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Potential Applications of Biogas Produced in Small-Scale UASB-Based Sewage Treatment Plants in Brazil

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Abstract: Rural sanitation is still a challenge in developing countries, such as Brazil, where the majority population live with inadequate services, compromising public health and environmental safety. In this context, this study analyzed the demographic density of these rural agglomerations using secondary data from the Brazilian Institute of Geography and Statistics (IBGE). The goal was to identify the possibilities associated with using small-scale upflow anaerobic sludge blanket (UASB) reactors for sewage treatment, mainly focusing on biogas production and its conversion into energy for cooking, water heating and sludge sanitization. Results showed that most rural agglomerations lacking the appropriate sewage treatment were predominant from 500 to 1500 inhabitants in both northern and southern Brazilian regions. The thermal energy available in the biogas would be enough to sanitize the whole amount of sludge produced in the sewage treatment plants (STPs), producing biosolids for agricultural purposes. Furthermore, the surplus of thermal energy (after sludge sanitization) could be routed for cooking (replacing LPG) and for water heating (replacing electricity) in the northern and southern regions, respectively. This would benefit more than 200,000 families throughout rural areas of the country. Besides the direct social gains derived from the practice of supplying biogas for domestic uses in the vicinity of the STPs, there would be tremendous indirect gains related to the avoidance of greenhouse gas (GHG) emissions. Therefore, an anaerobic-based sewage treatment may improve public health conditions, life quality and generate added value products in Brazilian rural areas.

Keywords: anaerobic treatment; bioenergy; energy assessment; rural sanitation; sludge; wastewater

1. Introduction

Sanitation is closely related to public health, environmental safety and life quality worldwide. Particularly in developing countries, sanitation has been debated in terms of human rights, highlighting situations of extreme violation [1]. In Brazilian rural areas, the Federal Sanitation Policy (Law n° 11,445/2007) determines social inclusion and the reduction of regional inequalities, seeking to provide adequate conditions of environmental health to rural populations and small isolated urban centres. In this context, sanitation plans, programs and projects in areas occupied by low-income populations should be given priority. Moreover, solutions attending to indigenous people and traditional populations should be compatible with their social and cultural characteristics. Finally, the referred legislation indicates the unity and articulation of different institutional agents, as well as the development of their organisation, technical aspects, management, and financial and human resources capacity, considering local specificities [2].

Nevertheless, despite the legislation, sparsely populated areas, characterized by low demographic densities, are commonly neglected due to the principle of economy of scale. The rural invisibility to public policies results in a precarious health situation and a wide regional inequality. In addition, rural agglomerations and/or communities in urban areas but distant from the urban sanitation infrastructure are examples of possibilities for developing collective small-scale sustainable sewage treatment plants (STPs).

In this context, an anaerobic sewage treatment has been investigated and applied in developing countries, such as Brazil. In fact, this country has the largest number of installed upflow anaerobic sludge blanket (UASB) reactors treating sewage in the world. In a recent publication, anaerobic-based STPs using UASB reactors accounted for 667 systems among the 1667 systems acknowledged (i.e., 40%), comprising systems serving from 5000 to 1 million inhabitants [3]. Moreover, an investigation of 2734 STPs in six Latin American and Caribbean countries showed that, besides Brazil, UASB reactors have been extensively used in Mexico, Colombia, Dominican Republic and Guatemala. Such anaerobic reactors represented up to 20% of the total number of STPs for all of the assessed countries [4]. It is worth mentioning that full-scale UASB reactors have also been successfully applied in India [5].

The advantages and potentialities of this technology are related to several aspects, noteworthy are the low sludge production and implementation and operation costs, compared with conventional aerobic (e.g., activated sludge) or physicochemical processes [6]. Moreover, an anaerobic sewage treatment generates biogas, which may be converted into electric or thermal energy for use in the STP itself or in the nearby community. The energy conversion process and its application depend on many factors, such as the STP size, energy policies and subsides, climatic conditions and socio-economic local characteristics. In general, biogas use in small-scale STPs in rural areas is designated to thermal energy conversion, such as water heating, cooking and sludge sanitization. For small- and medium-scale STPs (PE > 2000; PE < 100,000, where PE represents population equivalent), biogas use for the cogeneration of electricity and heat is generally not feasible, due to energy costs, lack of incentive programs for energy recovery from biogas and the poorly developed market for combined heat and power (CHP) engines [7].

The present study aimed at characterizing the potential for biogas generation in Brazilian rural agglomerations which are currently unattended by sanitation services. These agglomerations were organized in three categories using secondary data from the Brazilian Institute of Geography and Statistics (IBGE): (a) rural areas in urban area; (b) isolated rural areas with large settlements and; (c) isolated rural areas with small settlements. The goal was to identify the possibilities associated with using small-scale UASB reactors for sewage treatment, mainly focusing on biogas production and its conversion into energy for cooking, water heating and sludge sanitization, considering the different climate conditions amongst Brazilian regions. Additionally, carbon emissions were also assessed for the proposed technological flowsheets.

2. Material and Methods

2.1. Identification of Rural Agglomerations: Secondary Data

The most recent Brazilian demographic census was used to identify and analyze sewage sanitation infrastructure in the rural areas [8]. Secondary data collected aimed at classifying situations that lack an appropriate treatment, such as rudimentary pit, ditch or direct discharge into rivers, lakes or the sea. The available data of rural agglomerations were further reclassified by the National Program of Rural Sanitation (PNSR) [9], in order to better match the demographic densities of the different Brazilian localities/agglomerations. After the reclassification, four categories of rural households were adopted, identifying them with each specific sanitation demand and possible biogas uses, as shown in Table 1.

Table 1. Rural household classification and recommended sanitation solutions according to the National Program of Rural Sanitation.
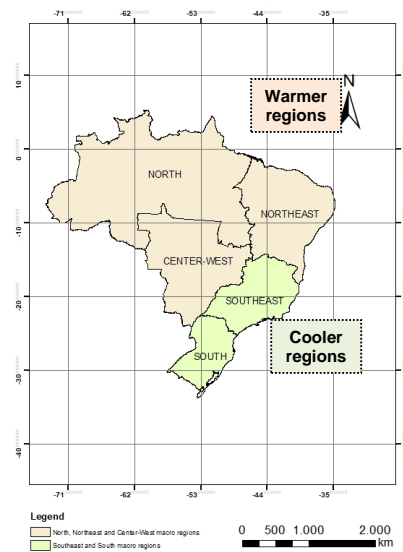
Population Category	Description	Recommended Sanitation Solutions
A	Peripheric agglomerations in urban territory	The same as those practiced in cities (urban areas)
B	Isolated agglomerations with urban characteristics	Economy of scale justify the use of decentralised solutions and self-sufficient management model
C	Isolated agglomerations with rural characteristics	Individual and collective actions coexist; the management may require external support
D	Dispersed rural settlements	Individual actions prevail

Note: For this study, only "A", "B" and "C" were considered. Isolated stands for agglomerations far from the central core of the municipality (urban area).

As can be seen, Table 1 summarizes the description and recommended sanitation solutions considered for each population category. Category A comprises agglomerations located in peripheric regions of an urban area and, therefore, technological options for sewage treatment may be carried out as in cities. In those cases, UASB reactors may be developed as a decentralized option for recovering possible by-products for local use, such as biogas. Categories B, C and D are isolated or far from urban areas. Agglomerations classified as category B have a more urban-like lifestyle, while C and D have an agricultural economy and fewer services (e.g., transportation). For category B, an option for sanitation solutions may be decentralized systems comprising UASB reactors, while STP management may be conducted by a group of users that benefit from valued by-products. Agglomerations from category C may also use collective STP systems with UASB reactors when settlements are nearby, while a familiar approach would be applied for isolated houses. Individual solutions may require external technical support from public services, although collective solutions may possibly be managed through a local auto-organization approach. In fact, a recent study is being conducted in an *urban* occupation without wastewater treatment services, showing the possible scenarios of users and residents that manage the system and benefits from generated by-products, such as biofertilizer. Category D consists of isolated and dispersed occupation, leading to individual sanitation solutions. Therefore, this category was not considered for implementing UASB reactors and biogas recovery.

For this study, the surveyed agglomerations considered all populations from 500 to 3000 inhabitants associated with categories A, B and C, as they can be potentially served by decentralized small-scale STPs Moreover, data were analyzed according to the geographic region and, therefore, separated in two groups: northern region (North, Northeast and Centre-West) and southern region (South and South-East), as illustrated in Figure 1. These were chosen to discuss the different uses for the potential biogas produced, based on the different climate conditions amongst Brazilian regions. The average annual temperature in the southern region is around 20 °C, while in the northern regions it raises to around 28 °C [10]. Of course, the wide variety of local geographic conditions alongside the country is implied in the variations in such values. In any case, anaerobic digestion in UASB reactors has been successfully carried out throughout the country [3].

A previous study developed by our group [11] identified that the highest environmental, economic and also social gains of biogas recovery are associated with its primary use for sludge sanitization, as this allows the production of safe biosolids that can be used for agricultural purposes. This practice, besides contributing for closing nutrient (nitrogen and phosphorus) cycles, also plays a role for reducing the demand on chemical fertilizers, and for avoiding sludge transportation and disposal in landfills. Further potential uses of biogas produced in small anaerobic-based STPs are for cooking (an attractive alternative for all Brazilian regions, North and South) and for water heating, a choice especially appealing for the South Region, where cooler temperatures prevail. These recommended biogas uses according to each population category are summarized in Table 2.

Figure 1. Groups of Brazilian regions considered for the distribution of the rural population under the categories A, B and C (detailed in Table 1).

Table 2. Recommended biogas end uses based on population categories and geographic regions.

Geographic Region	Population Category	Recommended/Potential Biogas End Uses
North	A, B and C	Sludge sanitization Cooking
South	A, B and C	Sludge sanitization Water heating

2.2. Energy Assessment and Carbon Emissions Evaluation

Biogas potential applications and end use depend on the amount of biogas generated, which is primarily a direct function of the STP size. Biogas production and energy recovery options for small-scale STPs using anaerobic reactors were estimated as follows. The equations used to perform the calculations were adapted from Soares et al. [12] (Equations (1)–(10)) and the parameters used are summarised in Table 3.

Table 3. Parameters used for determining the biogas production and energy recovery potential in small-scale sewage treatment plants (STPs) (adapted from [7,8]).

Parameters	Variable Name	Unit	Value	Reference
Daily per capita sewage generation	Q_{PC}	L PE^{-1} d^{-1}	160	[13]
Daily biogas consumption for cooking	$BC_{cooking}$	Nm^3 biogas family^{-1} d^{-1}	0.25	[14]
Unitary methane yield	Y_{CH4}	NL CH$_4$ m^{-3} sewage	64	[15]
Methane content in biogas	%$_{CH4}$	%	75	[16]
Lower calorific value of methane	LCV_{CH4}	MJ Nm^{-3}CH$_4$$^{-1}$	35.8	[17]
Lower calorific value of LPG[1]	LCV_{LPG}	MJ Nm^{-3}CH$_4$$^{-1}$	120.4	[17]
Daily per capita sludge (as DS[2]) generation in UASB reactors	DS_{PE}	gDS PE^{-1} d^{-1}	15	[18]
Water specific heat	H_w	kJ kg^{-1} °K^{-1}	4.18	[17]
Sludge specific heat	H_s	kJ kg^{-1} °K^{-1}	1.05	[12]
Sludge temperature	T_s	°C	20	[19]
Sanitized sludge temperature	T_{ss}	°C	70	[19]
Excess sludge concentration	C_{sludge}	%	4	[20]
Sludge specific mass	γ_s	kg m^{-3}	1020	[18]
Energy loss through the walls of the sanitizing tank	$EL_{sanit\text{-}tank}$	%	15	[12]
Difference between tap water and bath temperatures	Δw	°C	30	Assumed value
Thermal efficiency of boilers	$TE_{boilers}$	%	90	Standard engine reference
Emission factor for LPG burn	$\grave{E}F_{LPG}$	kgCO$_2$ eq m^{-3} LPG	1507.1	[21]
Emission factor for the electricity generation in Brazil	EF_{elec}	gCO$_2$ eq kW^{-1} h^{-1}	125	[22]

Note: [1] LPG: liquefied petroleum gas; [2] DS: dry solids.

The energy potential of methane ($E_{CH4\text{-potential}}$) was calculated in terms of unitary methane yield (Y_{CH4}), daily per capita sewage generation (Qpc), person equivalent (PE) and the lower calorific value of methane (LCV_{CH4}), as in Equation (1).

$$E_{CH4\text{-potential}} \ (\text{MJ d}^{-1}) = Y_{CH4} \times Qpc/1000 \times PE \times LCV_{CH4} \tag{1}$$

The thermal energy potential ($E_{th\text{-potential}}$) was calculated in terms of the energy potential of methane and the thermal efficiency of boilers ($E_{boilers}$), as in Equation (2).

$$E_{th\text{-potential}} \ (\text{MJ d}^{-1}) = E_{potential\text{-CH4}} \times E_{boilers}/100 \tag{2}$$

Daily sludge production in UASB reactors ($P_{sludge\text{-UASB}}$) was calculated in terms of the daily dry sludge production per capita (DS_{PE}) and the person equivalent (PE), as in Equation (3).

$$P_{sludge\text{-UASB}} \ (\text{kgDS d}^{-1}) = DS_{PE}/1000 \times PE \tag{3}$$

The mass of water in sludge (M_{water}) was assumed using the daily sludge produced in reactors ($P_{sludge\text{-UASB}}$), the sludge specific mass (γ) and the excess sludge concentration (C), as in Equation (4).

$$M_{water} \ (\text{kg}) = P_{sludge\text{-UASB}}/(\gamma \times C/100) \tag{4}$$

The daily energy demand for sludge sanitization ($E_{th\text{-sludge}}$) was calculated in terms of the daily sludge produced in reactors ($P_{sludge\text{-UASB}}$), sludge specific heat (H_s), the difference between the sludge temperature and the sanitized sludge temperature (Δs), the mass of water in sludge (M_{water}), water specific heat (H_w) and, the energy loss through the walls of the sanitizing tank ($EL_{sanit\text{-tank}}$), as in Equation (5).

$$E_{th\text{-sludge}} \ (\text{MJ d}^{-1}) = [(P_{sludge\text{-UASB}} \times H_s \times \Delta s) + (M_{water} \times H_w \times \Delta s)] \times (1 + EL_{sanit\text{-tank}}/100)/1000 \tag{5}$$

The daily surplus of thermal energy ($E_{th\text{-surplus}}$) was calculated in terms of the daily thermal energy potential ($E_{th\text{-potential}}$) subtracted from the daily energy demand for sludge sanitization ($E_{th\text{-sludge}}$), as in Equation (6).

$$E_{th\text{-surplus}} \ (\text{MJ d}^{-1}) = E_{th\text{-potential}} - E_{th\text{-sludge}} \tag{6}$$

The daily water heating potential ($W_{potential}$) was calculated in terms of the daily surplus of thermal energy ($E_{th\text{-surplus}}$), the daily thermal efficiency of boilers ($E_{boilers}$), water specific heat (H_w) and the difference between the tap water temperature and the temperature of a bath (Δw), as in Equation (7).

$$W_{potential} \ (\text{m}^3 \ _{water} \ \text{d}^{-1}) = [(E_{th\text{-surplus}} \times E_{boilers}/100)/(H_w \times \Delta w)]/1000 \tag{7}$$

The daily use of biogas for cooking ($BU_{cooking}$) was calculated in terms of the daily surplus of thermal energy ($E_{th\text{-surplus}}$), the lower calorific value of methane (LCV_{CH4}), the daily biogas consumption for cooking ($BC_{cooking}$) and the methane content in biogas ($\%_{CH4}$), as in Equation (8).

$$BU_{cooking} \ (\text{MWh d}^{-1}) = (E_{th\text{-surplus}} \times 1000/LCV_{CH4})/(BC_{cooking} \times \%_{CH4}) \tag{8}$$

The montly avoided CO_2 emission due to replacement of LPG for cooking (Avoided CO_2 $_{cooking}$) was calculated in terms of the surplus of thermal energy ($E_{th\text{-surplus}}$), the lower calorific value of methane (LCV_{CH4}), the lower calorific value of LPG (LCV_{LPG}) and the CO_2 equivalent emission factor for LPG burn (EF_{LPG}), as in Equation (9).

$$\text{Avoided } CO_2 \ _{cooking} \ (\text{kgCO}_2 \ \text{month}^{-1}): E_{th\text{-surplus}} \cdot 30 \times LCV_{CH4}/LCV_{LPG} \times EF_{LPG} \tag{9}$$

The monthly avoided CO_2 emission due to electricity replacement for water heating (Avoided CO_2 heating) was calculated in terms of the surplus of thermal energy ($E_{th-surplus}$) and the CO_2 equivalent emission factor for the electricity generation in Brazil (EF_{elec}), as in Equation (10).

$$\text{Avoided } CO_2 \text{ heating } (kgCO_2 \text{ month}^{-1}) = E_{th-surplus} \times 30 \times EF_{elec.} \qquad (10)$$

For small volumes of produced biogas (1–5 Nm^3 d^{-1}), directly burning them after the hydrogen sulphide (H_2S) removal is the most traditional biogas use for domestic applications, such as for heat production especially for cooking. In population agglomerations with agricultural practices, biogas could also be routed for sludge sanitization. These technological arrangements are illustrated in Figure 2. A simplified desorption column followed by a biofilter was considered in the flowsheet for the H_2S and CH_4 abatement due to the presence of these gases in the anaerobic effluent, therefore, no additional energy gains were achieved because methane is not recovered. The idea in this case is just to avoid greenhouse gas and odorous emissions.
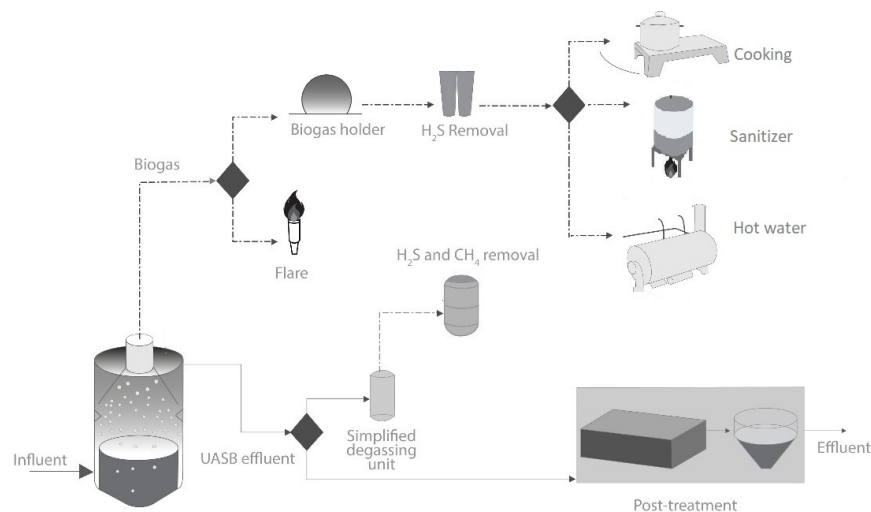
Figure 2. Flowsheet of the proposed biogas uses for small-scale STPs (adapted from [12]).

These gaseous management schemes were also evaluated in terms of carbon emissions using the tool "Sulphide and Carbon Emission Avoidance and Energy Recovery in STPs" [23]. The tool estimates the corresponding amount of methane supposed to be emitted into the atmosphere by anaerobic-based STPs, which is then converted to a CO_2 equivalent, allowing the assessment of the carbon footprint of the STP.

3. Results and Discussion

### 3.1. Rural Agglomerations in Brazil

The secondary data gathered from the demographic census [8] show that rural agglomerations lacking an appropriate sewage treatment were predominant from 500 to 1500 inhabitants, for all three categories analyzed (A, B and C) in both groups (northern and southern regions), as depicted in Figure 3. This population range embraces more than 5.0 and 2.5 million inhabitants in the northern and southern regions of Brazil, respectively, accounting for more than 92% of the Brazilian rural population gathered in categories A, B and C. This is a clear indication of the need for appropriate sewage treatment solutions for such small settlements.

A clearer picture of the population distribution in the whole assessed range (500 to 3000 inhabitants) considering the three categories is shown in Figure 4. Most of the population live in "rural areas of urban extension" (category A—Table 1), totalling almost 5.3 million inhabitants, followed by the population

that live in "isolated rural areas where small settlements prevail" (category C—Table 1), accounting for around 2.4 million inhabitants. It is worth mentioning that approximately 94% of the population in category C is located in the northern region. A much lower population contingent (less than 600,000 inhabitants) lives in "isolated rural areas where large settlements prevail" (category B—Table 1). Bearing these numbers, one can realize that the population living in all three categories of such small settlements could potentially benefit from using the by-products generated in sustainable small-scale anaerobic-based STPs, especially biogas (for cooking, water heating and/or sludge sanitization), sanitized sludge and treated effluent (both for agricultural purposes), as further discussed in the following section.
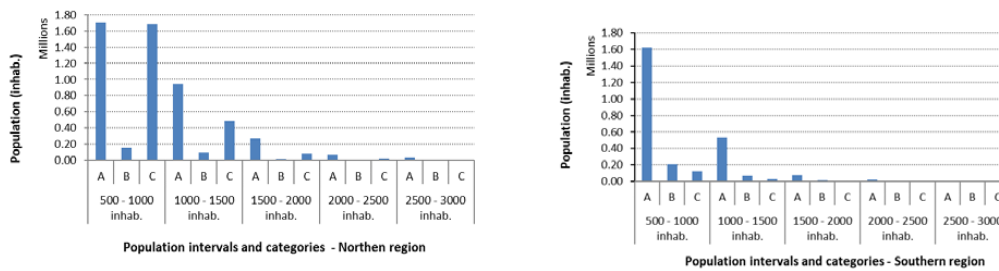
Figure 3. Distribution of the Brazilian rural population of the northern and southern regions according to intervals and categories. Categories A, B and C as shown in Table 1.
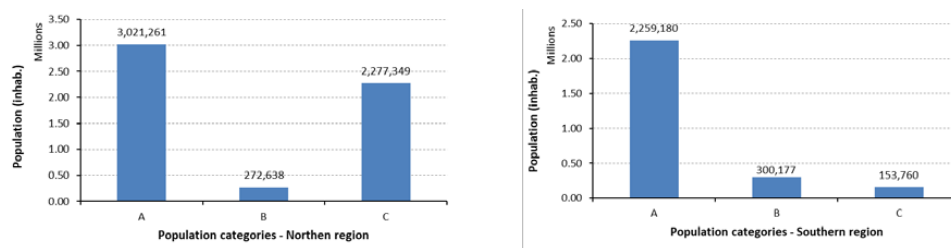

Figure 4. Distribution of the Brazilian rural population of the northern and southern regions according to categories. Categories A, B and C as shown in Table 1.

3.2. Proposed Flowsheet for Sewage Treatment and by-Products Recovery/Use

In order to better exemplify some of the environmental, economic and social gains associated with the use of by-products (biogas, sludge and water) generated in small-scale anaerobic-based STPs, we considered the treatment and by-product end uses flowsheet depicted in Figure 5. Although there are other possibilities of destination/uses of such by-products, depending on many factors (e.g., economic activities nearby the STP, applied process units, STP size, etc.), we carried out the study considering only the alternatives schematically represented in Figure 5 and further summarized in Table 4, specially focussing on potential biogas uses.

Table 4. By-products' (biogas, sludge and water) end uses considered in this study.

| Geographic Region	Population Category	Population Equivalent (Inhabitants)	By-Products end Uses		
			Biogas	Sludge	Effluent
North	A	3,021,261	Sludge sanitization Cooking	Agriculture	Fertirrigation
	B	272,638			
	C	2,277,349			
	Total	5,571,248			
South	A	2,259,180	Sludge sanitization Water heating	Agriculture	Fertirrigation
	B	300,177			
	C	153,760			
	Total	2,713,117			
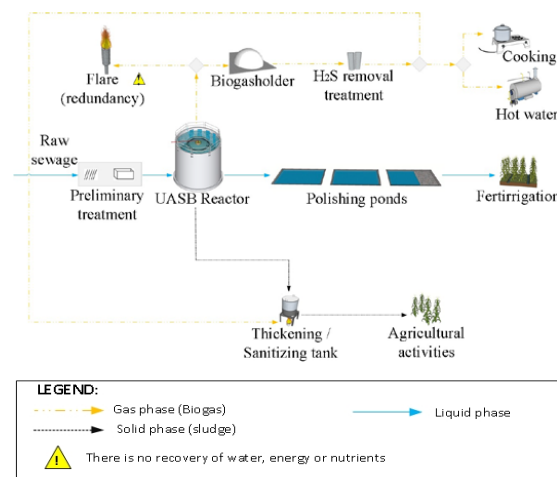
Figure 5. Schematic flowsheet representation of the small-scale anaerobic-based STP and by-products' end uses considered in the study. Source: Adapted from [24]

3.3. Potential Uses of the Biogas Produced in Small-Scale Anaerobic-Based STPs in the Northern and Southern Regions of Brazil

3.3.1. Use of Biogas for Sludge Sanitization

Thermal sludge sanitization can be achieved by means of a boiler fed on biogas and a simple heated concrete tank. This tank should be preferably fed once a day, in order to avoid the need of a big biogas holder. The sludge needs to be heated to 70 °C for 30 min (pasteurization) by means of a heat exchanger installed in the tank. After the sanitization process, the sludge can be routed to simple dehydration units (e.g., drying beds) or it can be directly spread on the agricultural land to be fertilized.

The results presented in Figure 6 show that the thermal energy generated by a boiler fed on biogas is much higher than the demand for sludge sanitization (less than 30% of the available energy), considering the typical parameters presented in Table 3. Therefore, the surplus of thermal energy (more than 70%) can be used for other purposes, such as for cooking (northern region) and/or for water heating (southern region), as discussed in the following section.
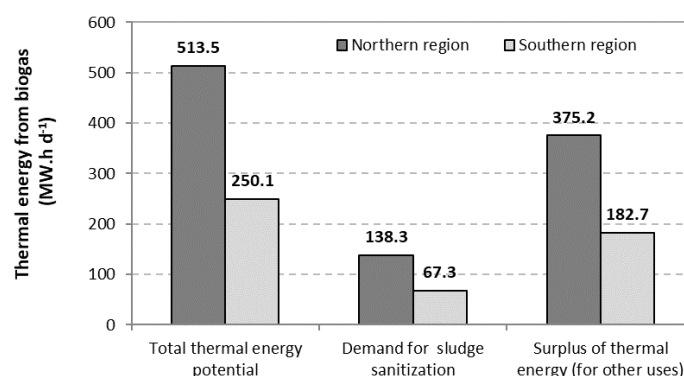
Figure 6. Potential thermal energy generation from biogas and supplied demands (sludge sanitization and other uses—cooking/water heating).

3.3.2. Use of Biogas for Cooking and Water Heating

The results presented in Figure 7 show that the direct use of biogas (after attending the demand for sludge sanitization) would allow more than 200,000 families to cook without the need of another external source of heat in the northern area of Brazil. This means that an equivalent population of approximately 800,000 inhabitants, or close to 15% of the total rural population that live in northern

Brazil (categories A, B and C altogether), could be supplied with the generated biogas. This possibility of biogas use is of great importance for this region, since the delivery (and costs) of liquefied petroleum gas (LPG) is a matter of concern. In this case, biogas can be supplied at much lower costs than LPG when considering the acquisition and transportation for delivering the fuel. In Brazilian rural areas, there are no gas pipelines and generally road infrastructure is inadequate. In addition, biogas is considered a clean and renewable source of energy, therefore, its use in the replacement of LPG would represent remarkable environmental gains due to the extremely high CO_2 emission factor of the latter (a petroleum-derived gas). Finally, this study considered agglomerations with no infrastructure in terms of sanitation. Therefore, the recovery of biogas for cooking is an added benefit of having a sewage treatment solution, which can also foster the implementation of new decentralized STPs. As a matter of fact, a recent study on a rural household in Costa Rica found that a family would save the equivalent of USD 26/month with the acquisition and transportation of LPG if biogas is used for cooking [14].

Likewise, the results depicted in Figure 7 indicate that the surplus of thermal energy (after attending the demand for sludge sanitization) would be enough to produce almost 5000 m^3 of hot water per day (50 °C). Considering a family with four persons and a consumption of 30 liters of hot water per bath/shower, the amount of produced hot water would be enough to supply almost 40,000 families per day in the southern region of Brazil (around 160,000 persons, or approximately 6% of the total rural population living in this region). This also has an associated positive social impact, as electricity usually represents a large share (~50%) in the monthly bill paid by families.
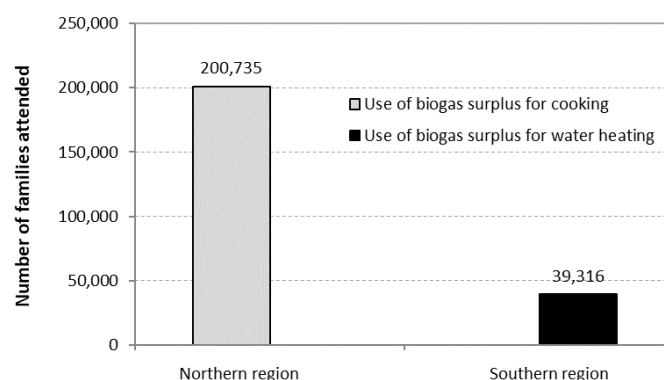

Figure 7. Thermal energy surplus (after sludge sanitization) and families attended with heat for cooking (northern region) and for water heating (southern region).

3.3.3. Avoided Emissions of GHG

According to the results presented in Figure 8, a remarkable negative carbon footprint would be achieved if the surplus biogas (after its main use for sludge sanitization) was used for cooking in the northern region of Brazil. In this case, approximately 6.1 Gt $CO_{2eq} \cdot y^{-1}$ (per capita of 1100 kg $CO_{2eq} \cdot PE^{-1} \cdot y^{-1}$) would be avoided to be emitted into the atmosphere. Such a CO_{2eq} reduction relates to the replacement of LPG by biogas. This may be compared with the per capita GHG emission in the Brazilian energy sector, which is approximately 60 kg $CO_{2eq} \cdot PE^{-1} \cdot y^{-1}$.

Although a much lower avoidance of GHG emissions would be achieved with the use of the surplus thermal energy from biogas for water heating, there would still be a contribution for neutralizing the overall STP carbon footprint, avoiding the emission of approximately 8 Mt $CO_{2eq} \cdot PE^{-1} \cdot y^{-1}$ (per capita of 3 kg $CO_{2eq} \cdot PE^{-1} \cdot y^{-1}$). In this case, the CO_{2eq} reduction is associated with the replacement of electricity by biogas, considering the emission factor of the Brazilian electric matrix and the energy consumption of an electric shower (Table 3).
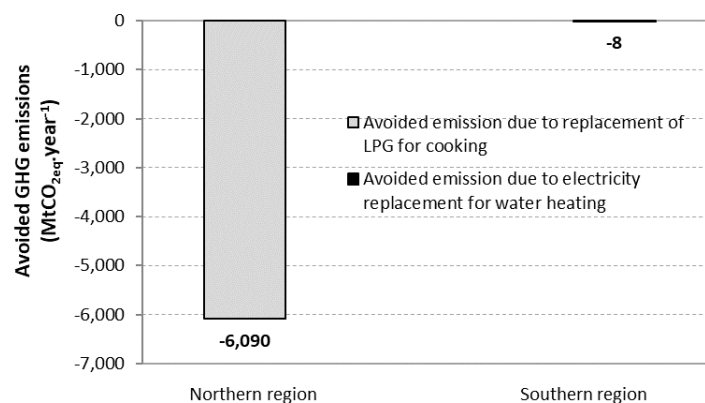
Figure 8. Avoided greenhouse gas (GHG) emissions due to the use of biogas instead of liquefied petroleum gas (LPG) for cooking (northern region) and for water heating (southern region).

3.4. Comparison with Biogas Use in Other Rural Contexts

Biogas has been used in rural areas in different regions worldwide and with different feedstock supplies to the anaerobic reactors. As may be observed, in most cases, biogas use in rural areas worldwide is applied to individual/family biodigesters treating agricultural and manure feedstock. For instance, China has the highest number of household biogas plants in the world, with 19% of the total population in rural areas (0.9 billion people) using biogas. However, an anaerobic digestion application relies on biodigesters fed with animal manure and agricultural residues [25]. Similarly, rural biodigesters developed in the Latin America region have also been used for treating animal manure, with some applications in agricultural residue and cooking grease. However, no data were found with biodigesters fed with sewage, not even co-digested with other substrates [26]. Nonetheless, both reviews identified similar bottlenecks, such as the low anaerobic biodegradability of lignocellulosic biomass, low temperatures in the winter season (~10 °C), low understanding of proper biogas use and limited management and technical support. Some of them such as the interest and involvement of the local population, as well as technical support and management, are also possible bottlenecks that rural STPs with UASB reactors may have.

4. Final Remarks

The overall balance of biogas production and thermal energy generation that could be achieved via the implementation of small-scale anaerobic-based STPs to attend to the Brazilian rural population grouped in categories A, B and C (around 8.3 million inhabitants) is extremely relevant and should not be neglected by designers and policy makers. The thermal energy available in the biogas would be enough to sanitize the whole amount of sludge produced in the STPs, making this material (biosolid) available to small farmers or even to encourage the practice of family farming nearby the plants. Besides contributing for closing the nutrient (N and P) cycles and lowering the production costs of agricultural products, there would still be a huge indirect benefit derived from the destination shift of this material, nowadays simply transported and disposed of in landfills.

Moreover, the surplus of thermal energy (after sludge sanitization) would be sufficient to attend to the demand of more than 200,000 families in the northern region with biogas for cooking (replacing LPG), and around 40,000 families in the southern region with biogas for water heating (replacing electricity). Again, besides the direct social gains derived from the practice of supplying biogas for domestic uses in the vicinity of the STPs, there would be tremendous indirect gains related to the avoidance of GHG emissions, especially when biogas is used to replace LPG. In this case, we estimated negative (avoided) GHG emissions equivalent to 6.1 Gt $CO_{2eq}y^{-1} \cdot y^{-1}$.

Likewise, an anaerobic treatment process may benefit small communities not only due to biogas and biosolids production but also with water reuse for agriculture. In this case, a simple post-treatment system (e.g., polishing pond) can meet the disinfection standards for restricted irrigation purposes [27].

Additionally, nitrogen that remains in the effluent can be considered a bonus for land irrigation. Therefore, an anaerobic sewage treatment can be faced as a low-cost technology that generates added value by-products and may improve public health conditions and life quality in Brazilian rural areas.

References

1.　United Nations General Assembly (UNGA). *Human Right to Water and Sanitation*; UN Document A/RES/64/292, UNGA: Geneva, Switzerland, 2010. Available online: https://undocs.org/en/A/RES/64/292 (accessed on 17 November 2019).

2.　Presidência da República, Casa Civil, Subchefia para Assuntos Jurídicos. LEI N° 11.445, DE 5 DE JANEIRO DE 2007. Available online: http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2007/lei/l11445.htm (accessed on 21 November 2019).

3.　Chernicharo, C.A.L.; Bressani-Ribeiro, T.; Garcia, G.B.; Lermontov, A.; Pereira, C.B.; Platzer, C.J.; Possetti, G.R.C.; Leites, M.A.L.; Rosseto, R. Panorama do tratamento de esgoto sanitário nas regiões Sul, Sudeste e Centro-Oeste do Brasil: Tecnologias mais empregadas (Overview of sewage treatment in the south, south-east and center-west regions of Brazil: Most employed technologies). *Rev. DAE* **2018**, *213*, 5–19.

4.　Noyola, A.; Padilla-Rivera, A.; Morgan-Sagastume, J.M.; Güereca, L.P.; Hernández-Padilla, F. Typology of Municipal Wastewater Treatment Technologies in Latin America. *Clean Soil Air Water* **2012**, *40*, 926–932. [CrossRef]

5.　Seghezzo, L.; Zeeman, Z.; Van Lier, J.B.; Hamelers, H.V.M.; Lettinga, L. A reiview: The anaerobic treatment of sewage in UASB and EGSB reactors. *Bioresour. Technol.* **1998**, *65*, 175–190. [CrossRef]

6.　Chernicharo, C.A.L.; Bressani-Ribeiro, T.; von Sperling, M. Introduction to anaerobic sewage treatment. In *Anaerobic Reactors for Sewage Treatment: Design, Construction and Operation*; Chernicharo, C.A.L., Bressani-Ribeiro, T., Eds.; IWA Publishing: London, UK, 2019; pp. 1–7.

7.　Possetti, G.R.C.; Rietow, J.; Cabral, C.B.G.; Moreira, H.C.; Platzer, C.; Bressani-Ribeiro, T.; Chernicharo, C.A.L. Energy recovery from biogas in UASB reactors treating sewage. In *Anaerobic Reactors for Sewage Treatment: Design, Construction and Operation*; Chernicharo, C.A.L., Bressani-Ribeiro, T., Eds.; IWA Publishing: London, UK, 2019; pp. 194–236.

8.　IBGE. *2010 Population Census. Results of the Universe*; IBGE: Rio de Janeiro, Brazil, 2011.

9.　National Rural Sanitation Program. Available online: http://www.funasa.gov.br/documents/20182/38564/MNL_PNSR_2019.pdf/08d94216-fb09-468e-ac98-afb4ed0483eb (accessed on 12 November 2019).

10.　INMET (National Institute of Meteorology). Average Annual Temperature. Available online: http://www.inmet.gov.br/portal/index.php?r=clima/page&page=anomaliaTempMediaAnual (accessed on 17 March 2020). (In Portuguese)

11.　Bressani-Ribeiro, T.; Lobato, L.C.S.; Chamhum-Silva, L.A.; Chernicharo, C.A.L. Sustainable STPs and public policies. In *Soluções Baseadas na Natureza e os Desafios das Águas: Acelerando a Transição Para Cidades Mais Sustentáveis*; Herzog, H., Freitas, T., Wiedman, G., Eds.; European Commission—Directorate-General for Research and Innovation: Brussels, Belgium, 2020.

12.　Soares, A.; Mota, C.R.; Fdz-Polanco, F.; Huang, X.; Passos, F.; Bressani-Ribeiro, T.; Chernicharo, C.A.L. Closing cycles in anaerobic-based sewage treatment systems. In *Anaerobic Reactors for Sewage Treatment: Design, Construction and Operation*; Chernicharo, C.A.L., Bressani-Ribeiro, T., Eds.; IWA Publishing: London, UK, 2019; pp. 379–406.

13. Von Sperling, M.; Chernicharo, C.A.L. *Biological Wastewater Treatment in Warm Climate Regions (2 vols)*; IWA Publishing: London, UK, 2005.

14. Jiménez, F.M.; Zambrano, D. A Consumo de biogas en hogares rurales y sus implicaciones económicas y ambientales. *Caso El Porvenir, Limón. RedBioLAC* **2018**, *2*, 52–58.

15. Lobato, L.C.S.; Chernicharo, C.A.L.; Souza, C.L. Estimates of methane loss and energy recovery potential in anaerobic reactors treating domestic wastewater. *Water Sci. Technol.* **2012**, *66*, 2745–2753. [CrossRef] [PubMed]

16. Cabral, B.G.C.; Chernicharo, C.A.L.; Hoffmann, H.; Neves, P.N.P.; Platzer, C.; Bressani-Ribeiro, T.; Rosenfeldt, S. *Resultados do Projeto de Medições de Biogás em Reatores Anaeróbios/Probiogás (Results of the Biogas Measurement Project in Anaerobic Reactors/Probiogás)*; Deutsche Gesellschaf für Internationale Zusammenarbeit GmbH, Ed.; GIZ/Ministério das Cidades: Brasília, Brazil, 2016.

17. Moran, M.J.; Shapiro, H.N.; Boettner, D.D.; Bailey, M.B. *Fundamentals of Engineering Thermodynamics*, 8th ed.; Wiley: Hoboken, NJ, USA, 2014.

18. Andreoli, C.V.; von Sperling, M.; Fernandes, F. *Lodo de Esgoto: Tratamento e Disposição Final (Sewage Sludge: Treatment and Final Disposal)*; Department of Sanitary and Environmental Engineering of UFMG: Curitiba, Brazil, 2001; Volume 6, p. 484.

19. Borges, E.S.M.; Godinho, V.M.; Chernicharo, C.A.L. Thermal higienization of excess anaerobic sludge: A possible self-sustained application of biogas produced in UASB reactors. *Water Sci. Technol.* **2005**, *52*, 227–234. [CrossRef] [PubMed]

20. Chernicharo, C.A.L.; Bressani-Ribeiro, T. *Anaerobic Reactors for Sewage Treatment: Design, Construction and Operation*; IWA Publishing: London, UK, 2019; p. 420, ISBN 9781780409221.

21. U.S. EPA. 2014 Emission Factors for Greenhouse Gas Inventories. In *Report of the United States Environmental Protection Agency*; United States Environmental Protection Agency: Washington, DC, USA, 2014.

22. Ministério da Ciência, Tecnologia e Inovação. *Brasil 2017 Annual Estimates of Greenhouse Gas Emissions in Brazil (Estimativas Anuais de Emissões de Gases de Efeito Estufa no Brasil)*, 2nd ed.; Ministério da Ciência, Tecnologia e Inovação: Brasília, Brazil, 2017. (In Portuguese)

23. Chernicharo, C.A.L.; Brandt, E.M.F.; Bressani-Ribeiro, T.; Melo, V.R.; Bianchetti, F.J.; Mota Filho, C.; McAdam, E. Development of a tool for improving the management of gaseous emissions in UASB-based sewage treatment plants. *Water Pract. Technol.* **2017**, *12*, 917–926. [CrossRef]

24. Bressani-Ribeiro, T.; Mota Filho, C.R.; Melo, V.R.; Bianchetti, F.J.; Chernicharo, C.A.L. Planning for achieving low carbon and integrated resources recovery from sewage treatment plants in Minas Gerais, Brazil. *J. Environ. Manag.* **2018**, *242*, 465–473. [CrossRef] [PubMed]

25. Garfí, M.; Martí-Herrero, J.; Garwood, A.; Ferrer, I. Household anaerobic digesters for biogas production in Latin America: A review. *Renew. Sustain. Energy Rev.* **2016**, *60*, 599–614. [CrossRef]

26. Chen, Y.; Yang, G.; Sweeney, S.; Feng, Y. Household biogas use in rural China: A study of opportunities and constraints. *Renew. Sustain. Energy Rev.* **2010**, *14*, 545–549. [CrossRef]

27. Von Sperling, M.; Almeida, P.G.S.; Bressani-Ribeiro, T.; Chernicharo, C.A.L. Post-treatment of anaerobic effluents. In *Anaerobic Reactors for Sewage Treatment: Design, Construction and Operation*; Chernicharo, C.A.L., Bressani-Ribeiro, T., Eds.; IWA Publishing: London, UK, 2019; pp. 285–348.