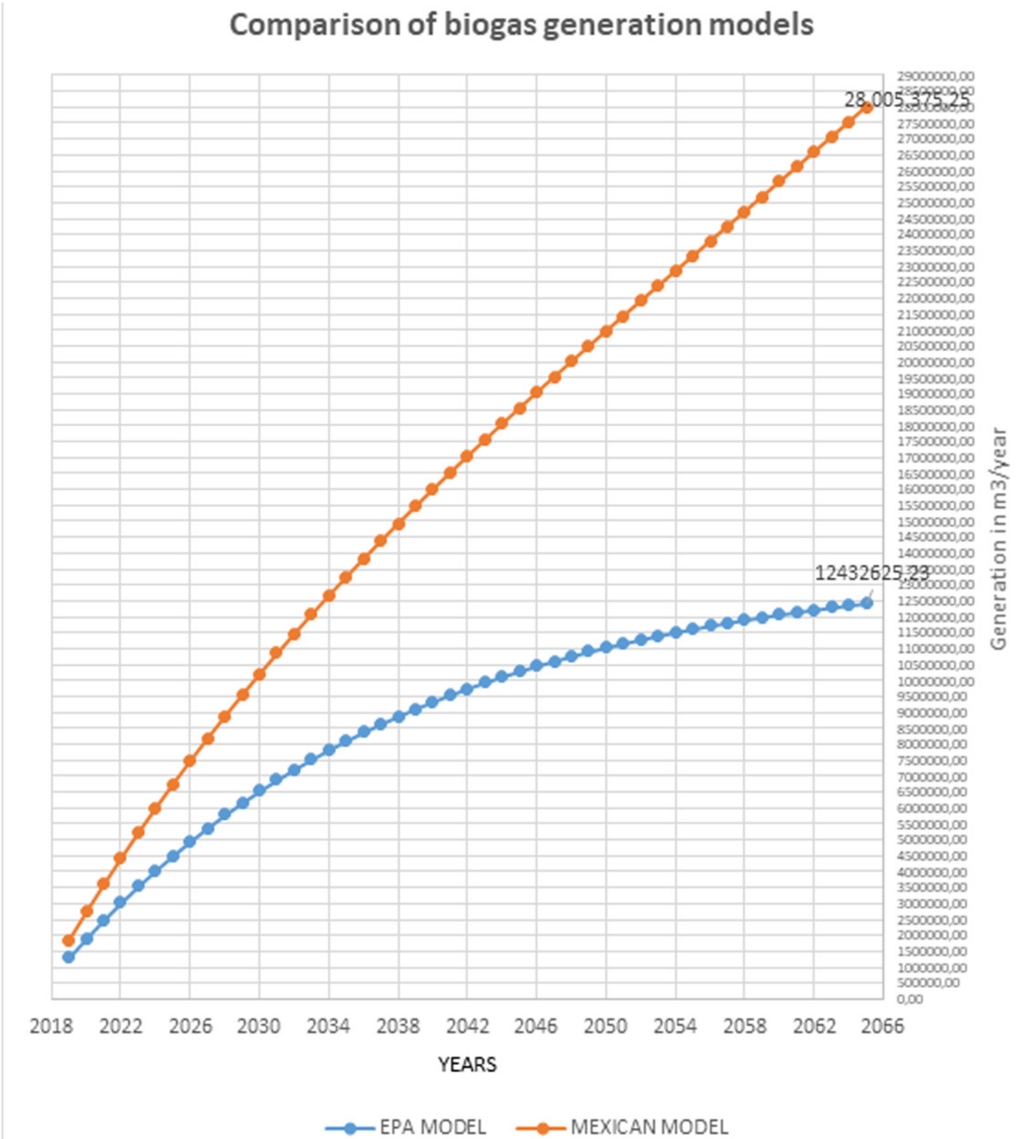
As the projections or estimates for biogas generation have already been established with both the EPA model and the Mexican Model 2.0.

Table 9: Biogas generation (m3/year and m3/h), for the time period from 2018, to 2065 - "MEXICAN MATHEMATICAL MODEL 2.0"

Year	RSU Tn/ year	EPA MODEL		MEXICAN MODEL	
		m3/year	m3/hr	m3/year	m3/hr
2018	28548.77	0.00	0	0.00	0
2019	28945.60	666840.71	76.12	949 160.17	108.35
2020	29347.94	1301159.22	148.53	1 865 222.58	212.92
2021	29755.88	1904541.65	217.41	2 749 984.82	313.93
2022	30169.49	2478496.77	282.93	3 605 159.34	411.55
2023	30588.84	3024459.76	345.26	4 432 377.67	505.98
2024	31014.03	3543795.83	404.54	5 233 194.41	597.40
2025	31445.12	4037803.58	460.94	6 009 090.96	685.97
2026	31882.21	4507718.29	514.58	6 761 479.19	771.86
2027	32325.37	4954714.99	565.61	7 491 704.84	855.22
2028	32774.70	5379911.40	614.15	8 201 050.79	936.19
2029	33230.26	5784370.73	660.32	8 890 740.14	1014.93
2030	33692.16	6169104.36	704.24	9 561 939.21	1091.55
2031	34160.49	6535074.30	746.01	10 215 760.31	1166.18
2032	34635.32	6883195.67	785.75	10 853 264.44	1238.96

Year	RSU Tn/ year	EPA MODEL		MEXICAN MODEL	
		m3/year	m3/hr	m3/year	m3/hr
2033	35116.75	7214338.97	823.55	11 475 463.80	1309.98
2034	35604.87	7529332.22	859.51	12 083 324.27	1379.38
2035	36099.78	7828963.07	893.72	12 677 767.63	1447.23
2036	36601.56	8113980.74	926.25	13 259 673.83	1513.66
2037	37110.33	8385097.95	957.20	13 829 883.03	1578.75
2038	37626.16	8642992.60	986.64	14 389 197.58	1642.60
2039	38149.16	8888309.59	1014.65	14 938 383.94	1705.29
2040	38679.44	9121662.33	1041.29	15 478 174.45	1766.92
2041	39217.08	9343634.32	1066.62	16 009 269.05	1827.54
2042	39762.20	9554780.61	1090.72	16 532 336.90	1887.25
2043	40314.89	9755629.17	1113.66	17 048 017.93	1946.12
2044	40875.27	9946682.23	1135.47	17 556 924.32	2004.22
2045	41443.44	10128417.53	1156.21	18 059 641.90	2061.60
2046	42019.50	10301289.49	1175.95	18 556 731.45	2118.35
2047	42603.57	10465730.38	1194.72	19 048 730.03	2174.52
2048	43195.76	10622151.40	1212.57	19 536 152.15	2230.15
2049	43796.18	10770943.68	1229.56	20 019 490.93	2285.33
2050	44404.95	10912479.27	1245.72	20 499 219.18	2340.09
2051	45022.18	11047112.08	1261.09	20 975 790.46	2394.50
2052	45647.99	11175178.78	1275.71	21 449 640.07	2448.59
2053	46282.49	11296999.59	1289.61	21 921 185.99	2502.42
2054	46925.82	11412879.13	1302.84	22 390 829.78	2556.03
2055	47578.09	11523107.16	1315.42	22 858 957.44	2609.47
2056	48239.42	11627959.31	1327.39	23 325 940.20	2662.78
2057	48909.95	11727697.75	1338.78	23 792 135.35	2715.99
2058	49589.80	11822571.89	1349.61	24 257 886.91	2769.17
2059	50279.10	11912818.97	1359.91	24 723 526.40	2822.32
2060	50977.98	11998664.65	1369.71	25 189 373.46	2875.50
2061	51686.57	12080323.58	1379.03	25 655 736.52	2928.74
2062	52405.01	12157999.96	1387.90	26 122 913.38	2982.07
2063	53133.44	12231888.01	1396.33	26 591 191.82	3035.52
2064	53872.00	12302172.51	1404.36	27 060 850.13	3089.14
2065	54620.82	12369029.19	1411.99	27 532 157.65	3142.94
2066	0.00	12432625.23	1419.25	28 005 375.25	3196.96

Figure 6. Biogas generation (m3/year and m3/h), for the time period from 2018 to 2065 - "MEXICAN MATHEMATICAL MODEL 2.0".



In accordance with Table 9 and Figure 7, it was verified that the amount of BIOGAS produced based on the generation of solid waste, obtained maximum values corresponding to a value of 28 005 375.25 m3/year (of total Biogas generated, including Methane and Carbon Dioxide), or its equivalent in m3/h units whose maximum value was 1 598. 48 m3/h for the estimation using the MEXICAN BIOGAS MODEL and 12 432 625.23 m3/year respectively to the mentioned data (for the year 2066), for the estimation using the EPA MATHEMATICAL MODEL, constituting a ratio of 2.25, obtaining the highest quantity the MEXICAN BIOGAS MODEL 2.0, for the period from the year 2018 to 2065, in the province of JAÉN.

Conclusions

Proper solid waste management emerges as a crucial element when considering its potential for biogas generation in Jaén, Cajamarca. The complexity of the decomposition process, from the aerobic phase to stabilization, highlights the importance of understanding the temporal dynamics and environmental factors involved.

The variety of mathematical models, such as the IPCC default methodology and the first-order kinetic model, provides flexible tools to accurately estimate biogas production, adapting to different levels of detail and data availability. The direct influence of landfill operational management underscores the need for effective practices to optimize biogas generation over time.

Emission projection, especially using mathematical models, provides strategic information for environmental and energy planning. In this context, the EPA's LandGEM model stands out as a valuable tool for calculating landfill emission rates, providing a decay equation with first-order kinetics and allowing the estimation of various emissions associated with decay. Taken together, these considerations point to the need for a comprehensive approach, combining effective management practices with advanced mathematical models, to fully exploit the potential for biogas generation from solid waste in Jaén, Cajamarca, with positive implications from both environmental and energy perspectives.

The implementation of high precision measurement instruments is suggested to carry out a meticulous estimation of biogas generation from solid waste in Jaén, located in the province of Jaén, Cajamarca region. This approach will allow a comparative study between the actual values obtained and the theoretical values proposed in this academic research project, thus contributing to a more accurate assessment.

Recommendations

It is essential to establish sound policies and regulations at the national level that support integrated solid waste management and promote biogas generation as a renewable energy source. These policies can include tax incentives and subsidies to encourage investment in infrastructure and technology related to biogas production. The formation of strategic partnerships between government, the private sector, non-governmental organizations and the local community is critical to ensure project success. These partnerships can facilitate collaboration in infrastructure implementation, environmental education and other related activities.

Public education and awareness campaigns on the importance of proper solid waste management and the potential of biogas as an alternative energy source are crucial. These campaigns can include educational programs, community workshops, public events, and media campaigns. Providing training and capacity building to key stakeholders involved in the project, such as municipal workers, waste managers and farmers, is necessary to ensure efficient and effective implementation. This will help maximize the social, economic and environmental benefits of the project.

Continuing research and technological development in the field of solid waste management and biogas production is essential. This may include adapting existing technologies, innovating new processes, and improving the efficiency and cost-effectiveness of biogas production facilities. Establishing continuous monitoring and evaluation systems to assess the impact of the project in terms of biogas generation, greenhouse gas emission reductions and other aspects is critical. This will allow adjustments and improvements to be made to the project over time.

Creating incentives to encourage private investment in solid waste management and biogas production projects is important. This can include innovative financing schemes, such as soft loans and carbon emission certificates, that help mitigate risks and improve the profitability of investments. Implementing these recommendations can contribute significantly to successful large-scale project implementation in Peru, maximizing the social, economic and environmental benefits for the country and its communities.

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