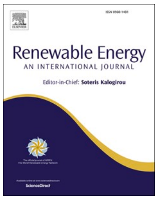
Renewable Energy 221 (2024) 119751

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene



Biogas potential of biowaste: A case study in the state of Rio de Janeiro, Brazil

Helena Rodrigues Oliveira [a,b], Betina Kozlowsky-Suzuki [c,d,e], Annika Björn [f,g], Sepehr Shakeri Yekta [f,g], Cristiane Fonseca Caetano [a,b], Érika Flávia Machado Pinheiro [h], Humberto Marotta [i], João Paulo Bassin [j], Luciano Oliveira [k], Marcelo de Miranda Reis [l], Mario Sérgio Schultz [m], Norberto Mangiavacchi [n], Viridiana Santana Ferreira-Leitão [o,p], Daniel Oluwagbotemi Fasheun [o,p], Fernanda Geraldo Silva [n], Igor Taveira [a,q], Ingrid Roberta de França Soares Alves [l], Júlia Castro [q,r], Juliana Velloso Durão [k], Juliana Guimarães [a,q], Mariana Erthal Rocha [n], Marina Tomasini [o,p], Pedro Vitor de Oliveira Martins [o], Rogerio Presciliano [q], Stella Buback dos Santos [o,p], Tamires Marques Faria [s], Tarcísio Corrêa [a], Thiago de Nuno Mendes Pery de Linde [t], Fernanda Abreu [a,q], Alex Enrich-Prast [b,f,g,u,*]

[a] *Programa de Pós-graduação em Biotecnologia Vegetal e Bioprocessos, Universidade Federal do Rio de Janeiro, 21941-902, Rio de Janeiro, RJ, Brazil*
[b] *Unidade Multiusuário de Análises Ambientais, Instituto de Biologia, Universidade Federal do Rio de Janeiro, 21941-902, Rio de Janeiro, RJ, Brazil*
[c] *Departamento de Ecologia e Recursos Marinhos, Universidade Federal do Estado do Rio de Janeiro, 22290-240, Rio de Janeiro, RJ, Brazil*
[d] *Programa de Pós-graduação em Ciências Biológicas, Biodiversidade Neotropical, Universidade Federal do Estado do Rio de Janeiro, 22290-240, Rio de Janeiro, RJ, Brazil*
[e] *Programa de Pós-graduação em Ecoturismo e Conservação, Universidade Federal do Estado do Rio de Janeiro, 22290-240, Rio de Janeiro, RJ, Brazil*
[f] *Department of Thematic Studies, Environmental Change, Linköping University, 581 83, Linköping, Sweden*
[g] *Biogas Solution Research Center, Linköping University, 581 83, Linköping, Sweden*
[h] *Departamento de Agrotecnologias e Sustentabilidade, Universidade Federal Rural do Rio de Janeiro, 23890-000, Seropédica, RJ, Brazil*
[i] *Department of Geography, Graduate Program in Geosciences (Environmental Geochemistry), Biomass and Water Management Research Center (NAB-UFF), Ecosystems and Global Change Laboratory (LEMG-UFF)/International Laboratory of Global Change (LINCGlobal), Universidade Federal Fluminense, 24210-310, Niterói, RJ, Brazil*
[j] *COPPE, Universidade Federal do Rio de Janeiro, 21941-594, Rio de Janeiro, RJ, Brazil*
[k] *Energy Research Office, Environmental Department, 20091-040, Rio de Janeiro, RJ, Brazil*
[l] *Defense Engineering Program, Instituto Militar de Engenharia (IME), 22290-270, Rio de Janeiro, RJ, Brazil*
[m] *Instituto de Biodiversidade e Sustentabilidade - NUPEM, Universidade Federal do Rio de Janeiro, 27965-045, Macaé, RJ, Brazil*
[n] *Department of Mechanical Engineering, Group for Environmental Studies and Simulations (GESAR), Rio de Janeiro State University, 20940-903, Rio de Janeiro, RJ, Brazil*
[o] *National Institute of Technology, Ministry of Science, Technology, and Innovation (MCTI), Laboratory of Biocatalysis, 20081-312, Rio de Janeiro, RJ, Brazil*
[p] *Departamento de Bioquímica, Universidade Federal do Rio de Janeiro, 21941-909, Rio de Janeiro, RJ, Brazil*
[q] *Instituto de Microbiologia Paulo de Góes, Universidade Federal do Rio de Janeiro, 21941-902, Rio de Janeiro, RJ, Brazil*
[r] *Programa de Pós-graduação em Microbiologia, Universidade Federal do Rio de Janeiro, 21941-902, Rio de Janeiro, RJ, Brazil*
[s] *Nuclear and Energy Research Institute (IPEN/USP - SP), University of São Paulo, 05508-000, São Paulo, SP, Brazil*
[t] *Oceans and Land Dynamics Program, Geosciences Institute, Universidade Federal Fluminense, 24210-310, Niterói, RJ, Brazil*
[u] *Institute of Marine Science, Federal University of São Paulo (IMar/UNIFESP), 11015-020, Santos, SP, Brazil*

ARTICLE INFO

Keywords:
Anaerobic digestion
Organic residues
Biogas potential estimation
Agricultural residues
Bioelectricity

ABSTRACT

Anaerobic digestion has been widely applied for waste treatment, renewable energy generation and biofertilizer production. The biogas potential in Brazil is sizable, but the state of Rio de Janeiro is largely dependent on fossil fuels, and there is a lack of biogas potential assessments in the state. Thus, this study evaluated biomethane, electricity and biofertilizer potentials in the region. Three different scenarios of biomass supply were considered for four major biowaste streams: sewage sludge; cattle manure; sugarcane processing waste; and food waste. Biomethane generation from the assessed sources could reach 0.6–1.3 billion Nm^3 $year^{-1}$, corresponding to

---

* Corresponding author. Dept. of Thematic Studies – Environmental Change, Linköping University, 581 83, Linköping, Sweden.
E-mail address: alex.enrich.prast@liu.se (A. Enrich-Prast).

https://doi.org/10.1016/j.renene.2023.119751
Received 18 January 2023; Received in revised form 29 October 2023; Accepted 25 November 2023
Available online 29 November 2023
0960-1481/© 2023 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/).

1,768–3,961 GWh year^{-1} of electricity and 1.6–3.3 million Mg year^{-1} of biofertilizer. Cattle manure was responsible for 73–84% of the projected biomethane production, presenting an opportunity to reduce the significant emissions from livestock farming. The estimated biofertilizer production could meet the demands of the state, and the produced electricity could offset up to 10% of the demand. The gas grid could facilitate the distribution of upgraded biomethane, and 10–22% of the natural gas demand could be met. The findings of this work highlight the high potential for biogas generation in Rio de Janeiro, which is up to seven times larger than the current production.

Abbreviations

AD	Anaerobic Digestion
ANP	National Agency for Petroleum, Natural Gas and Biofuels
CAM	Campos dos Goytacazes
COD	Chemical Oxygen Demand
CHP	Combined Heat and Power
DM	Dry Mass
FW	Food Waste
GHG	Greenhouse Gases
LPG	Liquefied Petroleum Gas
MRC	Macaé-Rio das Ostras-Cabo Frio
MSW	Municipal Solid Waste
OFMSW	Organic Fraction of Municipal Solid Waste
PET	Petrópolis
RJA	Rio de Janeiro
SS	Sewage Sludge
RJ	State of Rio de Janeiro
VS	Volatile Solids
VRB	Volta Redonda-Barra Mansa

1. Introduction

To meet the rise in energy consumption and the Sustainable Development Goals of the United Nations 2030 Agenda (SDG), a significant effort should be made to increase renewable energy production. Biobased residues have been increasingly used to produce fuels, electricity and heat worldwide, increasing the valorization of organic wastes and demonstrating the concept of a circular biobased economy [1]. The conversion of biowaste into valuable products such as biogas and biofertilizers via anaerobic digestion (AD) represents a strategic circular biotechnology contributing to the offset of a fossil fuel-based economy. AD is applied to several organic substrates, e.g., animal manure, agricultural-based residues, food waste, and sewage sludge, to produce biogas, which is mainly composed of methane (CH_4) and carbon dioxide (CO_2) [2].

Biogas can be directly converted into energy and heat or upgraded to biomethane and injected into a natural gas grid, providing a renewable and clean energy source [3]. Furthermore, the residue from AD processes, called digestate, is commonly applied as biofertilizer, since it is usually rich in several nutrients, including nitrogen, potassium, and phosphorus [4,5]. Biofertilizers can reduce the use of NPK mineral fertilizers by 50%, resulting in better conditions for plant growth and decreased energy consumption [6,7]. Therefore, it is imperative that countries with agricultural production and low mineral fertilizer production, such as Brazil, implement sustainable solutions to ensure the supply of nutrients necessary for agriculture.

Denmark, Sweden and Germany are examples of European countries that successfully apply AD processes for waste treatment and energy generation, with strategic investments and policies that encourage biogas production and use [8,9]. In 2020, 18 billion m^3 of biogas was produced in Europe, and the aim is to reach 35 billion m^3 by 2030 [10]. Although developing countries have large potential for the implementation of biogas solutions, they have a much lower biogas production rate, which is only 2.35 billion m^3 year^{-1} in Brazil, for example [11].

During the 21st Conference of the Parties (COP 21) of the United Nations Framework Convention on Climate Change (UNFCCC), held in 2015, Brazil presented its Intended Nationally Determined Contribution to reduce greenhouse gas (GHG) emissions by 43% until 2030 compared to 2005 levels [12]. The state of Rio de Janeiro (RJ) has the third largest population in Brazil, with over 17 million inhabitants living in a densely populated area [13], and accounts for 10% of the Brazilian gross domestic product [14]. Although it is one of the most developed states in Brazil, RJ relies heavily on nonrenewable fossil-based energy sources [15]. Furthermore, it exhibits high discharges of urban sewage [16] and biomass from rural areas [17], in addition to organic urban waste landfilling [18], which are important sources of soil, air and water degradation.

Therefore, the aim of this study is to assess the potential for biomethane and biofertilizer production associated with electrical power generation from major biowaste sources in RJ. Considering the lack of similar assessments in the region, this work could contribute to the promotion of biogas technology as a sustainable pathway to replace the current predominant fossil fuel-based economy and as a model for developing countries.

2. Material and methods

2.1. Study design and data compilation

Biogas potential was estimated for the five regions of RJ: Rio de Janeiro (RJA), Volta Redonda-Barra Mansa (VRB), Petrópolis (PET), Campos dos Goytacazes (CAM), and Macaé-Rio das Ostras-Cabo Frio (MRC). RJA is the most populous region; it is highly urbanized and houses the state’s capital. CAM is the largest region, characterized by significant livestock and agricultural production, which is also seen to a lesser extent in PET. VRB also has some livestock production, while MRC is responsible for 13% of the state’s crop production.

Based on their availability in RJ, four sources of biowaste were considered for AD: sewage sludge (SS), cattle manure, sugarcane processing waste, and food waste (FW). FW and SS are two major waste streams in highly populated and urban areas [19], which is the case for RJ [13]. Nearly 500 million m^3 year^{-1} of sewage is treated in the 371 treatment plants in RJ [20,21]. Although agricultural production in the state is less expressive than in other areas of Brazil, the sugarcane production of 2.4 million Mg year^{-1} comprises almost 61% of the crop production in RJ [22]. With 2.6 million animals [23], cattle are the largest livestock source in the state and represents the largest contribution of RJ to Brazilian animal production [24].

A dataset was compiled from trusted public and private sources, as specified in the following sections. Three scenarios for potential biogas production were considered: minimum, medium and maximum, defined by different assumptions of substrate availability (Table 1). As a prospective approach to support the implementation of AD in developing countries, the potential for biomethane, electricity and biofertilizer production in the different regions of RJ was estimated by applying conversion values from the literature for each available biowaste

Table 1
Minimum, medium and maximum scenarios considered for the estimation of the biogas potential in the state of Rio de Janeiro.

Biowaste	Scenario		
	Minimum	Medium	Maximum
Sewage sludge	Sludge from 50% of treated sewage	Sludge from 100% of treated sewage	Sludge from 100% of collected sewage
Cattle manure	Dairy cattle and feedlot beef cattle manure	Dairy cattle and 50% beef cattle manure	Dairy cattle and 100% of beef cattle manure
Sugarcane processing waste	Waste from ethanol production (2021–2022 harvest season)	Waste from operation with 50% capacity in ethanol plants	Waste from operation with 100% capacity in ethanol plants
Food waste	25% of the generated food waste	50% of the generated food waste	100% of the generated food waste

(Table 2).

2.2. Waste and biomethane production estimation

2.2.1. Sewage sludge

The data on the amount of collected and treated sewage were obtained from the Water and Sewage Services Diagnosis of 2019, released by the Brazilian National System of Information on Water and Sanitation [20]. The minimum and medium potential scenarios considered only treated sewage for the estimation of SS availability for biogas production, while the maximum potential was based on all collected sewage. The biomethane production potential was calculated assuming a solid sludge generation of 350 g m^{-3} of treated sewage [25], a volatile solids (VS) content of 77.5% of dry mass (DM) [26] and an average biomethane yield for a mixture of primary and secondary sludge of 249.3 Nm^3 Mg^{-1} VS [27–29].

2.2.2. Cattle manure

The amount of cattle manure was estimated based on the total number of cows in RJ [23] and the percentage of feedlot beef cattle was obtained from the agricultural census [36]. The scenarios for the estimation of biogas and biofertilizer potential were designed according to the ease of manure collection, with the minimum potential scenario considering only feedlot cattle and the maximum potential scenario taking manure from all cattle into account. Manure production, VS content and biomethane yield were estimated according to Mito et al. [30]. For beef and dairy cattle, the daily manure production per animal was 43.9 and 93.7 L d^{-1}, the VS content was 80.19 and 68.59 g L^{-1}, and the biomethane yield was 230 and 210 Nm^3 Mg^{-1} VS, respectively. For biofertilizer estimation, DM was calculated considering a VS/DM content of 83.7% and 85.3% in beef and dairy manure, respectively [37].

2.2.3. Sugarcane processing waste

Quantification of sugarcane processing waste was conducted based on the ethanol production in the 2021/2022 harvesting season, according to the National Supply Company [33] or the ethanol production capacities of plants in RJ, as obtained from the National Agency for Petroleum, Natural Gas and Biofuels (ANP) database for biofuel producers [38]. The minimum potential scenario considered the ethanol production in RJ, while the medium and maximum scenarios considered 50% and 100% of the ethanol plants capacities, respectively. An average vinasse production of 13 L $L^{-1}{}_{ethanol}$ [31] and an ethanol production of 72.4 L $Mg^{-1}_{sugarcane}$ [33] were considered. The amounts of sugarcane straw and filter cake were 140 kg $Mg^{-1}_{sugarcane}$ and 35 kg $Mg^{-1}{}_{sugarcane}$, respectively [34]. While all vinasse and filter cake generated were considered for AD, only 50% of the sugarcane straw was assumed to be available, as half of it is usually left in the field [39,40]. The chemical oxygen demand (COD), DM and VS contents of sugarcane processing

Table 2
Equations used to calculate the biomethane potential of different biowaste sources.

Equations		Variables
(1)	$SS_t = \frac{SG \times Sewage}{10^6}$	• SS_t: sewage sludge (Mg DM $year^{-1}$) • SG: solid sludge generation (350 g DM m^{-3}) [25] • $Sewage$: volume of sewage (m^3 $year^{-1}$) [20]
(2)	$BMP_{SS} = SS_t \times SS_{VS} \times Y_{SS}$	• BMP_{SS}: sewage sludge biomethane potential (Nm^3 $year^{-1}$) • SS_{VS}: sewage sludge volatile solids (77.5% DM) [26] • Y_{SS}: sewage sludge biomethane yield (249.3 Nm^3 Mg^{-1} VS) [27–29]
(3)	$BMP_{Dairy} = \frac{M_{Dairy} \times VS_{Dairy}}{10^6} \times Y_{Dairy} \times 365$	• BMP_{Dairy}: dairy cattle manure biomethane potential (Nm^3 $year^{-1}$) • M_{Dairy}: dairy cattle daily manure production (93.7 L d^{-1}) [30] • VS_{Dairy}: dairy manure VS content (68.59 g L^{-1}) • Y_{Dairy}: dairy cattle manure biomethane yield (210 Nm^3 Mg^{-1} VS) [30]
(4)	$BMP_{Beef} = \frac{M_{Beef} \times VS_{Beef}}{10^6} \times Y_{Beef} \times 365$	• BMP_{Beef}: beef cattle manure biomethane potential (Nm^3 $year^{-1}$) • M_{Beef}: beef cattle daily manure production (43.9 L d^{-1}) [30] • VS_{Beef}: cattle manure VS content (80.19 g L^{-1}) • Y_{Beef}: beef cattle manure biomethane yield (230 Nm^3 Mg^{-1} VS) [30]
(5)	$BMP_{CM} = BMP_{Dairy} + BMP_{Beef}$	• BMP_{CM}: cattle manure biomethane potential (Nm^3 $year^{-1}$)
(6)	$BMP_{Vin} = E \times SP_{Vin} \times \frac{COD_{Vin}}{1000} \times Y_{Vin}$	• BMP_{Vin}: sugarcane vinasse biomethane potential (Nm^3 $year^{-1}$) • E: ethanol production (m^3 $year^{-1}$) • SP_{Vin}: vinasse specific production (13 m^3 $m^{-3}_{ethanol}$) [31] • COD_{Vin}: sugarcane vinasse COD (27.25 g L^{-1}) [32] • Y_{Vin}: vinasse biomethane yield (274 Nm^3 Mg^{-1} COD) [32]
(7)	$SC = \frac{E}{SP_E} \times 1000$	• SC: sugarcane used for ethanol production (Mg $year^{-1}$) • SP_E: ethanol specific production (72.4 L $Mg^{-1}_{sugarcane}$) [33]
(8)	$BMP_{Str/FC} = \frac{SC \times SP_{Str/FC}}{1000} \times Y_{Str/FC}$	• $BMP_{Str/FC}$: sugarcane straw or filter cake biomethane potential (Nm^3 $year^{-1}$) • $SP_{Str/FC}$: sugarcane straw or filter cake specific production yield (140 kg $Mg^{-1}_{sugarcane}$ and 35 kg $Mg^{-1}_{sugarcane}$, respectively) [34] • $Y_{Str/FC}$: sugarcane straw or filter cake biomethane yield (129 Nm^3 Mg^{-1} and 54 Nm^3 Mg^{-1}, respectively) [32]
(9)	$BMP_{SW} = BMP_{Vinasse} + \frac{BMP_{Str}}{2} + BMP_{FC}$	• BMP_{SW}: sugarcane processing waste biomethane potential (Nm^3 $year^{-1}$)
(10)	$MSW_t = 365 \times \sum_i MSW_i \times Pop_i$	• MSW_t: Municipal solid waste (Mg $year^{-1}$) • MSW_i: per capita municipal solid waste generation of each municipality (Mg $inhab^{-1}$ d^{-1}) [25] • Pop_i: population of each municipality [13, 25]
(11)	$FW = MSW_t \times \%OFMSW \times \%FW$	• FW: food waste (Mg $year^{-1}$) • $\%OFMSW$: organic fraction of municipal solid waste (53%) [25] • $\%FW$: food waste fraction of OFMSW (73%) [35]
(12)	$BMP_{FW} = FW \times VS_{FW} \times Y_{FW}$	• BMP_{FW}: food waste biomethane potential (Nm^3 $year^{-1}$) • VS_{FW}: food waste volatile solids content (%) [35] •Y_{FW}: food waste biomethane yield (341 Nm^3 Mg^{-1}VS) [35]

wastes were estimated according to Janke et al. [32]. The biomethane potentials for vinasse, straw and filter cake were 274 $Nm^3\ Mg^{-1}_{COD}$, 129 $Nm^3\ Mg^{-1}$ and 54 $Nm^3\ Mg^{-1}$, respectively [32].

2.2.4. Food waste

FW generation was estimated based on municipal solid waste (MSW) production, with 53% of the total MSW produced annually considered as the organic fraction of MSW (OFMSW) [25], while FW content was assumed to be 73% of OFMSW [35]. MSW production was based on the population [13] and per capita MSW generation index of the municipalities, provided by the State's Solid Waste Plan [25]. The minimum and medium potential scenarios considered that 25% and 50% of MSW would be destined for AD, which are the mid- and long-term goals of energy recovery from waste in the state [25]. The maximum scenario estimated the biogas potential from 100% of the FW generated in RJ. A biomethane potential of 341 $Nm^3\ CH_4\ Mg^{-1}$ VS was considered for FW, assuming that all components of the OFMSW contribute equally to the mass of VS, so the average DM and VS contents for FW are 229.5 kg Mg^{-1} and 200.5 kg Mg^{-1}, respectively [35].

2.3. Biofertilizer potential

The potential for biofertilizer production (in DM) from the digestate generated in the biogas process of each biowaste stream considered in this study was calculated according to Eq. (13) [41]. The estimated DM and VS contents of the different biomasses were obtained from previous studies, as detailed in Sections 2.2.1-2.2.5 [26,30,37,32,35].

$$Biofertilizer = DM - VS + 0.4 \times VS \tag{13}$$

where DM is the dry mass and VS is the volatile solids of the biowaste (Mg).

2.4. Electricity production from biomethane

The potential electricity generation from the biomethane produced from each biowaste source was calculated using Eq. (14).

$$P = V_{CH4} \times LHV \times \eta \tag{14}$$

where P is the potential electricity generated from biomethane (kWh $year^{-1}$), V_{CH4} is the volume of biomethane produced ($Nm^3\ year^{-1}$), LHV is the lower heating value of methane (9.97 kWh $Nm^{-3}\ CH_4$) and η is the engine's conversion efficiency (30%) [35].

2.5. Greenhouse gases avoided emissions

The avoidance of GHG emissions by the implementation of AD to generate electricity and biomethane was calculated based on the emissions from conventional energy sources that would be replaced [35]. Net electricity generation from AD was calculated considering the difference between electricity produced from biomethane and electricity consumed in the AD process, which was 67.9 kWh Mg^{-1} DM of waste [42]. Avoided emissions were then calculated considering the net electricity generation and the current emissions of the Brazilian electricity mix (78.8 kg $CO_{2eq}\ MWh^{-1}$) [43]. For biomethane application as vehicle fuel, only the replacement of fossil fuels by biomethane in passenger cars was considered for the estimation of avoided emissions. Emission factors for gasoline and natural gas of 164 and 124 g $CO_{2eq}\ km^{-1}$, respectively [44], and a biomethane consumption yield of 2.02 km Nm^{-3} [35] were applied in the calculations.

3. Results and discussion

A total annual production of up to 1324 million Nm^3 of CH_4, 3961 GWh of electricity and 3.3 million Mg of biofertilizer could be obtained in RJ with the implementation of AD for treating the biowaste streams assessed in this study (Table 3). The total potential from the medium and maximum scenarios was approximately 1.5 and 2.2 times higher than that from the minimum scenario. Cattle manure had by far the highest potential, being responsible for 73–84% of the total projected biomethane and electricity production and 78–87% of the biofertilizer production, while sewage sludge had the lowest potential (3–5%). Brazil is one of the largest cattle producers in the world; therefore, cattle manure management and its AD potential are important in the country [45].

3.1. Biomethane potential

Even the lowest estimated biomethane potential of 591 million $Nm^3\ year^{-1}$ is considerably larger than the current biogas production in RJ of 327 million $m^3\ year^{-1}$ [11]. Assuming a CH_4 content in biogas of 60% [46,47], the biomethane potentials calculated in the minimum and maximum scenarios were, respectively, 3.0 and 6.7 times larger than the current methane production in RJ. Among the different regions of RJ, the estimated potentials were much higher than the current production, except in RJA (Fig. 1). In this region, which is responsible for 88% of the state's biogas production, the minimum potential did not surpass the current production. This may be due to an underestimation of the potential in the minimum scenario, in addition to the presence of biogas production from industrial residues in RJA [11], which were not considered in this study. Furthermore, it is noteworthy that the region with the largest potential, CAM, is also the one with the least amount of biogas currently produced, since most of the production in the state comes from MSW and sewage treatment and is concentrated in the metropolitan area of the capital [11].

The geographical distribution of biomethane potential in RJ was different among the biowaste streams (Fig. 2). This is directly related to the different biowaste generation rates across the regions of the state (Table S1).

SS production from treatment plants in RJ was estimated to be 174,641 Mg DM $year^{-1}$, resulting in a potential biomethane production of 17–54 million $Nm^3\ year^{-1}$. RJA contains more than 3/4 of the total state population and presents by far the largest potential (83%) for biomethane production (Fig. 2A). Although it has the third largest population, VRB has the lowest methane potential (2% of the SS potential) in the minimum and medium scenarios, as less than 30% of the sludge is treated; in the maximum scenario, which considers the potential production if all collected sewage was treated, the contribution of this region increased to 5%. Conversely, the MRC region has one of the highest collected sewage treatment indices (85.8%), being responsible for a potential biomethane production of 2.5 million $Nm^3\ year^{-1}$ in the medium scenario.

Table 3
Potential biomethane, electricity and biofertilizer production from different biowaste sources in the state of Rio de Janeiro.

	Scenario	Biomethane ($10^6\ Nm^3\ year^{-1}$)	Electricity (GWh $year^{-1}$)	Biofertilizer (10^3 Mg $year^{-1}$)
Sewage sludge	Minimum	16.9	50.5	46.7
	Medium	33.7	100.9	93.4
	Maximum	54.2	162.2	150.1
Cattle manure	Minimum	498.0	1489.6	1356.8
	Medium	733.6	2194.2	1966.0
	Maximum	972.6	2909.1	2584.0
Sugarcane processing waste	Minimum	30.6	91.5	74.3
	Medium	57.5	171.8	139.6
	Maximum	114.9	343.7	279.2
Food waste	Minimum	45.6	136.5	72.9
	Medium	91.3	272.9	145.8
	Maximum	182.5	545.9	291.5
Total	Minimum	591.1	1768.1	1550.7
	Medium	916.1	2739.8	2344.8
	Maximum	1324.3	3960.9	3304.8

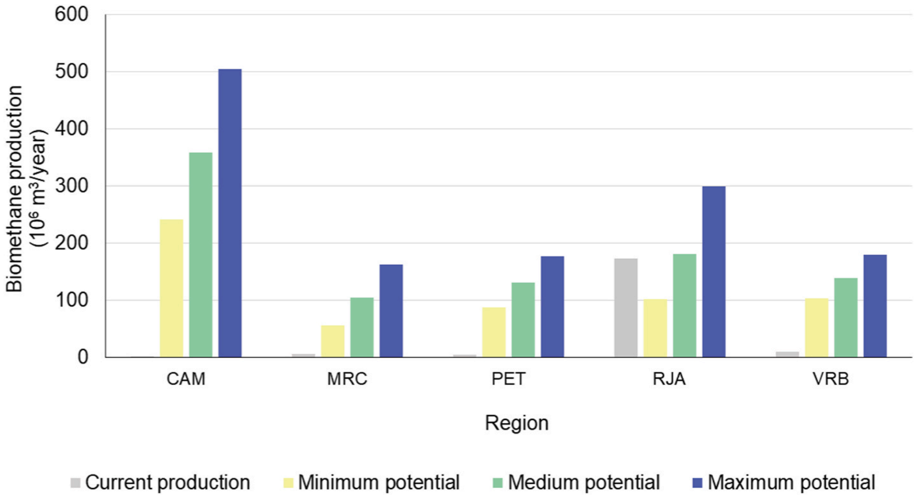


Fig. 1. Comparison of estimated biomethane potential with current production [11] considering a methane content of 60% in biogas. CAM: Campos dos Goytacazes; MRC: Macaé-Rio das Ostras-Cabo Frio; PET: Petrópolis; RJA: Rio de Janeiro; VRB: Volta Redonda-Barra Mansa.

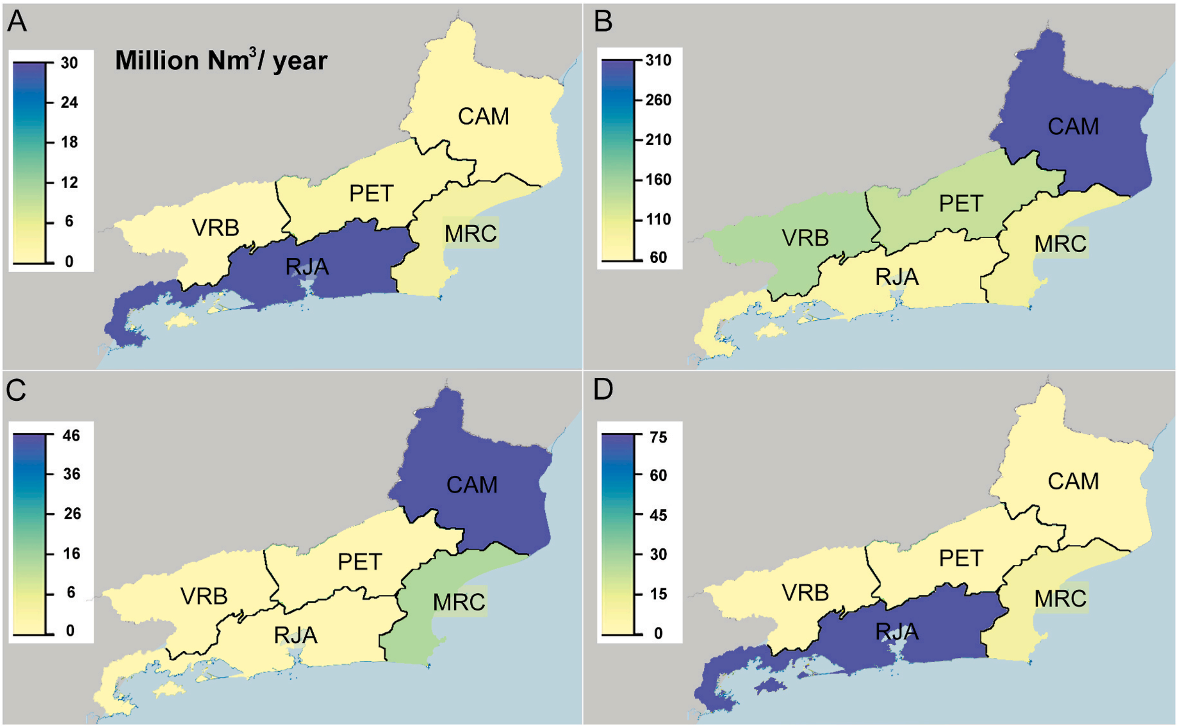


Fig. 2. Potential production of biomethane (million Nm^3 year^{-1}) in the medium scenario from sewage sludge (A), cattle manure (B), sugarcane processing waste (C), and food waste (D) in the regions of the state of Rio de Janeiro. RJA: Rio de Janeiro; VRB: Volta Redonda-Barra Mansa; PET: Petrópolis; CAM: Campos dos Goytacazes. MRC: Macaé-Rio das Ostras-Cabo Frio.

When sludge from all collected sewage was considered (maximum scenario), the biomethane potential from SS increased by 61% in comparison with the scenario in which only sludge from treated sewage was considered for biogas production (medium scenario). Moreover, the potential for biomethane production from sewage that is neither collected nor treated also exists. In RJ, only 64% of the population has access to sanitation, 63% of the collected sewage is treated [20], and the development of sewage collection and treatment infrastructure would be needed for AD. The possibility for biogas production could become an additional motivation to develop more extensive sanitation programs.

According to the State's Solid Waste Plan [25], the generated sludge is placed in sanitary landfills throughout RJ. Therefore, the application of AD to treat this waste would allow for the recycling of nutrients and a reduction in operating costs due to energy generation.

There are 2.6 million cattle heads in RJ, with 1.6 million beef cattle and 1.0 million dairy cattle. As most of the cattle in the state come from CAM, this region has the highest potential for biomethane production (42%) from cattle manure (Fig. 2B). The other regions each account for 9%–20 % of the potential CH_4 generation, with the lowest potential in RJA, a highly urbanized area.

The cattle industry is responsible for 80% of the emissions from agricultural activities in RJ, with manure management alone contributing to the emission of 232 Gg CO_{2eq} in 2015 [48]. Worldwide, less than 9% of the generated manure is treated, with most of it being left in the fields [49]. According to the World Biogas Association, livestock manure is one of the main sources of energy generation through AD [50] and is expected to play a crucial role in most countries in future years, achieving up to 1900 million Nm^3 of methane every day [51]. Even if livestock farming is not the main economic activity of a region, this study shows that biogas production from livestock residues could be of extremely high value. Legislation to enforce and encourage manure treatment via AD and to stimulate its energetic use are needed to realize the global potential for biogas generation from manure [50].

Cattle for milk production are usually placed in a confined space twice a day; therefore, a significant amount of manure could be concentrated in these locations, which facilitates manure management. On the other hand, beef cattle are more dispersed, which makes manure management more difficult and expensive. As a result, 64% of dairy manure is treated in some way, while only 1% of beef cattle manure is adequately managed [49]. In RJ, most of the cattle production farms have relatively small pasture areas (<20 ha), especially in RJA, where 57% of the establishments have less than 10 ha of pasture, which could facilitate manure management [36]. There is a need to encourage the appropriate management of manure, especially that from beef cattle, to achieve a more sustainable production process.

Family farming is the basis for the cattle industry in RJ [22], with the average number of heads per producer being between 74 (PET) and 142 (VRB) [36]. Solutions for small producers depend on collaboration among farmers, who must gather enough raw material to enable biogas production. Most local milk producers are associated with cooperatives, and more than 65% of them use collective cooling tanks [52]. This indicates an existing relationship among farmers that could facilitate the development of joint AD facilities to collectively treat wastes and allow for an increase in scale. Another possibility is the establishment of centralized AD facilities near large producers, which would allow for high-capacity biogas plants, decreasing specific capital and operational costs of production [53].

There are four large sugar-ethanol processing plants in RJ, three of which are in CAM and one in MRC [38]. Altogether, they have the capacity to produce 1270 $m^3_{ethanol}$ d^{-1}, which would generate 6 million m^3 $year^{-1}$ of vinasse, 896 thousand Mg $year^{-1}$ of straw (with only half being considered for AD), and 224 thousand Mg $year^{-1}$ of filter cake. This capacity is much higher than the actual ethanol production, which was reported to be only 123,400 $m^3_{ethanol}$ $year^{-1}$ in the 2021/2022 harvest season. The biomethane potential would increase 276% if the full capacity was utilized (maximum scenario) in comparison to the current ethanol production (minimum scenario), presenting the potential to improve both bioethanol and biogas production in RJ. CAM is responsible for 79% of the biomethane production potential (Fig. 2C).

Vinasse and filter cake are generally used as fertilizers, but this practice might affect soil structure and cause contamination, salinization and acidification of soil, and surface and groundwaters [54,55]. Therefore, AD of these wastes could help to reduce the environmental impacts of ethanol production and allow for the recovery of energy and nutrients. However, low pH, low C:N ratio, and macro- and micronutrient deficiency [56] could hamper biogas production from vinasse. Vinasse also contains high concentrations of sulfur, leading to the formation of H_2S, which can impair biogas production and decrease biogas quality, requiring a desulfurization step [56].

RJA, where the state capital is located, has the highest population density [13] and per capita MSW generation index in the state (1.19 kg $inhabitant^{-1}$ d^{-1}) [25] and thus has the highest potential for biomethane production from the AD of FW (82%) (Fig. 2D).

Source-segregated organic waste is preferable for AD since it facilitates reactor maintenance and digestate processing, allowing the digestate to meet the criteria needed to be used in food production [57]. In RJ, there is no collection of source-separated organic waste, but some municipalities have specific legislation [25] for the separate collection of organic residues from large waste generators, such as restaurants and supermarkets.

Although this residue is usually disposed in sanitary landfills, which wastes opportunities for resource recovery and energy generation, organic waste from large generators is currently being used in a pilot plant in Rio de Janeiro City for the production of biomethane [35]. According to the National Solid Residue Plan [58], this is the only facility in RJ where AD technology is applied to OFMSW, of which 73% is FW [35], and the facility can treat up to 30 Mg d^{-1}, producing 1000 Nm^3 d^{-1} of biomethane. This plant also produces digestate, which is used by the municipality in reforestation programs [59]. However, the treatment capacity of this facility corresponds to only 0.4% of the FW production in RJ, showing the need for the implementation of policies to increase sustainable organic waste management.

Solid waste management measures in Brazil are focused on eliminating improper waste disposal, so the implementation of source-segregation could be difficult, requiring a change in societal behavior and the enforcement and promotion of new public policies. Thus, post-separation technologies would be essential at present for separating FW from MSW.

3.2. *Application of biogas to offset electricity and fossil-fuel demands in the state of Rio de Janeiro*

The produced biogas could be used as a substitute for cooking gas. The application of biogas from small-scale plants for cooking has environmental, economic, and social benefits for rural and low-income areas [60,61]. This could help offset the effects of the rising liquefied petroleum gas (LPG) prices in RJ. In 2020, 3.2 million tons of LPG were used in the whole Southeast region of Brazil [62], which is equivalent to nearly 41,464 GWh [63], which could be offset by 14–32% by the energetic potential of methane estimated in this study.

RJ already has a natural gas distribution grid connecting its five regions, covering almost 60% of the municipalities (Fig. 3), that could be used for biomethane distribution. RJA has several municipalities connected to the grid, while CAM, which has the highest biomethane potential, has only one. However, the only two current biogas facilities that produce biomethane in the state do not inject it into the gas grid; instead, they sell it directly to the final consumer (e.g., gas stations and industrial clients) [46], which can be attributed to inconsistencies in the legislation for biomethane distribution (Section 3.5).

The produced biomethane could be easily distributed to households and businesses connected to the natural gas distribution grid. According to the natural gas distributor in RJ, Naturgy, 16.6 million m^3 of gas is distributed every day, which would be equivalent to a demand of nearly 6.1 billion m^3 every year [64,65]. The estimated biomethane production could provide between 10 and 22% of this demand, reducing dependency on fossil fuels and improving the contribution of renewable energy sources in the state. Biomethane is commonly applied in the vehicle fuel sector in countries such as Sweden [8]. Although the number of vehicles that use biomethane in RJ is quite low (286), more than 1.3 million vehicles run on natural gas (Fig. S1), highlighting an enormous market for biomethane. Almost 3.4 million m^3 day^{-1} of natural gas is commercially used as vehicle fuel [64,65], and all this demand could be supplied by biogas production from the sources selected in this study. The development of biogas solutions in the state could encourage a shift in vehicle fuel consumption, along with government policies and incentives for the production and use of renewable energy.

Despite economic advantages, the initial investments into biogas upgrading can be costly [66], and the produced biomethane would have to be competitive with natural gas. Alternatively, biogas could be used for heat and electricity production in a CHP system. The electricity could help supply the biogas plant and waste-generating activities (e.g., farms, sugar-ethanol plants, and wastewater treatment systems). For example, sewage treatment plants that use activated sludge systems have very high electricity demands associated with the aeration of reactors, and the integration of CHP is the most accepted option to increase energy recovery [67]. In RJ, the total electricity consumption in sewage systems is approximately 107 GWh $year^{-1}$ [20], of which 47% could be supplied by electricity generation from biogas from SS in the more conservative

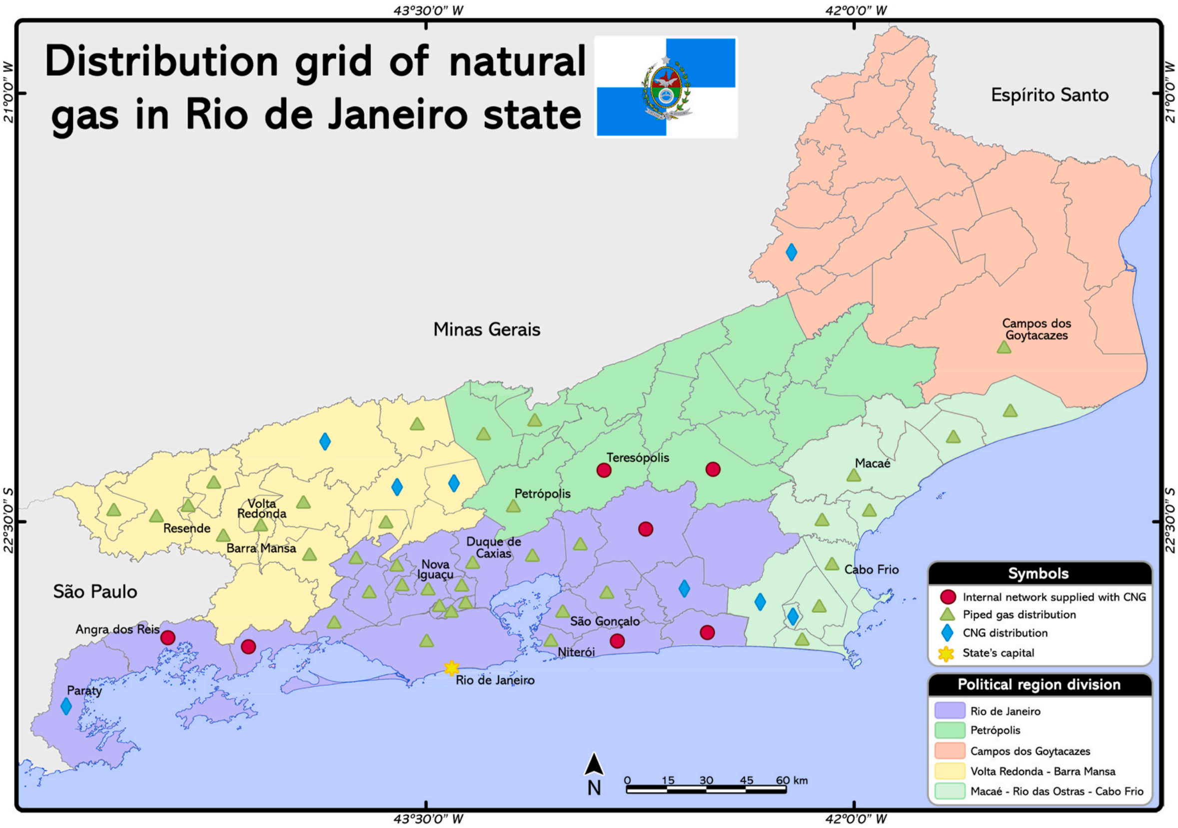


Fig. 3. Gas distribution in the state of Rio de Janeiro [64,65]. Compressed Natural Gas (CNG).

scenario. With the expansion of sewage treatment and the AD of sewage sludge (maximum potential scenario), all electricity could be provided by biogas, and profits could be obtained from selling the excess energy.

If the electricity is not used within the biogas plant, it could be distributed locally. A total of 39,244 GWh was consumed in RJ in 2019 [68]; thus, the electricity potential estimated from all streams considered in our study could offset 5–10% of the electricity from the power grid. Heat is also generated within the system, which could be utilized in other parts of the process, such as during pretreatment or for heating reactors.

3.3. *Digestate utilization: achieving a circular economy*

Digestate can help neutralize acid soils, since its pH usually ranges from 7 to 8.5, and enhance soil fertility, both as a source of nutrients [69] and by improving soil cation exchange capacity, which is crucial for RJ low fertility soils. It can also be used as a substrate for plant beds, especially for Atlantic Forest trees in RJ [70]. In summary, digestates from suitable feedstocks could act as secondary nutrient sources, promoting a circular biobased economy.

CAM has the highest potential for biofertilizer production from AD of

Table 4
Biofertilizer and nutrient production from digestate and demand in each region of the state of Rio de Janeiro. CAM: Campos dos Goytacazes; MRC: Macaé-Rio das Ostras-Cabo Frio; PET: Petrópolis; RJA: Rio de Janeiro; VRB: Volta Redonda-Barra Mansa.

Region	Scenario	Biofertilizer (Mg year^{-1})	N (Mg year^{-1})	P (Mg year^{-1})	K (Mg year^{-1})
CAM	Minimum	648,331	29,160	7,923	41,299
	Medium	947,999	41,580	11,297	60,582
	Maximum	1,314,190	54,696	14,841	84,604
MRC	Minimum	148,853	6,633	1,861	9,237
	Medium	271,945	12,091	3,404	16,832
	Maximum	413,827	17,691	4,941	25,811
PET	Minimum	304,847	14,918	4,096	18,968
	Medium	415,815	20,354	5,613	25,741
	Maximum	531,559	26,015	7,215	32,658
RJA	Minimum	238,257	11,947	4,052	10,840
	Medium	407,069	20,498	7,181	17,313
	Maximum	643,417	31,907	11,314	25,760
VRB	Minimum	210,423	10,283	2,822	13,071
	Medium	301,928	14,750	4,063	18,662
	Maximum	401,849	19,691	5,510	24,445
Total	**Minimum**	**1,550,711**	**72,941**	**20,754**	**93,416**
	Medium	**2,344,756**	**109,274**	**31,557**	**139,130**
	Maximum	**3,304,842**	**150,000**	**43,820**	**193,279**
RJ Demand[a]	**-**	**52,802**	**8,976**[b]	**5,280**[b]	**7,920**[b]

[a] Source: NPCT [72].

[b] Considering the N–P–K composition of the southeast region of Brazil (17-10-15%).

the studied biowastes, with more than twice the potential of any other region, while MRC has the lowest potential (Table 4). The produced biofertilizer can be used in agricultural production, since CAM is responsible for 61% of the state's production, mainly related to sugarcane [22]. Alternatively, the biofertilizer could be used for the cultivation of soybean and other grains, which has been encouraged and identified as one alternative to occupy the areas that were previously used by sugarcane in the North and Northwest of Rio de Janeiro [71].

The biofertilizer production projected in this study could surpass the fertilizer demand in RJ, of 52,802 Mg year^{-1} [72], providing at least 8, 4 and 12 times the amount of N, P and K needed, respectively. In the maximum potential scenario, the application of AD to treat the studied wastes could provide up to 17, 8 and 24 times the needed N, P and K, respectively. The replacement of mineral fertilizers for biofertilizers usually results in a reduction in GHG emissions and energy consumption in fertilizer production, reducing the use of fossil fuels [7,73].

Digestate characteristics vary widely with feedstock. Digestate from FW has the highest nitrogen (N) content, while that from SS has the highest phosphorus (P) concentration, and those from cattle manure and sugarcane waste have the highest potassium (K) content (Table S2). Biosolids produced from sewage treatment stations in RJ after AD and drying are suitable for agricultural application, complying with the legal quality requirements [70,74], but sludge is landfilled due to the absence of a state sludge recycling program [25,70]. Cattle manure and OFMSW-based digestates can have pathogens, impurities and contaminants, which negatively affect digestate processing and the possibility of land application [57,75,76].

Furthermore, for farmland application, the land should be located near the biogas plant, and for land that is farther away, volume reduction and digestate treatment must be considered to reduce transportation costs [5,57]. For longer distances, ammonia stripping can result in cost reduction, and if a CHP system is used, excess heat can be used to increase stripping efficiency [5]. Additionally, pelletization of the end-product may improve its fertilization properties, reduce transportation costs and facilitate land application [75].

Since the calculated digestate potential is much higher than the fertilizer demand in RJ, alternative uses in addition to soil application should be considered. For example, co-combustion of digestate can be performed for power generation [57]. Thermal conversion technologies such as combustion, pyrolysis and gasification are usually applied for energy recovery from digestate while also producing biochar, which could be utilized as a soil amendment [75]. Gasification is commercially available for urban digestates, and several operating plants exist in the United States [75]. The produced gas could be used either in pretreatment steps, to heat the reactor or in the digestate drying process.

3.4. *Avoided greenhouse gas emissions*

Brazil has one of the most sustainable energy matrices mainly due to the contribution of sugarcane biomass (19%) and hydropower (13%), with 48% of the energy produced coming from renewable sources (Fig. S2A) in 2020, in comparison with 14% in the world [77]. However, in 2016 (the latest available data), RJ was strongly dependent on nonrenewable sources for energy (88%) and electricity (78%) production [15] (Fig. S2).

Studies have noted that the energy produced from biogas contributes to lower GHG emissions compared to fossil fuels [78,79]; therefore, the implementation of AD technology can help improve the energetic status of RJ. Emissions of up to 439 thousand Mg CO_{2eq} could be avoided if gasoline was replaced by the estimated biomethane produced from the studied biowaste streams as vehicle fuel. A total of 332 thousand Mg CO_{2eq} would be avoided if natural gas was replaced. In this study, only passenger vehicles were considered, and further opportunities for GHG reduction exist if biomethane was used in heavy transportation.

If biogas is used to generate electricity, the emission of 275 thousand Mg CO_{2eq} could be avoided based on the Brazilian electricity mix. If the RJ electricity mix were to be considered, this impact would be even higher due to the higher dependency of the state on nonrenewable sources (Fig. S2B). However, it is important to emphasize that anaerobic digester energy and GHG emissions can differ depending on the input substrates and end-use applications [80], which could change the value of the calculated avoided emissions.

Due to its higher biomethane potential, CAM is the region that could have the largest avoided GHG emissions, with 104, 167 and 126 thousand Mg CO_{2eq} avoided when biomethane is used to substitute electricity, gasoline, and natural gas, respectively (Fig. S3). Conversely, the MRC region has the lowest reduction potential, with less than 54 thousand Mg CO_{2eq} avoided for these applications. RJA, which is the most urbanized region, could achieve up to 99 thousand Mg CO_{2eq} avoided.

3.5. *Current legal framework*

In Brazil, in addition to legislation regulating biogas production and its subsequent commercialization and consumption, there are also policies to encourage or enforce the use of renewable energy sources (Table S3). One of the most important policies in the biogas scenario is the National Biofuels Policy (RenovaBio - law 13,576/2017). It aims to promote the increase of biofuel contribution in the energy matrix, with an emphasis on energy security and efficiency, predictability in the fuel market and reduction of GHG emissions at all stages.

The Brazilian Electricity Regulatory Agency (ANEEL) provides tax reductions for power plants that use biodigestion (Normative Resolution 77/2004) and allows that the energy generated from renewable sources to be used by producers or be distributed in the local electricity grid (Normative Resolution 482/2012). Additionally, ANP sets standards for quality control and specifications for biomethane destined for vehicular use and use in residential, industrial, and commercial installations to be sold throughout Brazil (Normative Resolution 685/2017, Resolution 08/2015). This allowed the first authorization for commercialization of biomethane from landfills in the state (ANP Dispatch 1,084/2017).

In RJ, there is also a legal framework that could influence the development of the biogas sector, with the aim being to increase energy generation from renewable sources (Decree 41,318/2008, Law 5,690/2010, Resolution 65/2012, Law 6,361/2012, Decree 46,476/2018). However, many of the goals have not yet been executed or evaluated. The State Policy of Renewable Gas should be highlighted, as it encourages the production and consumption of biomethane in RJ and states that gas distributors must replace 10 % natural gas with biomethane when available. However, it also establishes a maximum price for biomethane sale to natural gas distribution companies, which is often not advantageous for biomethane producers, who currently choose to sell biomethane directly to the final consumer.

Despite the number of policies in place that encourage the production and use of renewable energy, few are focused on biogas and other AD products. This clearly indicates that a governmental agenda focused on legal, political, and regulatory challenges is necessary to allow for the development of AD technology in Brazil [81].

3.6. *Challenges for biogas production in the state of Rio de Janeiro and comparison with other regions*

Despite the importance of RJ to the national economy, the state has only 10 (out of 755) biogas plants under operation, that are responsible for approximately 17% of the biogas in Brazil [47]. Our estimates, however, indicate that RJ alone could approach the current biogas production of the entire Southeast region (1.42 billion Nm^3) [47]. This region, which comprises RJ, São Paulo, Minas Gerais and Espírito Santo, is responsible for 60% of the current national production, with São Paulo being the largest regional and national producer. Despite the fact that 84% of the biogas plants in the Southeast region belong to the agricultural and livestock sectors, and the enormous biogas potential of cattle manure in RJ, no biogas plant in the state currently treats these feedstocks. A previous assessment of the biomethane potential in the state of São Paulo [82], estimated a potential production of 2,992 million m^3 $year^{-1}$, which is 3.5 times higher than the estimated potential in our maximum scenario. This difference was expected, since São Paulo has a much larger population and more expressive agricultural activity [13,24,83]. Similar to our findings, the estimation was significantly higher than the current biogas production in the state.

In spite of all this potential, hindrances to expansion are manifold. They include a low level of knowledge about biogas and the use of cheaper and less technologically challenging options (e.g., composting), a mismatch in funding opportunities and financial requirements for biogas projects, poor interactions among actors, and high variability in geography and types of feedstocks, which collide with a highly centralized policy development, and the lack of a national biogas agenda [84–86]. Many of the specific barriers for biogas development noted in the present study, such as poor collection and segregation of waste, long digestate transportation distances, and lack of political support are also present in other Latin American and developing countries [87].

We compared our estimates with some recently published biomethane potential data from the world's leading producers of sugarcane and cattle manure and/or upper middle-income level countries with considerable agriculture production. Large variation in biomethane potential between regions or states is, for instance, also observed in India, China, Thailand and Turkey [88–91]. In our study, the largest potential comes from CAM mostly due to a combined potential of cattle manure and sugarcane processing waste (Figs. 1 and 2) with estimates that are comparable to those from regions with low to moderate potentials from animal and agricultural residues in Turkey (52–472 million Nm^3 $year^{-1}$) [90], India (150–600 million Nm^3 $year^{-1}$) [88]; Thailand (<819 million Nm^3 $year^{-1}$) [91] or in the Hubei Province in China (<494 million Nm^3 $year^{-1}$) [89]. Although Brazil is the world's largest producer of sugarcane and one of the largest cattle producers, production in RJ is not as expressive. For instance, while the Southeast region is responsible for 63% of the sugarcane produced in Brazil, the contribution of RJ is only 0.3% [33].

The International Energy Agency [92] reported the potential for biogas generation throughout the world. While Europe generates more than twice the biogas of China, which is the second largest producer, Asia, Central and South America have much higher potential than Europe. Successful biogas production has been shaped by the application of policies and incentives to realize existing potential. Therefore, developing countries located in Asia, and in Central and South America have much scope for increasing biogas production, if adequately supported. Accordingly, assessing the potential in these regions is the first step to promote a discussion of the development of AD.

Regarding biogas end utilization, almost two-thirds of the global biogas generated in 2018 was used for electricity and heat generation, with only a small share upgraded to biomethane [92]. One reason for this is a gap between natural gas and biomethane prices in Central and South America. Biomethane production from landfill gas upgrading is typically the least expensive option.

Northern Europe has the largest proportion of renewable energy within Europe, with most of it coming from bioenergy generation [93], and can be used as an example of successful implementation of bioenergy. In Germany, which is the largest biogas producer in the region, 92% of biogas comes from agricultural plants [93]. This highlights that the development of biogas solutions in rural areas may be an important driving force in establishing a strong biogas sector. The benefits go beyond bioenergy and biofuel production, and the abatement of GHG emissions, with clear positive outcomes regarding employment and development of rural areas and an increase in energy security [93,94].

4. Conclusion

This study showed substantial potential for biogas generation from different biowastes in RJ, especially via AD of cattle manure, which was the substrate with the highest estimated potential. Potential biomethane generation from the assessed biowaste streams was at least three and up to seven times greater than the current production in RJ and would be able to considerably offset the cooking gas, natural gas, or electricity demands of the state. The presence of a gas distribution grid throughout the state could be an important factor promoting the utilization of the produced biomethane as a substitute for natural gas. Furthermore, the biofertilizer potential would be enough to supply the nutrient demand for agriculture in the state, even in the most conservative scenario, and the digestate could be valorized in other ways. To date, the existing legal framework does not consider the specificities of the biogas industry, and policy implementation needs to be improved.

CRediT authorship contribution statement

Helena Rodrigues Oliveira: Methodology, Investigation, Formal analysis, Writing – original draft. **Betina Kozlowsky-Suzuki:** Writing – original draft, Conceptualization, Writing – review & editing. **Annika Björn:** Funding acquisition, Supervision, Writing – review & editing. **Sepehr Shakeri Yekta:** Supervision, Writing – review & editing. **Cristiane Fonseca Caetano:** Writing – review & editing. **Érika Flávia Machado Pinheiro:** Writing – review & editing. **Humberto Marotta:** Writing – review & editing. **João Paulo Bassin:** Writing – review & editing. **Luciano Oliveira:** Writing – review & editing. **Marcelo de Miranda Reis:** Writing – review & editing. **Mario Sérgio Schultz:** Writing – review & editing. **Norberto Mangiavacchi:** Writing – review & editing. **Viridiana Santana Ferreira-Leitão:** Writing – review & editing. **Daniel Oluwagbotemi Fasheun:** Methodology, Investigation. **Fernanda Geraldo Silva:** Methodology, Investigation. **Igor Taveira:** Methodology, Investigation. **Ingrid Roberta de França Soares Alves:** Methodology, Investigation. **Júlia Castro:** Methodology, Investigation. **Juliana Velloso Durão:** Methodology, Investigation, Writing – review & editing. **Juliana Guimarães:** Methodology, Investigation. **Mariana Erthal Rocha:** Methodology, Investigation. **Marina Tomasini:** Methodology, Investigation. **Pedro Vitor de Oliveira Martins:** Methodology, Investigation. **Rogerio Presciliano:** Methodology, Investigation. **Stella Buback dos Santos:** Methodology, Investigation. **Tamires Marques Faria:** Methodology, Investigation. **Tarcísio Corrêa:** Methodology, Investigation. **Thiago de Nuno Mendes Pery de Linde:** Methodology, Investigation. **Fernanda Abreu:** Supervision, Writing – review & editing, Visualization, Writing – review & editing. **Alex Enrich-Prast:** Conceptualization, Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was developed during the course "Biogas and biofertilizer production" coordinated by Linköping University, Sweden, and the authors thank the Graduate Program in Biological Sciences (Neotropical Biodiversity) - PPGBIO at Universidade Federal do Estado do Rio de Janeiro (UNIRIO) for hosting the course. The study received financial support from Vinnova (project number 2019–05382) by the Swedish Energy Agency [Grant number: 35624-2] conducted within the Biogas Research Solution Center hosted by Linköping University, Sweden and by the funding agency Formas [Grant number: 2021-02429]. The authors also thank the Brazilian National Council for Scientific and Technological Development (CNPq), Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) and Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.renene.2023.119751.

References

[1] A. Fagerström, T. Al Seadi, S. Rasi, T. Briseid, The role of anaerobic digestion and biogas in the circular economy, IEA Bioenergy Task 37 (2018). https://www.ieabioenergy.com/wp-content/uploads/2018/08/anaerobic-digestion_web_END.pdf%0A. https://www.ieabioenergy.com/wp-content/uploads/2018/08/anaerobic-digestion_web_END.pdf%0A. http://task37.ieabioenergy.com/files/daten-redaktion/download/Technical Bro.

[2] EBA, Biogas Basics, 2019.

[3] I. Angelidaki, L. Xie, G. Luo, Y. Zhang, H. Oechsner, A. Lemmer, R. Munoz, P. G. Kougias, Biogas upgrading: current and emerging technologies, in: Biofuels Altern. Feed. Convers. Process. Prod. Liq. Gaseous Biofuels, second ed., Academic Press, 2019, pp. 817–843, https://doi.org/10.1016/B978-0-12-816856-1.00033-6.

[4] W.A.V. Stiles, D. Styles, S.P. Chapman, S. Esteves, A. Bywater, L. Melville, A. Silkina, I. Lupatsch, C. Fuentes Grünewald, R. Lovitt, T. Chaloner, A. Bull, C. Morris, C.A. Llewellyn, Using microalgae in the circular economy to valorise anaerobic digestate: challenges and opportunities, Bioresour. Technol. 267 (2018) 732–742, https://doi.org/10.1016/j.biortech.2018.07.100.

[5] B. Drosg, W. Fuchs, T. Al Seadi, M. Madsen, B. Linke, Nutrient Recovery by Biogas Digestate Processing, 2015. http://www.iea-biogas.net/files/daten-redaktion/download/Technical Brochures/NUTRIENT_RECOVERY_RZ_web1.pdf%5Cn. http://www.iea-biogas.net/files/daten-redaktion/download/Technical Brochures/NUTRIENT_RECOVERY_RZ_web2.pdf.

[6] A. Cisse, A. Arshad, X. Wang, F. Yattara, Y. Hu, Contrasting Impacts of Long-Term Application of Biofertilizers and Organic Manure on Grain Yield of Winter Wheat in North China Plain, vol. 9, Agronomy, 2019, https://doi.org/10.3390/agronomy9060312.

[7] B. Dubis, A. Szatkowski, K.J. Jankowski, Sewage sludge, digestate, and mineral fertilizer application affects the yield and energy balance of Amur silvergrass, Ind. Crops Prod. 175 (2022), https://doi.org/10.1016/j.indcrop.2021.114235.

[8] M. Fallde, M. Eklund, Towards a sustainable socio-technical system of biogas for transport: the case of the city of Linkoping in Sweden, J. Clean. Prod. 98 (2015) 17–28, https://doi.org/10.1016/j.jclepro.2014.05.089.

[9] J. Edwards, M. Othman, S. Burn, A review of policy drivers and barriers for the use of anaerobic digestion in Europe, the United States and Australia, Renew. Sustain. Energy Rev. 52 (2015) 815–828, https://doi.org/10.1016/j.rser.2015.07.112.

[10] EBA, Breaking Free of the Energy Dependency Trap, Delivering 35 Bcm of Biomethane by 2030, 2022. https://www.europeanbiogas.eu/wp-content/uploads/2022/04/REPowerEU-with-biomethane-EBA.pdf.

[11] BiogasMap Cibiogas. https://mapbiogas.cibiogas.org/, 2022. (Accessed 1 February 2022).

[12] CEBDS, Opportunities and Challenges of the Brazilian NDC Commitments for the Business Sector, 2017. Rio de Janeiro, https://cebds.org/wp-content/uploads/2017/06/CEBDS_NDC_SUMEX_ING_navegavel.pdf.

[13] IBGE, Cidades, 2021. https://cidades.ibge.gov.br/. (Accessed 30 August 2021).

[14] IBGE, Produto Interno Bruto dos Municípios. https://www.ibge.gov.br/estatisticas/economicas/contas-nacionais/9088-produto-interno-bruto-dos-municipios.html?t=pib-por-municipio&c=3304557, 2018.

[15] A.O.P. Pereira Jr., Matriz Energética Do Estado do Rio de Janeiro: 2017-2031, Synergia, Rio de Janeiro, 2018.

[16] A.S. Fries, J.P. Coimbra, D.A. Nemazie, R.M. Summers, J.P.S. Azevedo, S. Filoso, M. Newton, G. Gelli, R.C.N. de Oliveira, M.A.R. Pessoa, W.C. Dennison, Guanabara Bay ecosystem health report card: science, management, and governance implications, Reg. Stud. Mar. Sci. 25 (2019), 100474, https://doi.org/10.1016/j.rsma.2018.100474.

[17] V.E.N. Santos, A. Magrini, Biorefining and industrial symbiosis: a proposal for regional development in Brazil, J. Clean. Prod. 177 (2018) 19–33, https://doi.org/10.1016/j.jclepro.2017.12.107.

[18] L.S. Franca, G.M. Ribeiro, G. de L.D. Chaves, The planning of selective collection in a real-life vehicle routing problem: a case in Rio de Janeiro, Sustain. Cities Soc. 47 (2019), 101488, https://doi.org/10.1016/j.scs.2019.101488.

[19] F. Battista, N. Frison, P. Pavan, C. Cavinato, M. Gottardo, F. Fatone, A.L. Eusebi, M. Majone, M. Zeppilli, F. Valentino, D. Fino, T. Tommasi, D. Bolzonella, Food wastes and sewage sludge as feedstock for an urban biorefinery producing biofuels and added-value bioproducts, J. Chem. Technol. Biotechnol. 95 (2020) 328–338, https://doi.org/10.1002/jctb.6096.

[20] SNIS, Diagnóstico dos Serviçoes de Água e Esgoto - 2019, 2020.

[21] GEOINEA, Esgotamento Geral: Estações de Tratamento - ERJ, 2023. https://geoportal.inea.rj.gov.br/portal/apps/mapviewer/index.html?layers=c7acdb23633e4a0891040891fa19008d&layerId=1. (Accessed 10 October 2023).

[22] EMATER-RIO, RELATÓRIO POR MUNICÍPIOS DO SISTEMA ASPA/AGROGEO, 2019. http://www.emater.rj.gov.br/images/municipios2019.htm. (Accessed 20 October 2020).

[23] EMATER-RIO, Bovinocultura, Pecuária de Leite/Corte, 2019.

[24] IBGE, Pesquisa, Pecuária Municipal, 2019. https://sidra.ibge.gov.br/pesquisa/ppm/tabelas/brasil/2019. (Accessed 20 October 2020).

[25] Rio de Janeiro, Plano Estadual de Resíduos Sólidos do Rio de Janeiro, Relatório Síntese, Rio de Janeiro, 2013.

[26] M. von Sperling, R.F. Gonçalves, Sludge characteristics and production, in: C. V. Andreoli, M. von Sperling, F. Fernandes (Eds.), Sludge Treat. Dispos, IWA Publis, 2007, https://doi.org/10.2166/9781780402130.

[27] V. Cabbai, N. De Bortoli, D. Goi, Pilot plant experience on anaerobic codigestion of source selected OFMSW and sewage sludge, Waste Manag. 49 (2016) 47–54, https://doi.org/10.1016/j.wasman.2015.12.014.

[28] G. Silvestre, A. Bonmatí, B. Fernández, Optimisation of sewage sludge anaerobic digestion through co-digestion with OFMSW: effect of collection system and particle size, Waste Manag. 43 (2015) 137–143, https://doi.org/10.1016/j.wasman.2015.06.029.

[29] G. Silvestre, A. Rodríguez-Abalde, B. Fernández, X. Flotats, A. Bonmatí, Biomass adaptation over anaerobic co-digestion of sewage sludge and trapped grease waste, Bioresour. Technol. 102 (2011) 6830–6836, https://doi.org/10.1016/j.biortech.2011.04.019.

[30] J.Y. de L. Mito, S. Kerkhoff, J.L.G. Silva, M.G. Vendrame, R.L.R. Steinmetz, A. Kunz, Metodologia para estimar o potencial de biogás e biometano a partir de plantéis suínos e bovinos no Brasil, Embrapa Suínos e Aves, Concórdia, 2018.

[31] C.L. Joppert, M.M. dos Santos, H.K.M. Costa, E.M. dos Santos, J.R.M. Simões, Energetic shift of sugarcane bagasse using biogas produced from sugarcane vinasse in Brazilian ethanol plants, Biomass Bioenergy 107 (2017) 63–73, https://doi.org/10.1016/j.biombioe.2017.09.011.

[32] L. Janke, A. Leite, M. Nikolausz, T. Schmidt, J. Liebetrau, M. Nelles, W. Stinner, Biogas production from sugarcane waste: assessment on kinetic challenges for process designing, Int. J. Mol. Sci. 16 (2015) 20685–20703, https://doi.org/10.3390/ijms160920685.

[33] Conab, Acompanhamento da safra brasileira de Cana-de-açúcar. Safra 2021/22, 2021. Brasília, http://www.conab.gov.br.

[34] L. Janke, A.F. Leite, H. Wedwitschka, T. Schmidt, M. Nikolausz, W. Stinner, Biomethane production integrated to the brazilian sugarcane industry: the case study of São Paulo state, in: In: 22nd Eur. Biomass Conf. Exhib, 2014, pp. 23–26, https://doi.org/10.5071/22ndEUBCE2014-3DV.2.4. Hamburg.

[35] B. Ornelas-Ferreira, L.C.S. Lobato, L.F.D. Colturato, E.O. Torres, L.M. Pombo, F.J. P. Pujatti, J.C. Araújo, C.A.L. Chernicharo, Strategies for energy recovery and gains associated with the implementation of a solid state batch methanization system for treating organic waste from the city of Rio de Janeiro - Brazil, Renew. Energy 146 (2020) 1976–1983, https://doi.org/10.1016/j.renene.2019.08.049.

[36] IBGE, Censo Agropecuário, 2017. https://sidra.ibge.gov.br/pesquisa/censo-agropecuario/censo-agropecuario-2017.

[37] EU-Agro-Biogas, Online European Feedstock Atlas, 2021. https://daten.ktbl.de/euagrobiogasbasis/navigation.do?selectedAction=Startseite. (Accessed 30 June 2021).

[38] ANP, Relatório Dinâmico de Autorizações - Produtores de Ethanol, 2021. https://app.powerbi.com/view?r=eyJrIjoiZWM3ZDI4YjEtOTliMi00NDY5LWJjZDktMTA0MTEzOGYzOGJjIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmLTEyNGFmY2FkYzkxMyJ9&pageName=ReportSection. (Accessed 21 June 2021).

[39] V. Ferreira-Leitão, L.M.F. Gottschalk, M.A. Ferrara, A.L. Nepomuceno, H.B. C. Molinari, E.P.S. Bon, Biomass residues in Brazil: availability and potential uses, Waste and Biomass Valorization 1 (2010) 65–76, https://doi.org/10.1007/s12649-010-9008-8.

[40] J.L.N. Carvalho, R.C. Nogueirol, L.M.S. Menandro, R. de O. Bordonal, C.D. Borges, H. Cantarella, H.C.J. Franco, Agronomic and environmental implications of sugarcane straw removal: a major review, GCB Bioenergy 9 (2017) 1181–1195, https://doi.org/10.1111/gcbb.12410.

[41] C. Ngumah, J. Ogbulie, J. Orji, E. Amadi, Potential of organic waste for biogas and biofertilizer production in Nigeria, Environ. Res. Eng. Manag. 63 (2013) 60–66, https://doi.org/10.5755/j01.erem.63.1.2912.

[42] H. Tian, X. Wang, E.Y. Lim, J.T.E. Lee, A.W.L. Ee, J. Zhang, Y.W. Tong, Life cycle assessment of food waste to energy and resources: centralized and decentralized anaerobic digestion with different downstream biogas utilization, Renew. Sustain. Energy Rev. 150 (2021), 111489, https://doi.org/10.1016/j.rser.2021.111489.

[43] EPE, Balanço Energético Nacional 2021: Relatório Síntese - Ano Base 2020, 2021. Rio de Janeiro.

[44] IRENA, Biogas for Road Vehicles: Technology Brief, 2018. Abu Dhabi.

[45] FAOSTAT, Livestock Manure, 2019. http://www.fao.org/faostat/en/#data/EMN. (Accessed 30 August 2021).

[46] É.M. da S. Guerreiro, Potential de Aproveitamento Energético de Biometano Gerado em Aterros Sanitários: Estudo de Casos, Universidade Estadual do Rio de Janeiro, 2020. http://www.peamb.eng.uerj.br/trabalhosconclusao/2020/Dissert-PEAMB-2020-Erica-Machado-Guerreiro.pdf.

[47] Cibiogas, Panorama Do Biogás No Brasil 2021, Foz Do Iguaçu, 2022.

[48] Rio de Janeiro, Inventário de Emissões de Gases de Efeito Estufa (GEE) do Estado do Rio de Janeiro - 2015, 2017. Rio de Janeiro.

[49] FAOSTAT, Livestock Manure, 2018. http://www.fao.org/faostat/en/#data/EMN. (Accessed 23 June 2021).

[50] World Biogas Association, Global Potential of Biogas, 2019.

[51] J.J. Chávez- Fuentes, A. Capobianco, J. Barbušová, M. Hutnan, Manure from our agricultural animals: a quantitative and qualitative analysis focused on biogas production, Waste and Biomass Valorization 8 (2017) 1749–1757, https://doi.org/10.1007/s12649-017-9970-5.

[52] FAERJ/SEBRAE, Diagnóstico da Cadeia Produtiva do Leite do Estado do Rio de Janeiro, 2010. Rio de Janeiro.

[53] L. Skovsgaard, H.K. Jacobsen, Economies of scale in biogas production and the significance of flexible regulation, Energy Pol. 101 (2017) 77–89, https://doi.org/10.1016/j.enpol.2016.11.021.

[54] L.T. Fuess, M.L. Garcia, Implications of stillage land disposal: a critical review on the impacts of fertigation, J. Environ. Manag. 145 (2014) 210–229, https://doi.org/10.1016/j.jenvman.2014.07.003.

[55] J.C. Delvaux, R. Carmargo, R.M.Q. Lana, M.H.R. Franco, M.C. Stanger, R. A. Gonçalves, E.M. Lemes, P.S.B. Miguel, Soil quality bioindicators in initial eucalyptus growth under organomineral fertilization based on sugarcane filter cake, Aust. J. Crop. Sci. 15 (2021) 602–609, https://doi.org/10.21475/ajcs.21.15.04.p3071.

[56] M. Parsaee, M. Kiani Deh Kiani, K. Karimi, A review of biogas production from sugarcane vinasse, Biomass Bioenergy 122 (2019) 117–125, https://doi.org/10.1016/j.biombioe.2019.01.034.

[57] M. Logan, C. Visvanathan, Management strategies for anaerobic digestate of organic fraction of municipal solid waste: current status and future prospects, Waste Manag. Res. 37 (2019) 27–39, https://doi.org/10.1177/0734242X18816793.

[58] Brasil, Plano Nacional de Resíduos Sólidos, 2020. Brasília, http://consultaspublicas.mma.gov.br/planares/wp-content/uploads/2020/07/Plano-Nacional-de-Resíduos-Sólidos-Consulta-Pública.pdf.

[59] Rio de Janeiro, PMGIRS - Plano Municipal de Gestão Integrada de Residuos Sólidos da Cidade do Rio de Janeiro, 2017. Rio de Janeiro, http://www.rio.rj.gov.br/dlstatic/10112/3372233/4123401/PMGIRS.pdf.

[60] H. Roubík, J. Mazancová, Small-scale biogas plants in central Vietnam and biogas appliances with a focus on a flue gas analysis of biogas cook stoves, Renew. Energy 131 (2019) 1138–1145, https://doi.org/10.1016/j.renene.2018.08.054.

[61] S.P. Lohani, B. Dhungana, H. Horn, D. Khatiwada, Small-scale biogas technology and clean cooking fuel: assessing the potential and links with SDGs in low-income countries – a case study of Nepal, Sustain. Energy Technol. Assessments 46 (2021), 101301, https://doi.org/10.1016/j.seta.2021.101301.

[62] Sindigas, GLP EM MOVIMENTO: PANORAMA DO SETOR DE GLP EM MOVIMENTO Janeiro 2021-44ª Edição, 2021. https://www.sindigas.org.br/Download/PANORAMAS/NOVO GLP EM MOVIMENTO_JANEIRO_2021_Rev5.pdf. (Accessed 20 July 2022).

[63] Bp, Approximate Conversion Factors - Statistical Review of World Energy, 2021, https://doi.org/10.1016/b978-075067856-8/50028-1.

[64] Naturgy, Informe Anual Integrado 2019 - CEG Rio, 2019. http://www.grupobimbo.com/informe/Bimbo-Informe-Anual-2011/descargas/Grupo-Bimbo-Informe-Anual-Integrado-2011.pdf.

[65] Naturgy, Informe Anual Integrado 2019 - CEG, 2019. http://www.grupobimbo.com/informe/Bimbo-Informe-Anual-2011/descargas/Grupo-Bimbo-Informe-Anual-Integrado-2011.pdf.

[66] B. Morero, R. Vicentin, E.A. Campanella, Assessment of biogas production in Argentina from co-digestion of sludge and municipal solid waste, Waste Manag. 61 (2017) 195–205, https://doi.org/10.1016/j.wasman.2016.11.033.

[67] G. Kor-Bicakci, C. Eskicioglu, Recent developments on thermal municipal sludge pretreatment technologies for enhanced anaerobic digestion, Renew. Sustain. Energy Rev. 110 (2019) 423–443, https://doi.org/10.1016/j.rser.2019.05.002.

[68] EPE, 2020 Statistical Yearbook of Electricity: 2019 Baseline Year, 2020. https://www.epe.gov.br/pt%0A. http://www.epe.gov.br.

[69] C.F. Matos, J.L. Paes, É.F.M. Pinheiro, D.V.B. de Campos, Biogas production from dairy cattle manure, under organic and conventional production systems, J. Brazilian Assoc. Agric. Eng. 37 (2017) 1081–1090.

[70] A.H.M. De Abreu, P.S.D.S. Leles, J.M. Alonso, E.L.D.S. Abel, R.R. De Oliveira, Characterization of sewage sludge generated in Rio de Janeiro, Brazil, and perspectives for agricultural recycling, Semin. Agrar. 38 (2017) 2433–2448, https://doi.org/10.5433/1679-0359.2017v38n4Supl1p2433.

[71] A.L. Ferreira, Pesquisa revela vocação do norte fluminense para o plantio de grãos, Embrapa, 2021. https://www.embrapa.br/busca-de-noticias/-/noticia/64381034/pesquisa-revela-vocacao-do-norte-fluminense-para-o-plantio-de-graos. (Accessed 25 May 2022).

[72] NPCT, Fertilizantes, 2017. https://www.npct.com.br/npctweb/npct.nsf/article/BRS-3132#consumo. (Accessed 5 July 2021).

[73] K. Timonen, T. Sinkko, S. Luostarinen, E. Tampio, K. Joensuu, LCA of anaerobic digestion: emission allocation for energy and digestate, J. Clean. Prod. 235 (2019) 1567–1579, https://doi.org/10.1016/j.jclepro.2019.06.085.

[74] T. Campos, G. Chaer, P. dos S. Leles, M. Silva, F. Santos, Leaching of heavy metals in soils conditioned with biosolids from sewage sludge, Floresta e Ambient 26 (2019) 1–10, https://doi.org/10.1590/2179-8087.039918.

[75] F. Guilayn, M. Rouez, M. Crest, D. Patureau, J. Jimenez, Valorization of digestates from urban or centralized biogas plants: a critical review, Rev. Environ. Sci. Biotechnol. 19 (2020) 419–462, https://doi.org/10.1007/s11157-020-09531-3.

[76] C. Le Maréchal, C. Druilhe, E. Repérant, E. Boscher, S. Rouxel, S. Le Roux, T. Poëzévara, C. Ziebal, C. Houdayer, B. Nagard, F. Barbut, A.M. Pourcher, M. Denis, Evaluation of the occurrence of sporulating and nonsporulating pathogenic bacteria in manure and in digestate of five agricultural biogas plants, Microbiol. 8 (2019) 1–10, https://doi.org/10.1002/mbo3.872.

[77] EPE, Brazilian Energy Balance 2021 Year 2020, 2021. Rio de Janeiro, https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-ben.

[78] E.M.M. Esteves, A.M.N. Herrera, V.P.P. Esteves, C. do R.V. Morgado, Life cycle assessment of manure biogas production : a review, J. Clean. Prod. 219 (2019) 411–423, https://doi.org/10.1016/j.jclepro.2019.02.091.

[79] N.I.H.A. Aziz, M.M. Hanafiah, S.H. Gheewala, A review on life cycle assessment of biogas production: challenges and future perspectives in Malaysia, Biomass Bioenergy 122 (2019) 361–374, https://doi.org/10.1016/j.biombioe.2019.01.047.

[80] W.G. Mezzullo, M.C. Mcmanus, G.P. Hammond, Life cycle assessment of a small-scale anaerobic digestion plant from cattle waste, Appl. Energy 102 (2013) 657–664, https://doi.org/10.1016/j.apenergy.2012.08.008.

[81] M.C.P.P. Mathias, J.F.C.M. Mathias, Biogas in Brazil: a governmental agenda, J. Energy Power Eng. 9 (2015), https://doi.org/10.17265/1934-8975/2015.01.001.

[82] C.L. Joppert, V.P. Garcilasso, M.M. Santos, A.S. Pereira, D. Perecin, M. Poveda, S. T. Coelho, The perspectives of biomethane to contribute to increase the natural gas supply in the state of SÃo Paulo, Eur. Biomass Conf. Exhib. Proc. (2018) 1503–1511, https://doi.org/10.5071/26thEUBCE2018-5BV.3.10.

[83] IBGE, Produção Agrícola Municipal, 2019. https://sidra.ibge.gov.br/pesquisa/pam/tabelas. (Accessed 20 October 2020).

[84] Brazil Energy Programme – BEP (Brazil), Biogas in Brazil: Barriers and Recommendations for Sector Development, São Paulo, 2021. https://i17.eco.br/wp-content/uploads/2022/11/RT01-2021.pdf.

[85] L.G.S. de Oliveira, Informing Systemic Policies to Promote Emerging Technologies: Fostering the Brazilian Biogas Innovation System, Utrecht University, 2022. https://dspace.library.uu.nl/handle/1874/416882%0A. https://dspace.library.uu.nl/bitstream/handle/1874/416882/informing systemic policies to promote emerging technologies - fostering the bra - 62746fc934deb.pdf?sequence=1.

[86] W. Kanda, H. Zanatta, T. Magnusson, O. Hjelm, M. Larsson, Policy coherence in a fragmented context: the case of biogas systems in Brazil, Energy Res. Social Sci. 87 (2022), 102454, https://doi.org/10.1016/j.erss.2021.102454.

[87] T. Nevzorova, V. Kutcherov, Barriers to the wider implementation of biogas as a source of energy: a state-of-the-art review, Energy Strategy Rev. 26 (2019), 100414, https://doi.org/10.1016/j.esr.2019.100414.

[88] P. Singh, A.S. Kalamdhad, A comprehensive assessment of state-wise biogas potential and its utilization in India, Biomass Convers. Biorefinery. 13 (2023) 12557–12579, https://doi.org/10.1007/s13399-021-02001-y.

[89] T. Liu, G. Ferrari, A. Pezzuolo, A. Alengebawy, K. Jin, G. Yang, Q. Li, P. Ai, Evaluation and analysis of biogas potential from agricultural waste in Hubei Province, China, Agric. Syst. 205 (2023), 103577, https://doi.org/10.1016/j.agsy.2022.103577.

[90] M.V. Aksay, A. Tabak, Mapping of biogas potential of animal and agricultural wastes in Turkey, Biomass Convers. Biorefinery. 12 (2022) 5345–5362, https://doi.org/10.1007/s13399-022-02538-6.

[91] W. Wang, K. Pornintа, P. Aggarangsi, N. Leksawasdi, L. Li, X. Chen, X. Zhuang, Z. Yuan, W. Qi, Bioenergy development in Thailand based on the potential estimation from crop residues and livestock manures, Biomass Bioenergy 144 (2021), 105914, https://doi.org/10.1016/j.biombioe.2020.105914.

[92] IEA, Outlook for biogas and biomethane, Prospects for Organic Growth, 2020.

[93] M.J. Stolarski, K. Warmiński, M. Krzyżaniak, E. Olba–Zięty, M. Akincza, Bioenergy technologies and biomass potential vary in Northern European countries, Renew. Sustain. Energy Rev. 133 (2020), https://doi.org/10.1016/j.rser.2020.110238.

[94] G. Ślusarz, D. Twaróg, B. Gołębiewska, M. Cierpiał-Wolan, J. Gołębiewski, P. Plutecki, The role of biogas potential in building the energy independence of the three seas initiative countries, Energies 16 (2023), https://doi.org/10.3390/en16031366.