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BIOFUELS FROM THE ORGANIC WASTE OF MUNICIPAL AND STREET MARKETS OF THE CITY OF SÃO PAULO

BIOCOMBUSTÍVEIS A PARTIR DE RESÍDUOS ORGÂNICOS DE MERCADOS MUNICIPAIS E FEIRAS LIVRES DA CIDADE DE SÃO PAULO

BIOCOMBUSTIBLES A PARTIR DE RESIDUOS ORGÁNICOS DE MERCADOS MUNICIPALES Y CALLEJEROS DE LA CIUDAD DE SÃO PAULO

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ABSTRACT

Food waste disposed of inappropriately is a global concern causing environmental and public health problems. Street markets in the city of São Paulo produce daily around 300 tons of Vegetable Solid Waste (VSW) to landfills. This study evaluates the potential for generating biogas to produce electricity or biofuels from anaerobic treatment of this VSW. If this VSW were sent to Anaerobic Digestion (AD) plants around the city, they would be able to produce 1,500 Nm^3/h of biogas with the potential to generate 25.75 GWh of electricity per year, using 3,100 kW motor generators. This biogas could be, otherwise, purified to biomethane and annually replace 7,800,000 Liters of diesel oil of fossil origin, avoiding the emission of 21,000 tons of fossil CO_2 to the atmosphere, in addition to capturing 8,000 tons of CO_2 from the process.

Keywords: Anaerobic Digestion. Circular Economy. Organic Waste. Energy Recovery from Waste. Sustainability.

RESUMO

O descarte inadequado de resíduos alimentares é uma preocupação global que causa problemas ambientais e de saúde pública. As feiras livres na cidade de São Paulo geram, diariamente, cerca de 300 toneladas de resíduos vegetais sólidos (RVS) que são destinados a aterros sanitários. Este estudo avalia o potencial de geração de biogás — para a produção de energia elétrica ou biocombustíveis — a partir do tratamento anaeróbio desses resíduos. Caso esses RVS fossem encaminhados para unidades de digestão anaeróbia (DA) distribuídas pela cidade, seria possível produzir 1.500 Nm^3/h de biogás, com potencial para gerar 25,75 GWh de energia elétrica por ano, utilizando motogeradores de 3.100 kW. Alternativamente, esse biogás poderia ser purificado para a obtenção de biometano, substituindo anualmente 7.800.000 litros de óleo diesel de origem fóssil; isso evitaria a emissão de 21.000 toneladas de CO_2 fóssil na atmosfera, além de permitir a captura de 8.000 toneladas de CO_2 provenientes do próprio processo.

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Palavras-chave: Digestão Anaeróbia. Economia Circular. Resíduos Orgânicos. Recuperação Energética de Resíduos. Sustentabilidade.

RESUMEN
La eliminación inadecuada de los residuos alimentarios constituye un problema global que genera repercusiones tanto para el medio ambiente como para la salud pública. Los mercados callejeros de la ciudad de São Paulo generan diariamente cerca de 300 toneladas de residuos vegetales sólidos (RVS) que terminan en vertederos. Este estudio evalúa el potencial de generación de biogás —destinado a la producción de electricidad o biocombustibles— mediante el tratamiento anaerobio de dichos residuos. Si estos RVS se destinaran a plantas de digestión anaerobia (DA) situadas en la ciudad, sería posible producir 1.500 Nm^3/h de biogás, con capacidad para generar 25,75 GWh de electricidad al año mediante el uso de motogeneradores de 3.100 kW. Alternativamente, este biogás podría purificarse para obtener biometano, sustituyendo anualmente 7.800.000 litros de diésel de origen fósil; esto evitaría la emisión de 21.000 toneladas de CO_2 de origen fósil a la atmósfera, además de permitir la captura de 8.000 toneladas de CO_2 durante el proceso.

Palabras clave: Digestión Anaerobia. Economía Circular. Residuos Orgánicos. Valorización Energética de Residuos. Sostenibilidad.



1 INTRODUCTION

The Food and Agriculture Organization of the United Nations points out that over 1 billion tons of food are wasted or lost along the production chains annually [1]. Food waste results in throwing away more than US$ 1 trillion every year [2]. This represents more than 30% of all food for human consumption produced that year on the planet [3, 4]. This wasted material is ultimately disposed of in garbage dumps or landfills where it decomposes naturally over the years and emits harmful polluting by-products [5]. The degradation of organic waste is one of the main sources of methane emissions to the atmosphere [6]. Landfill emissions are the world's third largest anthropogenic source of methane [7]. Recent aerial observations of landfills in the USA confirmed that found that landfills are methane "super-emitters", and that on average, emission rates were 1.4 times higher than what has been recorded in the Environmental Protection Agency's Greenhouse Gas Reporting Program [8, 9]. Food waste generates an estimated 8–10% of global greenhouse gas (GHG) emissions [2, 10].

The waste issue has several parallels with global warming and the climate crisis. Due to the importance of waste minimization, zero-waste policies are being discussed by several countries [11, 12]. Agricultural waste, food, and urban waste, can be treated through AD. The outputs of this process are biogas and digestate [13]. Biogas can be used as fuel for public transportation or burned to produce heat and electricity.

Life cycle assessment (LCA) studies have assessed AD systems worldwide, primarily in Europe, highlighting the benefits of these treatment systems for reducing waste, reducing the use of fossil fuels for electricity production, and replacing or reducing reliance on chemical fertilizers [14]. Information from these studies can help engineers improve the efficiency of systems and, public policymakers to identify systems suitable for large-scale implementation, aiming to reduce over-all environmental effects [15]. Some countries like Germany and Sweden have implemented zero-waste-to-landfill policies [12].

According to the Food Loss Index [1], 14% of food produced is lost from post-harvest up to (but not including) the retail level, and an additional 17% of food is wasted at the retail and consumer levels [10]. The United Nations Development Program and the Brazilian Agricultural Research Corporation point out that food loss in Brazil ranges from 20% to 60% of all the food produced in the country. Loss is intensified by the large amount of waste produced throughout the food supply chain. Sometimes, only 40% of what is grown is consumed.

In 2018-2019 Brazil generated daily around 217,000 tons of municipal solid waste (MSW). Of this amount, approximately 94,000 tons were of organic origin, corresponding to 45% [16]. In 2023, collected MSW reached 221,000 t/day, corresponding to 382 kg/inhabitant according to the Brazilian Association of Waste and Environment (ABREMA) [17].

1.1 CURRENT WASTE MANAGEMENT SCENARIO IN BRAZIL

Public policies for MSW treatment are not yet implemented in Brazil. The national scenario has evolved significantly since the approval of the National Solid Waste Policy (Act Nº 12,305/2010) [18] and its subsequent regulation through Decree Nr. 10,936/2022 [19]. This policy has been instrumental in generating vital data, information, and decision-making tools to support MSW management.

The National Plan for Integrated Solid Waste Management provided, in Article 54, for the total elimination of garbage dumps by 2014 and the reduction of organic waste destined for landfills. This goal has not been achieved, and the deadline was extended to 2024 [20]. However, this objective remains outstanding. The National Solid Waste Policy (PLANARES) states that 100% of waste should be treated, as well as the residues final disposal should be made in an environ-mentally appropriate manner [16]. More than 35% of collected solid waste is still disposed-off inappropriately causing environmental impacts [5, 17], leading to a large waste of material that could be used to produce fertilizer, biogas, biomethane, or to generate electricity. Only a meager 0.4% of organic waste collected annually undergoes composting. Only 211 Brazilian municipalities have composting units, consequently, a significant portion of this waste lacks proper disposal [16, 17].

The National Sanitation Information System collect and store data from 3,468 municipalities, only 62.3% of all. When considering the urban population, encompassing 151 million urban residents, this coverage increases to 85.6%. Considering all the collected MSW, 33.7% are recyclable materials (37,400 t/d–plastics; 27,000 t/d–paper, cardboard, and packages; 6,000 t/d–glass, 4,000 t/d–steel. and 1,100 t/d–Aluminum). 21% are classified as “other” and should be land-filled. However, organic waste responds on 45.3% of the total (101,000 t/d) [16, 17]. Organic waste should be properly disposed of and treated to comply with PLANARES [16].

1.2 ANALYSIS OF TREATMENT PROCESS

Municipal and street markets wastes are mainly organic and are generally referred to as VSW [21–23]. The technologies available for the treatment of organic waste to produce energy are thermal or biological. Thermal technologies are incineration, gasification, and pyrolysis. Biological technologies are composting and AD. The high moisture content of VSW hinders thermal conversion processes, making biological treatments more appropriate.

A small part of collected VSW are composted through aerobic digestion [24]. Compactor trucks collect the remaining VSW, which are sent to landfills. There-fore, it is still necessary the treat this waste by AD, a process that results in biogas, liquid effluent, and sludge [13, 25]

AD is the process of converting organic matter in the absence of free atmospheric oxygen (O_2). During AD, organic matter is decomposed, generating biogas and mineralized compost [26]. This process occurs naturally in swamps and land-fills. In AD the moisture actually accelerates hydrolysis by promoting enzymatic cleavage of complex molecules — carbohydrates, proteins, and lipids— and by dissociating into ions that stabilize intermediate reaction steps. The AD process can be described generically by the expression:

$$Biomass + H_2O \rightarrow CH_4 + CO_2 + NH_3 + H_2S + Heat + \cdots$$
$$\ldots + \text{Mineralized material} + \text{Undecomposed organic material}$$

AD is a dynamic process and depends on many factors that may lead to a wide range of the chemical oxygen demand (COD) being incorporated in the biogas composition, while 20% to 50% still remains in its byproducts.

On industrial scale, AD-reactors are used to produce biogas. Industrial AD-reactors are technological equipment, normally equipped with several sensors that require operation and maintenance, which are more sophisticated than composting yards. The process in confined reactors allows the control of the production and quality of biogas. AD offers benefits compared to the other disposal procedures for MSW considering a fundamental sensibility assessment [14]. The use of AD-reactors increases the productivity of biogas generation and allows its capture for use as a biofuel for heat generation, electricity generation, or biofuel production.

1.3 OBJECTIVE

This work aims to analyze the potential of using the VSW collected from CEAGESP, the municipal and street markets of the city of São Paulo, which are not used for composting, to produce biogas or biomethane. Estimate the potential for production of these energy vectors and identify opportunities for their use, considering a projection of the VSW generation in the next 20 years, aiming at the preliminary sizing of the necessary processing capacity. Finally, evaluate the reduction of the amount of materials to be disposed of in landfills resulting from AD of the collected VSW and the reduction of GHG emissions.

2 MATERIALS AND METHOD

2.1 MATERIALS

The material under consideration in this paper is the collected VSW in the city of São Paulo. The typical composition of VSW is similar throughout the country, despite regional and seasonal variations. However, due to the heterogeneity of the bulk material, researches found high standard deviations for all the characterization values. For every characteristic a wide range is indicated by the several researchers. This study considers the average value of the found in literature. Organic compounds account for about 84% of the VSW, while the remaining 16% are various materials such as plastics, metals, glass, paper, cardboard, rags, and other [13, 27, 28]. These materials should be removed before AD process.

Updates on this topic are released only sporadically due to irregular reporting and the lack of continuous data collection. Nevertheless, street-market operations have remained largely consistent. Despite inter-market differences and seasonal fluctuations, there have been no substantial changes in market structure, product offerings, or waste characteristics. The most recent and reliable data on VSW from markets' waste characteristics, drawn from seven references, are presented in Table 1.

Table 1

Main physicochemical characteristics of VSW.

Parameter	Unit	VAZ, *et al.* 2003 [27]	LEITE, *et al.* 2015 [23]	SILVA 2016 [29]	MARANA 2017 [30]	AGEM 2018 [31]	SERASA /ORIUM 2018 [28]	SRIVASTAVA 2020 [13]
Contaminants to remove	%	16.4					16	16
Moisture	%		76.4	76.7	76.8	68.9	70	
Specific weight	kg/m^3	660	-	-	-	185	-	
Volatile Solids (VS)	%	-	69.7	85.2	86.0	58.2	71.8	71.8
Organic Carbon	%	-	38.7	-	-	37.5	-	-
C/N ratio	1 :	-	16.8	28	-	18	-	25

The feedstock considered in this paper is exclusively VSW mainly composed of carbohydrates (over 85%). Bromatologic composition of VSW samples pointed proteins below 10% and fat around 3% [29].

VSW is a wet heterogeneous mixture of organic materials. It typically contains more than 70% water; the average moisture from 5 authors resulted 73.8% on wet basis [23, 28–31]. Its elemental composition was also considered as an average of several research results [13, 23, 28–31]. VSW has a typical C/N ratio of 28.5:1 [29]. The composition of VSW from the proximate analysis resulted 84.9% VS and 15.1% ash [29, 30]. The elemental composition from ultimate analysis, the molar composition, and Boyle's formula representing the VSW are shown in Table 2.

Table 2

Typical elemental composition of VSW.

Element		C	H	O	N	S	A
Composition in mass percentage	(%)	37.1	7.8	37.67	1.3	1.2	15.1
Atomic mass		12	1	16	14	32	
Molar composition coefficient		c^-	h^-	o^-	n^-	s^-	
		3.088	7.800	2.349	0.093	0.037	
Boyle's molar composition formula [32]		$C_{3.088}$	$H_{7.800}$	$O_{2.349}$	$N_{0.093}$	$S_{0.037}$	

2.2 METHOD

Based on the characterization and quantification of the VSW generated by the markets and open street markets of São Paulo provided above, this study proposes and designs a complete AD system to produce biogas of this feedstock and alternatives for its utilization as a fuel. The pretreatment of the feedstock, selection of suitable microorganisms, and optimization of process variables such as temperature and pH significantly improve digester's efficiency [13].

2.3 PROPOSED PROCESS

2.3.1 VSW collection and reception

Compactor trucks collect the VSW not sent to composting from various markets. VSW collecting trucks will be unloaded into a reception courtyard, which is an aerobic pretreatment area [13]. The collected material must be inspected and harmful materials such as plastic, glass, and metals must be removed [13, 27]. The presence of inert materials reduces the fraction of biodegradable substrate and causes dense particles to settle at the reactor base, disrupting mixing and limiting microbial contact. Their accumulation also leads to equipment abrasion, blockages, and more frequent maintenance. Removing these inerts boosts biogas production, enhances reactor stability, lowers operational costs, and extends the lifespan of AD equipment. Depending on site layout and engineering requirements, VSW inspection and removal of harmful substances can be carried out via manual sorting, mechanical screening, or a combination of both.

2.3.2 Preparation and pre-treatment

Forced aeration pretreatment for a period of a few days at ambient conditions can increase methane production of easily degradable feedstock like food waste from restaurants [33]. This favors the hydrolyzation process. Laboratory studies showed an increase in methane production in relation to the total volatile solids (VS) of the feedstock after short aeration periods. Material stored for 4 days produced 456 NmL CH_4/g VS, an increase of 22% compared to fresh samples without pretreatment that produced 375 NmL CH_4/g VS [33].

2.3.3 Homogenization

Difficult-to-degrade feedstocks are most effectively handled in multi-stage systems. VSW includes fibrous materials rich in cellulose and lignin, which resist digestion. Lignocellulosic biomass comprises polysaccharides —cellulose and hemicellulose— and lignin, forming a complex three-dimensional matrix that impedes enzymatic hydrolysis during AD [34].

Effective bacterial degradation of these substrates depends on optimizing a range of interdependent variables [35]. Consequently, intensive hydrolysis is required to cleave the long polymer chains at this stage.

To achieve this on an industrial scale, VSW is processed through a two-stage reactor configuration [36]:

1 - the first reactor intended for the hydrolysis of material with acidic pH;

2 - the second reactor, which is the digester itself, is intended for methanogenesis at neutral pH.

After aeration pretreatment, the material goes to a chopper witch reduces solids size before the actual process of AD and afterwards it is dumped into a tank for mixing and homogenization. Moisture content also increases the efficiency of AD. High moisture containing feedstock materials are operated preferably by standard pumps with a fixed pressure [13]. Continuous flow wet AD requires a dense and homogeneous substrate with a total solids content (TS) of around 15% that has favorable characteristics for pumping and mixing. Dilution water is added to the homogenization tank to obtain a suitable inflow substrate.

For VSW dilution, the digestate (liquid effluent from the process) is used. It is also used to clean the collecting trucks' compartment. When cleaning the trucks, the leachate accumulated at the bottom of the truck will also be taken to the homogenization tank. The integration of digestate reuse for truck cleaning and substrate dilution, not only reduces freshwater demand but also enhances hydrolysis efficiency due to the acidic nature of leachate (pH 3 to 5) [37].

Since these operations occur in discrete frequency as collecting trucks arrive, the homogenization tank serves also for provisory storage of the homogenized substrate to be transferred to the hydrolysis reactor according to the operator's convenience.

$$TS_{(i)} = \frac{m_s}{m_t} = \frac{m_s}{m_s + m_w} = 1 - M \qquad \text{(w.b.)} \qquad (1)$$

$$DF = \frac{m_w}{m_t} = \left(\frac{TS_{(i)}}{TS_{(f)}} - 1\right) \qquad (2)$$

Where: TS(i) is the original TS in VSW; TS(f) is the final TS in homogenized substrate; mt is the total mass of VSW; ms is the mass of solids; mw is the mass of water in the raw material; M is the moisture in a wet basis; DF is the dilution factor to obtain a substrate with a final solid content TS(f).

2.3.4 AD: Biogas production

The first step of the AD is hydrolysis. During hydrolysis, complex molecular bonds such as carbohydrates, proteins, and fats are broken by enzymes in a bio-chemical process, being released by a specific group of bacteria and giving rise to simple organic compounds such as amino acids, fatty acids, and sugars, consuming water as shown in Eq.(3).

$$RCOOR + H_2O \rightarrow RCOOH + ROH \quad (3)$$

This phase occurs in an acidic environment at room temperature. The ideal pH for this phase is in the range of 5.2 to 6.3.

In subsequent stages, acidogenic bacteria transform the substances resulting from hydrolysis into propanoic acid, butanoic acid, lactic acid, and alcohols, as well as hydrogen and carbon dioxide (Acidogenesis). The materials resulting from acidogenesis are transformed into ethanoic acid, acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria (Acetogenesis).

The main stage of AD is Methanogenesis. During this stage, acetic acid, hydrogen, and carbon dioxide are finally converted to methane and carbon dioxide through the action of methanogenic microorganisms classified in the domain of Archaea, distinct from bacteria due to their genetic characteristics [38]. This process occurs at neutral pH, in the range of 6.8 to 7.2, as methanogenic Archaea are extremely sensitive to pH. Archaea have unique and particular characteristics that allow them to live in specific environments where electron acceptors such as Oxygen (O_2) and Nitrates (NO_3-) are absent or exist in low concentrations.

Methanogenesis can be considered a type of “anaerobic respiration”. While acetoclastic methanogenic microorganisms (e.g. Methanosarcina) use acetic acid and methanol to generate methane and carbon dioxide, hydrogenotrophic methanogens (e.g. Methanobacterium and Methanospirillum) use Hydrogen and Carbon Dioxide to generate more Methane and Water. Reactions (4) and (5) respectively represent the action of each of the types of Archaea mentioned [39].

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (4)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (5)$$

This last reaction increases the methane content and replaces water. The operating parameters of VSW, AD-reactors must be adjusted to maximize the reaction of Eq.(5).

Sulfate-reducing bacteria compete with methanogenic Archaea for consumption of the same substrates (acetate and hydrogen). However, even though from the point of view of COD removal, sulforeducers are more efficient than methnogenic archaea, the competition for acetate and hydrogen reduces methane production. As VSW contains little sulfur the sulfatogenesis is less important.

Several factors affect the production of biogas, as it is a biological process. The characteristics of the sludge and the temperature are two of these factors. The temperature range of the methanogenic digester varies from 20º to 40ºC, with 35-37ºC being the ideal temperature for the mesophilic methanogenic archaea [40]. To maintain the temperature close to ideal, with variations of ±0.5ºC, the reactor walls must be insulated. Inside this reactor, a tubular bundle will allow the circulation of hot water to ensure the mesophilic condition close to optimum. Reactors constructed of concrete do not require additional thermal insulation.

The biogas, after proper demoistering and desulfurization, is stored in an appropriate low-pressure gasometer, from where, after adequate pressurization, it may be used for electrical generation in gas turbines or internal combustion engines coupled to electricity generators. Alternatively, it can be upgraded to biomethane and compressed to be fed into the natural gas pipeline network or used in the fleet. The liquid effluent resulting from the process (digestate) may be used as fertilizer to irrigate crops close to the plant, or sent to Sewage Treatment Stations (STS).

2.3.5 Theoretical methane potential

The theoretical dry mass conversion rate to methane (TMCR) in (Nm^3 CH_4/kg) is calculated by Eq.(6) from the elemental composition, using Boyle's formula [32], where $\bar{c}$, $\bar{h}$, $\bar{o}$, $\bar{n}$, and $\bar{s}$ are the molar composition coefficients (Table 2).

$$MCR = \frac{22.4\times\left(\frac{\bar{c}}{2}+\frac{\bar{h}}{8}-\frac{\bar{o}}{4}-\frac{3\bar{n}}{8}-\frac{\bar{s}}{4}\right)}{12.017\bar{c}+1.0079\bar{h}+15.999\bar{o}+14.0067\bar{n}+32.065\,\bar{s}} \qquad (6)$$

TMCR is calculated based on volatile solids (Nm^3 CH_4/kg VS). However, while TMCR provides an estimate of the maximum expected biogas production, the actual production will be lower due to several factors. These include the use of 5-10% of the biomass by microorganisms to synthesize cellular material, material loss with the effluent, limitations due to insufficient nutrients, and parts of the material being inaccessible to microorganisms.

Additionally, there are other factors related to the actual operation of the biodigestion equipment. Consequently, the conversion of biomass into methane in industrial reactors can vary from 65 to 95% of TMCR.

An empirical efficiency factor (EF) is used to estimate the real CH_4 emission of the system, considering factors such as the substrate, technology, type of equipment, and operating conditions. Eq.(7) represents this scenario and allows for the estimation of the effective methane emission (EME) for a given amount of raw substrate (Nm^3CH_4/kg of VSW), where A is the percentage of ash in the dry substrate and M is the moisture in working base.

$$EME = TMCR \times EF \times (1 - A) \times (1 - M) \quad (7)$$

2.3.6 Electricity from biogas

Biogas production is continuous, without interruptions (24 h/d and 365 days/year), but it depends on the action of microorganisms so that the production rate is not exactly uniform. The gasometer has the function of regulating this non-uniformity but is not intended for storing large quantities of gas. Therefore, the consumption of biogas for electricity production should be continuous.

Spark ignited motor generators adapted for biogas are considered for power production. Electrical power (WEl.) depends on losses in the system as a whole, so it is lower than mechanical power (system's efficiency). The energy produced annually by biogas will therefore be WEl. multiplied by 8,760 hours/year. To calculate the energy generation potential, Eq.s (8), (9), and (10) are used.

$$W_{Mec.} = \frac{Q \times LHV \times \eta_{engine}}{860} \quad (8)$$

$$W_{El.} = W_{Mec.} \times \eta_{gen.} \quad (9)$$

$$E = W_{el.} \times 8760 \quad (10)$$

Where: $W_{Mec.}$= Engine's mechanical power ($kW_{Mec.}$); $W_{El.}$= Electric power output (kWEl.); E= Energy produced yearly (kWh); Q= Biogas flow rate (Nm^3/h); LHV = Lower heating value ($kcal/Nm^3$); Conversion factor to I.S. units = 860 (kcal/h)/kW.

For 4-stroke Otto cycle biogas engines: $\eta_{engine} \leq 34\%$; For generators: $\eta_{gen.} = 95\%$.

If using gas turbines instead of internal combustion engines may result in different values.

2.3.7 Biomethane from biogas

The purification of biogas (a process called “upgrade”) consists of the removal of hydrogen sulfide and carbon dioxide. Biomethane is a gas consisting essentially of methane, derived from the purification of biogas, Eq.(11), which has a CH_4 content greater than 90%.

$$Biogas\ 60 \rightarrow Biomethane\ 90 + other\ gases \quad (11)$$

$$Biomethane = Biogas \times CH_{4_{molar\ fraction}} \times \eta_{upgrade} \quad (12)$$

$$CO_2 \approx Biogas - Biomethane \quad (13)$$

The biogas upgrading to biomethane can be performed by chemical methods or by physical methods, in which no chemical reactions occur. Molecular sieves and Pressure Swing Adsorption (PSA) can result in further purification of biomethane, however, lowest efficiency of scrubbing with water (Eq.12) resulted enough to produce biomethane within specifications and is a cheaper process [41].

Water scrubbing is an absorption processes with pressurized cold water, 4-10ºC. It uses the principle of solubility, where CO_2 has around 26 times greater solubility in cold water than CH_4 [41, 42]. In this process, various other gases that makeup biogas are removed, such as Hydrogen Sulfur Gas (H_2S), CO_2, Water Vapor, Atmospheric Air and Sulfur Dioxide (SO_2), leaving mainly CH_4. To achieve a 95% CH_4 concentration, the absorption column operating in the range of 4 to 6 bar have the lowest energy requirement [43]. Water scrubbing CO_2 removal efficiency varies form 94% to 99.8% [44].

This process is usually followed by drying and compression of the gases for storage. To be used as vehicular fuel compression to 25 MPa is required. Table 3 presents the typical gas composition before and after water scrubbing process.

Table 3

Biogas water scrubbing [41].

AD Biogas			Biomethane
Methane	CH_4	60%	94%
Carbon Dioxide	CO_2	40%	5%
Oxygen	O_2		0,7%
Hydrogen Sulfide	H_2S	ppm	0
Hydrogen	H_2	ppm	0
Removal efficiency	of CO_2		87%
Removal efficiency	of H_2S		100%

2.3.8 Sizing of the biodigestion plants

The per capita mass of household solid waste generation in southeastern Brazil, where the city of São Paulo is localized, is 452 kg/inhabitant/year [17]. It is assumed that it will maintain the same proportion, therefore, the waste generation will increase mainly due to the increase in population. Immediate implementation of a biodigestion system for the 300 t/d of VSW currently collected and not composted, deducting the inorganic materials that must be previously separated, results in a flow rate of 250 t/d for AD. The most suitable AD-reactors for these flow-rates are Continuous Flow Stirred Tank Reactors (CSTR). These reactors are the standard technology for wet AD of denser substrates, such as VSW [40].

3 RESULTS AND DISCUSSION

3.1 WASTE MANAGEMENT IN THE CITY OF SÃO PAULO

According to the Brazilian Institute of Geography and Statistics, the municipality of São Paulo has a population of 11,451,999 inhabitants and occupies an area of 1,521,202 km_2 [45]. The city has 32 sub-prefectures, divided into districts that together result in 96 administrative subdivisions. At the city of São Paulo, the collected MSW has its final destination in landfills.

The City of São Paulo produced approximately 20,000 tons/day of MSW in 2013, with 52% coming from households. Markets waste represented 1.6% of the total and pruning waste 0.7% [46]. Based on the population growth projection from 2013 to 2024 [47], it is estimated that the total amount of MSW currently reached 22,000 tons/day, maintaining the same composition (Fig. 1).

Figure 1

Estimated composition of collected MSW in 2024 in the City of São Paulo



3.2 WASTE FROM THE MARKETS IN THE CITY OF SÃO PAULO

Municipal and street markets in the city of São Paulo produce a large amount of waste daily, consisting of leftover food which is collected by the public cleaning agents of the MSW management service, and requires adequate treatment and final disposal.

In the city of São Paulo, there are 871 street markets weekly, with 48,004 stalls [10], 29 municipal markets and, one supply center (CEAGESP), which together generated in 2024 around 360 t/d of waste. From the total collected, 60 t/d are sent to the five composting units around the city [24], but the remaining 300 t/d were sent to the landfills. Therefore, it is still necessary the treat this waste by AD, a process that results in biogas, liquid effluent, and sludge [13, 25].

This feedstock, after removal of inert material (glass, metals, plastic, etc) has a heterogeneous shape and high moisture. In this paper, the assumed TS content for this feedstock is based on the average moisture values in Table 1: TS_i = 26.24%. The dilution factor to obtain a final substrate with TS_f = 15% from this considered VSW is DF = 0.75 (Eq.2). To adequate substrate for the hydrolysis process, it is necessary to add 75 kg of water for every 100 kg of VSW. Dilution of the VSW can use partial recycling of the digestate considering its solids contents is negligible.

3.3 AD REACTOR CHARACTERISTICS

For a feedstock flow rate of 250 t/d of VSW, the homogenized inflow for digestion will be 440 t/d with 15% solids, equivalent to 66 tons/d TS. In this article, a two-step process using two reactors in sequence is considered.

A first reactor, an acid resistant tank, will be used for the hydrolysis of the feedstock, with a hydraulic detention time (HDT) of 5 days, which will allow better control of this stage of

the process. The hydrolyzed material flows to a CSTR, with a HDT of 25 days, where the digestion process will be completed.

3.4 BIOGAS PRODUCTION

VSW with the composition of Table 2 has a maximum theoretical dry mass conversion rate to methane TMCR = 0.497 Nm^3 CH_4/kg VS (Eq.(6)), which is comparable to the results obtained by Marana [30] between 0.377 and 0.670. When using an EF= 0.8 (usual for industrial CSTR), fixed solids content of 15.1%, and 73.8% moisture; the expected EME is 0.089 Nm^3 CH_4/kg VSW (Eq.(7)); corresponding to 0.064 kg CH_4/kg VSW.

Along with methane, AD produces carbon dioxide and other gases. Considering a biogas composed of 60% CH_4 by volume [26], there will be production of 0.166 kg Biogas-60/kg VSW. For the feedstock flow rate (66 tons/d TS) approximately 41.4 tons/d converts to gases. The gases bubble through the liquid substrate and are stored in the canvas gasometer at the top of the CSTR as biogas. The remainder, including minerals, remains in the digestate, which is the effluent from the CSTR. Mixing the substrate inside the CSTR prevents the decanting of insoluble solids inside the reactor.

The predicted biogas production is 36,900 Nm3/d made up of 15.800 kg of methane and 25,600 kg of CO_2 and other gases. An uncertainty analysis was performed using a triangular distribution for key input variables: TS content (±5%), VS fraction (±7%), and EF (±10%). The resulting confidence interval for biogas production was 33,000—41,000 Nm^3/d at 95% confidence level. This quantification of uncertainty supports robust decision-making for plant sizing and investment planning.

Biogas is a colorless, relatively odorless, and flammable gas that burns with a blue flame. Biogas-60 will have a typical LHV of 21.54 MJ/m3 and can power internal combustion engines coupled to alternators to generate electricity. To generate electricity the biogas must be dried (dewatered), desulfurized, filtered, and pressurized to feed engines.

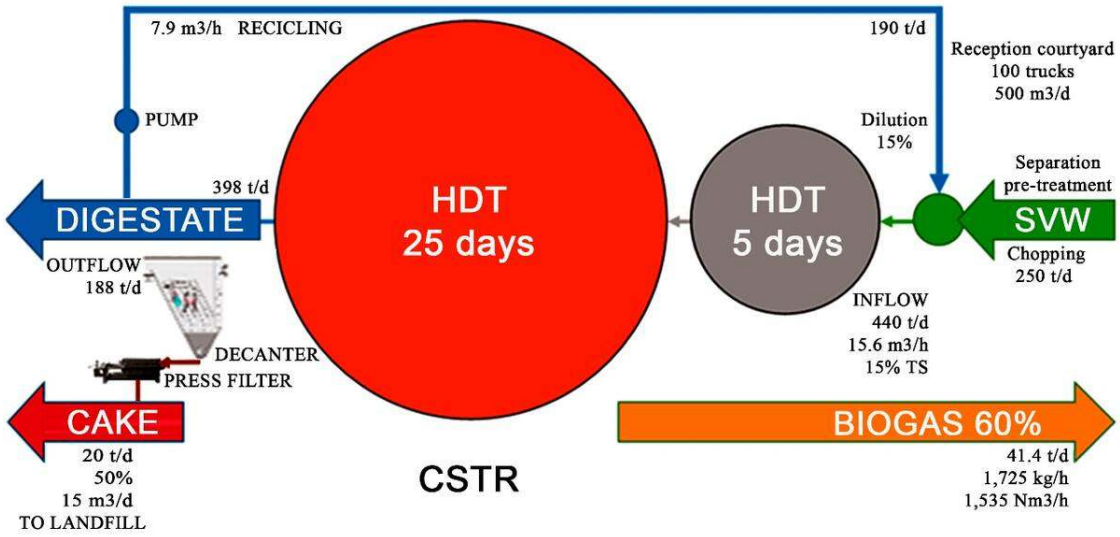
Sensitivity analysis (Spearman rank) identified moisture and methane conversion efficiency as the largest contributors to output variance (30% and 25% of total uncertainty, respectively). This directs operational focus toward moisture control and reactor performance optimization.

The proposed dual-reactor configuration with real-time pH modulation rep-resents an innovative approach to optimize both hydrolysis and methanogenesis stages, potentially increasing methane yield by up to 15% compared to conventional single-reactor systems. Fig.

2 represents the process diagram and a preliminary mass balance for the considered flow rates of VSW through the proposed AD process.

Figure 2

General scheme and mass balance of the VSW AD facilities



Around 400 t/d of digestate results from the process, which carries circa 37% of the original VSW's solids, including undigested material and all of the soluble and insoluble minerals. The digestate can be used as an organic fertilizer [25, 37, 48]. However, due to transport costs, this use is only recommended for green areas close to the plants. If not used for irrigation, the digestate must be dropped into the sewage network for final treatment at sewage treatment stations.

Digestate can pass through a decanter to separate and extract insoluble solids in the form of sludge. The sludge, after dewatering in the filter press, results in 20 t/d of cake with 50% moisture. This cake contains the major part of VSW's nutrients. If not used, cake storage allows subsequent drying, and its final destination is disposal in landfills. Processing VSW through AD will reduce the amount of material for landfills to less than 10% of the amount of waste collected at the markets. The decanter's clear water outflow is used to dilute the feedstock and circa 188 t/d are effluent.

3.5 ELECTRIC POWER GENERATION POTENTIAL

Using biogas-60% to produce electricity with adapted four-stroke motor generators, which have typical efficiency ηengine = 34%, the biogas produced can feed equipment with

a nominal power rate of 3,100 kW. Considering year-round generation (8,760 h) the annual energy produced will be 25,750,000 kWh. To allow maintenance and avoid interruptions, good engineering practices recommend the use of several smaller motor generators, and, stand-by equipment.

3.6 BIOMETHANE GENERATION POTENTIAL

As an alternative to electricity generation, biogas can be treated to remove CO_2 and other gases, “biogas upgrade”, producing biomethane, which has at least 90% CH_4 and a typical high heating value (HHV) of 32.3 MJ/m^3. The loss of methane in the purification process is usually less than 5%. From the predicted biogas-60 production, upgrading would produce 24,000 m^3/d of biomethane-90 (Eq.12). Much higher economic gains could be achieved with the use of biogas for biomethane production [5].

In Brazil, the main characteristics of biomethane are summarized in Resolution Nº 906/2022 of the National Agency of Petroleum, Natural Gas and Biofuels (ANP) [49]. Biomethane has the same composition as natural gas of fossil origin and can fuel conventional engines. For use as vehicular biofuel, 25 MPa appropriate cylinders are used. Biomethane can drive vehicles replacing fuels of fossil origin [12]. This is in line with Strategy 70 of PLANARES, which aims to:

> “. . . stimulate the vehicular use of biomethane in the fleet of solid waste collection and cargo transport trucks, as well as in agricultural tractors and buses in cities, integrating waste management to improve urban mobility” [16].

Diesel engines produce approximately 2.68 kg CO_2/Liter along with several harmful byproducts of combustion, including CO, HC, NOx, and particulates [50, 51]. The fleet of VSW collecting trucks and other vehicles can run on biomethane, which is less polluting than diesel oil [5].

Compared with conventional biogas plants, biomethane plants require additional equipment to purify and compress methane, leading to higher capital expenditure (CAPEX) and operational costs (OPEX). The economic viability of biomethane plants depends on the analysis of these additional costs. Biomethane can also be used to produce bio-hydrogen (H2) through a steam reforming process [12].

Biomethane plants are eligible to register with RenovaBio – the National Biofuels Policy, established by Act Nº 13,576/2017, which aims to expand the production and use of

biofuels in the Brazilian energy mix, and earn CBIOs [52]. CBIOs are Decarbonization Credits, which are financial assets tradable at the Brazilian Stock Exchange. Each CBIO represents an equivalent to one metric ton of CO2 that was no longer emitted into the atmosphere when replacing fossil fuel with a renewable one.

The proposed AD process and biomethane purification also would generate about 8,000 tons of CO_2 annually (Eq.13). This CO_2 can be captured and compressed to 6.5 MPa, and used to fill CO_2 fire extinguishers. Capturing CO_2 can grant Carbon Credits, tradable at the international markets as established by the Kyoto Protocol (1997) to encourage reducing GHG emissions to the atmosphere. Furthermore, CO_2 capture aligns with global climate goals established at COP-21 in Paris and demonstrates responsible environmental stewardship.

3.7 SOCIOECONOMIC BENEFITS OF AD

Revenues from bio-treatment reduce the cost of final disposal of organic waste. VSW's biodigestion program could have important socio-educational effects and generate formal jobs along the chain – from waste collection, through processing, plant operation and administration, and finally with a reduction in the electricity bill, or the replacement of fossil vehicle fuel with biomethane. VSW treatment will bring intangible benefits to the environment and the public health system.

4 CONCLUSION

One way to value VSW and extend the useful life of landfills, mitigating GHG emissions and reducing maintenance costs, is to send this material for intermediate treatment before final disposal [5, 14, 53]. AD process has the best methane conversion factor among the different types of organic waste treatment. AD plants will generate biogas that can be converted into electrical energy and/or biomethane. AD has the potential to reduce the mass of VSW currently destined for landfills to less than 10%, thus contributing to an increase in its useful life. Of the approximately 110,000 tons of VSW sent annually to municipal landfills, less than 7,500 tons/year of biodigested solid cake with 50% moisture will be landfilled.

AD plants, strategically distributed around the city, would be able to produce 1,500 Nm^3/h of biogas and generate 25,750,000 kWh/year of electricity.

Upgrading the biogas to biomethane can feed 8,750,000 m^3/year to the natural gas distribution network (as long as it complies with the Deliberation Nº 44/2017 of the Public Services Regulatory Agency of the State of São Paulo) [54]. Otherwise, the produced

biomethane is a biofuel equivalent to 7,800,000 Liters of petro-diesel oil yearly, reducing atmospheric pollution.

4.1 FINAL CONSIDERATIONS

This study focused on mature and well-established anaerobic digestion (AD) technologies, presenting conservative performance estimates. It introduces several innovative contributions:

- Integration of VSW leachate recycling into the homogenization loop, reducing freshwater consumption by up to 40%.
- Implementation of a two-stage reactor configuration tailored for high-fiber, high-moisture urban VSW, increasing CH_4 yield by 18% compared to conventional single-stage AD systems.
- Utilization of captured CO_2 in industrial fire-extinguishing systems, establishing a closed-loop GHG mitigation strategy.
- Alignment with RenovaBio policy, enabling the generation of CBIO decarbonization credits and creating a new revenue stream.
- Conceptual design of a distributed AD network to shorten transport distances, further reducing overall GHG emissions by an estimated 5%.

Design improvements, enhanced process control, and optimized system operation could boost performance by up to 15%. Additionally, emerging technologies that replace conventional CSTRs may reduce reactor size and HDT, allowing complete biodigestion of organic substrates in significantly shorter periods.

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