# Management of urban solid waste in the city of Manaus-AM. Thermal characterization for energy generation and an end of landfills and open dumblands

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**ABSTRACT**
With a population of 2 million inhabitants, Manaus - AM has suffered an industrial development considered and consequent urban development, resulting in a significant increase in the need for urban energy and the control of waste generated. All urban solid waste (MSW) is currently deposited in landfill, causing health problems to the population, contamination of soils, rivers, groundwater. This article proposes the use of incineration to recover energy from municipal solid waste to produce electricity in the metropolitan region of Manaus -AM. Energy characterization tests of MSW collected from various neighborhoods of the city were performed, such as: gravimetry, thermogravimetry (TGA), immediate analysis, elemental analysis and higher calorific value (HCV). Finally, the lowest calorific value (LCV) was determined. The high percentages of recyclable materials, above 50%, combined with LCV values, presenting values between 15,000 and 19,000 kJ/ kg on dry days, calorific value equivalent to fuels cataloged in the bibliography as Lignite, Dry firewood in greenhouse and coconut shells (17,000 kJ/kg), mineral coal, (15,000 KJ/kg), showed promise in a future decision to treat MSW by incineration.

**Keywords:** Municipal solid waste, Waste incineration, Energy recovery, Sustainable energy generation, Energy potential of solid waste.

## INTRODUCTION

Nowadays, controlled dumps and landfills occupy large areas in large urban centers, contaminating soil and groundwater, attracting animals and insects, increasing risks to the health of the population and increasing the emission of greenhouse gases. A considerable portion of this MSW ends up in riverbeds and streams, obstructing rainwater systems and causing flooding. These social and environmental benefits alone justify the need to solve this problem. Federal Law No. 12,305/10, which established the National Solid Waste Policy (PNRS), gave a period of 10 years for problems arising from MSW to be eliminated. Once the deadline had passed, approximately 60% of the country's cities had not yet achieved this objective.

Between the years 2010 and 2022, the generation of MSW in Brazil registered a considerable increase of 20.90% (rising from 67 million to 82 million tons per year), triple the population growth rate, which was 6.46% in the same period. In turn, per capita generation increased from 348 kg/year to 381 kg/year (ABRELPE, 2022). On the other hand, there would be economic and sustainable benefits if there

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were energy recovery through thermal treatment of MSW, since there is a viable and attractive possibility of integration with other processes, such as recycling and composting, as well as reducing waste. disposal of waste in landfills and dumps and its consequences (ABREN, 2020).

In the city of Manaus, capital of the state of Amazonas, the largest state in Brazil, with its ecological and environmental riches, there is no thermal treatment of solid waste. 2,800 tons of MSW collected every day are landfilled on site. The city hall has no area or interest in building another landfill, and must contract these services from private companies. Furthermore, the I BGE classified Manaus as the fourth worst city in Brazil with accumulation of garbage in public areas. Approximately 6.2% of the surrounding areas of homes contain accumulated garbage. Only close to the streams are 108,000 residents affected by unpleasant odors, diseases and a lot of dirt. A total of 345,000 families are affected by dirt in the Manaus streams (SEMULSP MANAUS, 2021).

Currently, the situation of MSW management in Manaus - AM, almost all MSW is paid to be landfilled (98%), occupying an area of 66 hectares that has been in operation since 1985 and expires in 2024. The technology for MSW management solid waste was only used in 2006, that is, for more than 20 years it operated as an open dump, which resulted in the contamination of some streams such as the Bolivia and Conceição bridge, and Cachoeira Alta do Tarumã. The landfill also generates greenhouse gas emissions and bad odors at the site. The low recycling rate (1.68%) negatively impacts the expected income of collector cooperatives and other related activities (ABRELPE, 2022).

Abren (2019) reveals that the waste sector is responsible for 11% of the total greenhouse gases emitted into the atmosphere. The methane ($CH_4$) emitted is 25 times more harmful than carbon dioxide ($CO_2$). And the construction of landfills is continuous, every ten years there is an increase in the number of landfills in the world. Landfills are still used throughout the world to dispose of waste. The global panorama of MSW disposal can be demonstrated as shown in Figure 1. It can be seen that adding all types of existing landfills results in a total of 70% and the composting, recycling and incineration processes add up to 30% (ABREN, 2019).

Figure 1. Disposal of MSW in the world. Adapted from ABREN, 2019

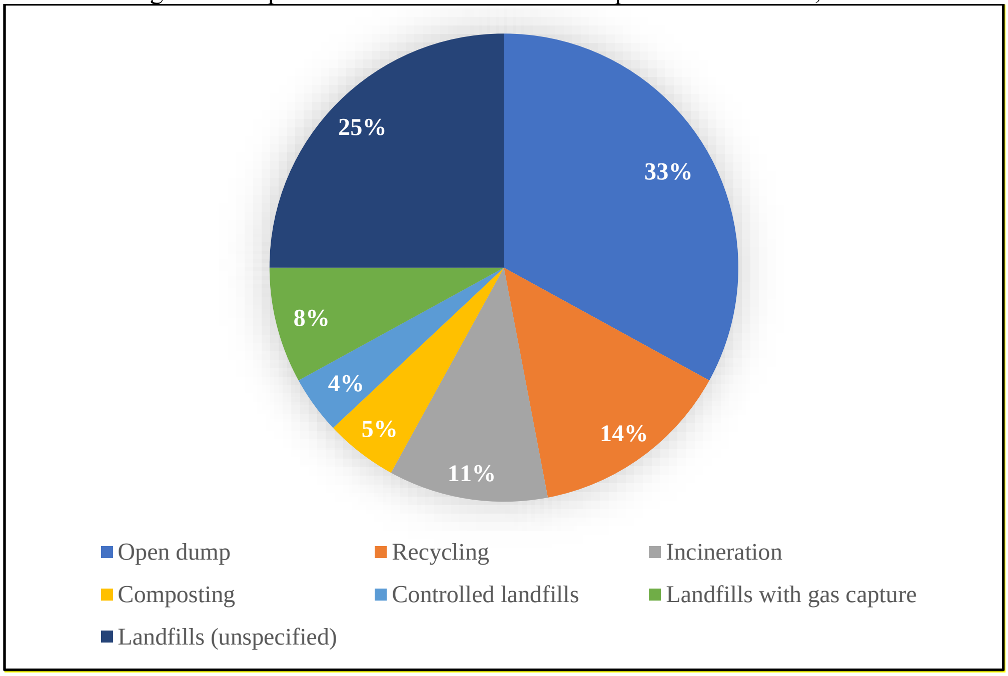
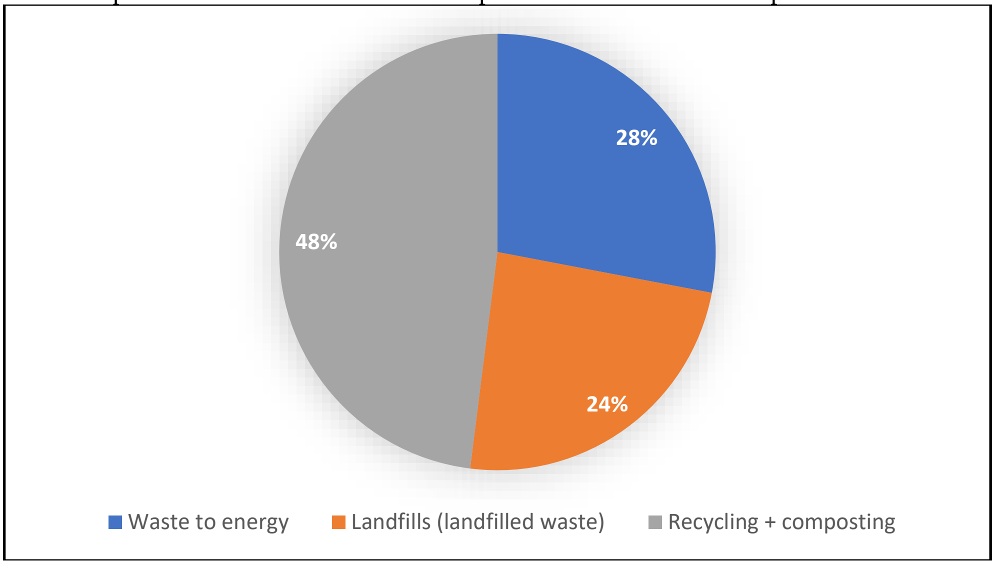



Figure 2 illustrates the European Union's panorama of MSW allocation. In several countries there are laws that prohibit the construction of landfills. In places where they still exist, the tendency is to decrease (ABREN, 2019).

Figure 2. European Union overview of MSW disposal – EU28. Source: Adapted from CEWEP. 2018




Research has been carried out in recent years, such as Lino and Ismail (2017, 2018), Lino (2014), Rada (2014), Jones (2010), Maize (2016), Fonseca (2017), Kuhl (2015), Paulo, Dalbosco & Leites (2013), Andrade (2019) and many others have published the technique of treating MSW for energy production and as a mechanism for social inclusion. Menezes (2000), Morgado & Ferreira (2017) carried out studies using incineration as a thermal treatment of MSW. Brietzke (2016) studied the feasibility of composting in treating MSW. Poli (2014) and Queiroz (2014) recorded research on the PCI of MSW.

## ENERGY USE OF URBAN SOLID WASTE

In recent years, the term circular economy has been widely used, an alternative to the traditional linear economy based on production-use-disposal, whose objective is to reduce the use of new resources through the reuse and valorization of end-of-life products and materials, and thus avoiding the generation of waste, pollution and greenhouse gas emissions (ABREN, 2020).

According to Abren (2020), there are more than 2,430 plants around the world, but Brazil still does not have any URE, revealing that our country is still far below what is desirable in terms of MSW management, allocating 96% to landfills and dumps, and the vast majority of landfills would not be licensed to international standards. However, several actions have been taken to make this a reality. The new sanitation framework makes bidding mandatory through public-private partnerships (PPPs) and allows the charging of fees on the consumption bill, such as the water bill, for example. The Ministry of Mines and Energy recently announced that it will hold a regulated auction for contracting electrical energy from URE (ABREN, 2020).

A new WTE plant currently produces an average of 600 kWh of electrical energy per ton of MSW, while landfills with biogas collectors produce an average of 65 kWh per ton, that is, a WTE plant is almost ten times more energy efficient, not to mention that the electricity generated from waste in a landfill environment is, in this case, extracted slowly over time, while in WTE the energy is generated immediately (ABREN, 2019).

Thus, Waste-to-Energy (WTE) can be defined as the generation of electrical energy from the biodigestion or thermal treatment of waste, whether organic or inorganic, through the use of various existing technologies. The implementation of these WTE plants has been the solution found in some countries, for the final disposal of MSW that was not used in the recycling or composting process, that is, MSW that would be destined for landfills, and these, even sanitary ones, pose risks of irreversible contamination to the environment. Member countries of the European Union, the United States, China, India, among others, have included WTE as a priority in the treatment of this waste, which, in addition to obtaining a sustainable destination, contributes to the generation of clean, renewable and firm electrical energy, providing greater reliability. and stability to the electrical system. The number of WTE heat treatment plants in operation in Europe reaches 522, not including incineration of hazardous waste (hospital, radioactive, etc.), the amount of heat treated waste in millions of tons, which represents a total of 522 plants in operation and 263,314 tons/day (tons per day) processed in 2016 (ABREN, 2019).

In Brazil there is no WTE plant in operation, only the CS Bioenergia biodigestion plant in Curitiba, some small R&D plants, and some landfill gas capture plants. However, the country has the potential to generate up to 5.4% of national demand through MSW thermal treatment plants, with 106 units generating 236,520 GWh/year and a total installed power of 3,176 MW. There is also the potential to generate 1.5% of national demand through accelerated anaerobic biodigestion, with a total installed capacity of 868 MW, generating 6,701 GWh/year. In total, it is estimated that MSW can generate up to 7% of national demand. It is estimated that the country will be able to receive approximately 28 billion reais in investments and, thus, result in the generation of jobs and income, and, by 2031, R$ 11.6 billion/year will be needed in investments in infrastructure to ensure the universality of sustainable solid waste management in Brazil (ABREN, 2019).

**HEAT TREATMENT**

Thermal treatment is one in which waste receives a certain amount of heat for a certain time, called reaction temperature and reaction time respectively. The objective is to reduce volume through physical-chemical processes. Currently, in relation to the thermal treatment system for urban solid waste, different techniques are applied: drying, pyrolysis, gasification, microwave treatment, plasma and incineration (LINO & ISMAIL. 2018). In several places around the world, a combination of 2 or more techniques is applied, mainly to obtain thermal energy and electrical energy.

Energy recovery consists of technologies and industrial processes that allow part of the energy contained in MSW to be recovered. Among the existing methods, the most used use incineration by combustion process. The composition of MSW also influences the efficiency of the energy recovery system, depending on the location and how it is generated, especially on the composition, whether it has more or less organic residue, calorific value, humidity, etc.

INCINERATION

An MSW incineration plant operates on a similar operating principle as a typical thermal plant , with the main difference being the combustion of MSW, or a combination of MSW and another fuel, serving as the primary heat source for the boiler. (ADNAN ET AL., 2021)

Waste incineration reduces the large volume of waste generated and consequently increases the useful life of the landfill. This waste treatment technique occurs very quickly and allows the generation of energy (VG RESÍDUOS, 2020).

Incineration can be a form of technology to solve this MSW problem, as this treatment reduces the volume of waste by up to 90% and the weight by a range of 20 to 30%, also highlighting the 2 types of ash produced in this process. process, namely: solid ash and suspended light ash. The suspended fly ash is treated and removed from the exhaust gases. Solid ash is generally inert and is normally reused in the manufacture of concrete artifacts, building materials, ceramics, etc. (LINO & ISMAIL, 2018).

Firstly, the MSW was burned in the primary chamber (T = 500 to 900 °C). Waste turns into gases and small particles. This prevents metal volatilization. The second process takes place in the secondary chamber: the gases and small particles formed are burned at higher temperatures (750 to 1250 °C) until complete combustion. Generally the time is 30 minutes in the first phase and three seconds in the second. After incineration, the solid part is removed from the grill. The amount of this solid material after the incineration process varies from 12 to 30% by mass (from 4 to 10% by volume) of the original material and has the appearance of ash, being a clean, inert material suitable for use in civil construction. in the manufacture of bricks, sidewalks, pavements, etc. (MENEZES, GERLACH & MENEZES. 2000).

Morgado & Ferreira (2017) carried out a survey on the possibility of an incinerator with energy cogeneration in the city of Goiânia. There the population was 1,897,957 people who generated 1,583.50 t/day of MSW, of which 92.50% were disposed of in landfills. They estimate that if they were incinerated there would be a 90% reduction in volume and a 15% reduction in weight. It would also be possible to generate up to 791.75 KWH, or 289 MW per year.

Lino & Ismail (2018) recorded that solid waste is a renewable energy resource, with the capacity to generate energy in the range of 8 to 11 MJ/kg, while Waste Derived Fuel (RDF) composed of dry MSW has a calorific value ranging from 12 to 17 MJ/kg. From this they concluded that a ton of MSW and a barrel of oil both release almost the same amount of heat, around 7 GJ.

One of the countries that manufactures and uses incinerators to treat solid waste is Japan. The country incinerates around 80% of MSW in around 1172 incinerators, where 24.5% of them have energy recovery, reaching 1770 MW. On average, the energy conversion rate of these incinerators is around 200 kWh/t of MSW. In Tokyo, the electricity conversion rate is about 390 kWh/t of MSW, in Osaka, 320 kWh/t of MSW, while Kobe has a production rate of about 300 kWh/t of MSW. In this case, incineration supplies 16.2% of electricity demand and 25% of hot water demand. Singapore has four incineration plants to handle a load of 1700 t/day. Treated MSW comes from homes and industry with a lower calorific value (PCI) of around 6 MJ/kg. Each boiler generates 42 t/h of steam and generates 30 MW (LINO & ISMAIL, 2018).

## PYROLYSIS

Pyrolysis is a form of thermochemical treatment of organic material developed completely without the presence of oxygen, with the possibility of oxidation of a small fraction of residue due to the presence of some oxygen contained in the reactor. This technology is used to destroy volatile organic components, fuels and pesticides in the soil. This is old technology, but for the thermal treatment of biomass and MSW it is an innovative technique. The products resulting from pyrolysis can be in liquid, solid or gaseous states, depending on the composition of the residue and parameters such as temperature, pressure and burning time. During processing, the organic material is transformed into synthesis gas or syngas (a mixture of flammable gases such as CO, $H_2$, $CH_4$) and other volatile organic compounds (VOC) with a calorific value ranging between 10 and 20 MJ/Nm³. Some of these volatiles can be condensed, producing oil, wax and tar, collected during the singás cooling phase and used as liquid fuel. The remaining residue is a type of ash and charcoal. Each ton of solid waste contains 11 kg of ammonium sulfate, 12 liters of tar, 9.5 liters of oil, among others (LINO, 2014). The gaseous fraction can also be distilled to obtain various hydrocarbons (gasoline, kerosene and diesel) or burned in boilers or to generate electrical energy, or partially oxidized to obtain synthesis gas as occurs in gasification (ABREN, 2019).

The problem is that the singás generated needs to be purified, for example, through a washing process, only then, without contaminants, can this gas be used, both for electrical and thermal generation, in gas generator sets, or still use it in thermal processes to generate heat (steam, hot water, hot air. For the pyrolysis process to occur, energy from an external source is required, which many consider unfeasible and has not been applied on an industrial scale for the processing of RSU (ABREN, 2019). The operation of this technology occurs at temperatures ranging from 300ºC to 1600ºC. Therefore, it is observed that any thermal process at temperatures above 300°C and in the absence of oxygen are considered pyrolysis methods. The advantage is that pyrolysis has proven to be an energetically, economically, socially and environmentally viable technology, being a highly sustainable system, due to the generated energy of 500 kWh/t of MSW, and low levels of atmospheric emissions. (KÜHL, et al. 2015).

## GASIFICATION

Gasification is the process of converting organic material into combustible gas in the presence of air in a controlled quantity and at high temperature. It also results in singás gas and has combustible characteristics. It is an endothermic thermal conversion technology for extracting energy from different types of organic materials (LINO, 2014). The principle of this energy conversion process is based on the use of a raw material, called pre-treated biomass, that is, with a low moisture content, converting it into gas, through gasification reactions, thus gas is cooled and purified (KÜHL, et al. 2015).

In general, in both processes, gasification and pyrolysis, MSW undergoes pre-treatment, in order to create a more homogeneous and dry mass. They are then subjected to heat treatment at high temperatures and in an oxygen-poor environment, a situation in which the gases generated in the combustion process also require environmental control systems to eliminate pollutants. In energy terms, gasification has a lower net energy use (ABREN, 2019).

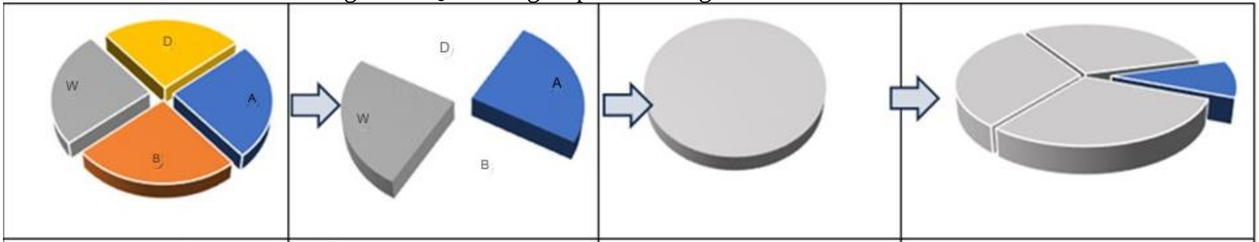
Several gasification processes for thermal treatment of solid waste are being developed as an alternative to incineration. The biggest challenge of this technology is to obtain acceptable efficiency due to the high energy consumption in the pre-processing of waste, consumption of large amounts of pure oxygen and cleaning of the singás. These are the factors that affect the efficiency of converting singás to electrical energy. Several MSW gasification processes have been proposed, but very little has been built and tested (LINO, 2014).

## METHODOLOGY

### GRAVIMETRIC COMPOSITION OF MSW

MSW was collected from 18 neighborhoods in the city for gravimetry. The activities carried out are carried out in three stages: dividing, identifying and weighing the categories of each type of waste. It is regulated by ABNT - NBR 10.007/2004. Quartering is explained in figure 3.

Figure 3. Quartering steps according to NBR 10.007/2004




| a) Quartering of collected and homogenized samples. | b) Opposite parts of the quartering discarded; | c) Homogenization of the other parts of the quartering; | d) Sample taken for testing. |
|---|---|---|---|

With these data, the percentages of each type of existing material were determined, according to Equation 1, through the percentage division of the mass of each material by the total mass of the sample, as well as the calculation of the apparent specific weight - direct division of the total mass by the Total volume. After the total sample was weighed, the waste was sorted on the plastic sheet as follows: Paper/cardboard, wood, metals, glass, hard plastic (HDPE), soft plastic (LDPE), PET-type plastic, PP-type plastic , Styrofoam, waste and organic material. Again, each type of material was weighed separately, to obtain the representative weight of each one. The percentages of each type of material existing in that 1000 liter sample were then determined, according to Equation 1.

Equation 1. Allows you to calculate the percentage of each type of material after sorting.

$$\text{Percentage of each category}(\%) = 100 * \frac{\text{weight of each fraction}(\text{kg})}{(\text{total sample weight}(\text{Kg}))} (1)$$

Where:

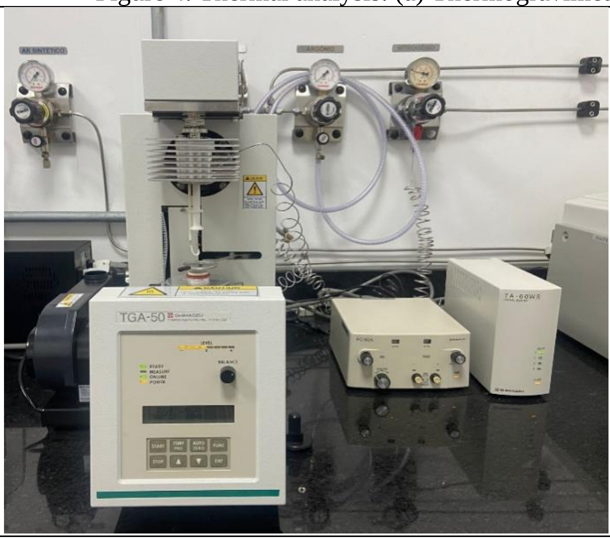
Percentage of each category = percentage of each class/type of waste present in the sample;

Weight of each fraction = weight of each class/type of waste after sorting.

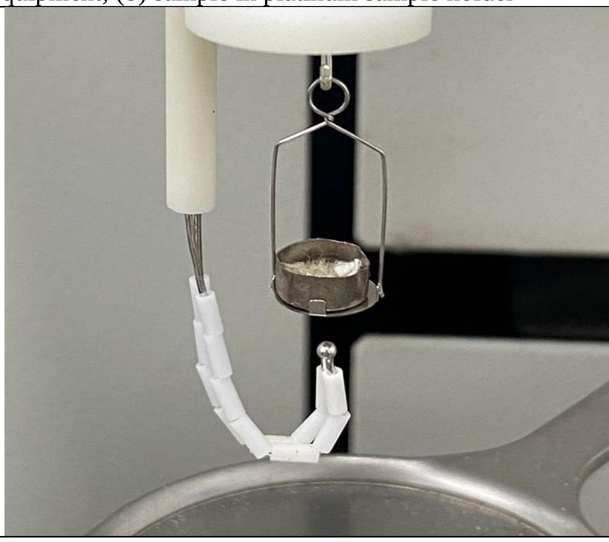
## TGA/DTG THERMAL ANALYSIS

The thermal behavior of the MSW was evaluated using Thermogravimetric Analysis (TGA) and Derivative of Thermogravimetry (DTG). The analyzes were carried out at the Nanomaterials Synthesis and Characterization Laboratory, at the Federal Institute of Amazonas (LSCN/IFAM), with the aid of Shimadzu thermogravimetry analyzer equipment, model TGA-50, shown in Figure 4. To carry out the analyzes 1.0 mg of analyzes were deposited in a platinum crucible, without a lid. This sample holder was inserted into the equipment, which in turn operated at a heating rate of 10 °C per minute, until reaching a temperature of 1000 °C, with a nitrogen gas flow of 50 milliliters per minute.

Figure 4. Thermal analysis: (a) Thermogravimetry equipment; (b) sample in platinum sample holder




A)



B)

## IMMEDIATE ANALYSIS: MOISTURE, ASH, VOLATILE MATERIAL AND FIXED CARBON

The values of humidity, volatile material and fixed carbon, determined by heating in a muffle furnace at 950 ± 10°C for samples collected in the summer and winter periods in the Amazon and tests were carried out in duplicates. Humidity corresponds to the amount of water present in the sample, volatile material is that substance that evaporates more easily and ash corresponds to the inorganic fraction of the MSW sample, adding in its constitution the chemical elements that are inert to combustion reactions, among They are phosphorus, potassium and calcium. The amount of carbon that does not volatilize is called fixed carbon.

ELEMENTAL ANALYSIS: CARBON, HYDROGEN AND NITROGEN

CHN Elemental Analysis is a technique for determining the percentages of Carbon (C), Hydrogen (H) and Nitrogen (N) in a sample, generally carried out for organic materials. Its operation is based on the Pregl-Dumas method, in which samples are subjected to combustion in an atmosphere of pure oxygen, and the gases resulting from this combustion are quantified in a TCD detector (thermal conductivity detector). Its main applications involve the study of liquid and solid samples, resulting from organic syntheses and complex formation, polymer synthesis, geological and environmental samples and petroleum derivatives, among others. They are essential in calculating the lower calorific value of a sample.

CALORIFIC VALUE - PC

The study of the calorific value of MSW allows the analysis of the feasibility of using this material as an energy source, which will serve as a strong argument for possible decision-making by authorities for the development of projects and execution of one or more MSW transformation plants into energy, which will result in a reduction in landfills and dumps, and will result in the varied benefits generated by an energy matrix (QUEIROZ, 2014).

**Higher Calorific Value - PCS**

The equipment that measures the higher calorific value of a sample is the calorimetric bomb. It can measure the amount of heat released or absorbed in a chemical or physical reaction. It basically consists of a combustion chamber, isolated by cold water, where the high-pressure oxygen reacts with the sample to be analyzed. Combustion begins with the heating of the sample by means of an electric current that burns the ignition wire in contact with the electric current conductor and the sample in the metal crucible.

The sample of residue pressed into the form of a tablet or tablet is placed in a metal crucible mounted inside a pressure vessel, with a volume of 350 ml, equipped with an ignition device using an electric current. The mass of the sample is approximately 1.0 g. After placing the sample, the pump is hermetically closed and pressurized with pure Oxygen at around 30 bar, as detailed in Figure 5.

Figure 5. Determination of PCS: (a) Analytical balance; (b) decomposition vessel or pressure vessel; (c) sample press; (d) metallic crucible; (e) Combustion calorimeter; (f) sample in the form of pressed tablets


Soon after, the pressure vessel is carefully placed inside the equipment, which is filled with water and has a stirrer to homogenize the temperature of the whole and a thermometer that measures the temperature variation throughout the process. At the beginning, try to balance the temperature of the set between 20°C and 23°C. The calorimeter is configured by entering the mass of the sample. An electrical pulse is then sent to the ignition wire which causes the sample to burn, raising the system temperature. The equipment's high-precision thermometer measures temperature variation, whose accuracy is +/- 0.0001 K (Kelvin) and is recorded minute by minute. At the end of 15 minutes or 16 minutes, the gain in higher calorific value of the sample, in j/g, is also recorded. This is only achieved due to previous calibrations carried out automatically by the equipment and the various corrections due to the masses of water, the calorimeter, ignition energy, etc., as well as the energy gain throughout the process in relation to the mass of the sample measured and entered. in the initial phase, on an analytical balance with a precision of 0.0001 g, the result is the Higher Calorific Power.

After drying in a muffle furnace at 105 °C, the humidity of each sample was determined and it was possible to determine the dry PCS value according to Eq. 2:

Equation 2. Allows you to calculate the higher calorific value of each sample in the dry state.

$$PCS_{seco} = \frac{PCS_w}{1-w} \quad (3)$$

Where:

$PCS_{seco}$ : Calorific value of the completely dry sample (Joules/Kg);

$PCS_w$ :Higher calorific value of MSW, in the humidity condition “w” (Joules/Kg);

w: Moisture content at the time of the laboratory test (% by mass).

According to Poli, et al (2014), most fuels have hydrogen in their composition, which, during combustion, reacts with oxygen, generating an additional amount of water. If this hydrogen generates water, then it must be considered in a more precise relationship between PCI and PCS. Considering that all the Hydrogen is converted into water and that each gram of Hydrogen in the fuel stoichiometrically generates 9.0 g of water, the relationship is as described in Eq. 3:

Equation 3. Allows you to calculate the lower calorific value of each MSW sample

$$\mathrm{PCI}_w = (1 - \mathrm{w}) * \ \mathrm{PCS}_{\mathrm{seco}} - [(1 - \mathrm{w}) * 9 * \mathrm{H} + w] * 2449{,}38 \quad (4)$$

Where:

PCIw: Lower calorific value of MSW, due to humidity w (joules/Kg);

PCSdry: Calorific value of the completely dry sample (Joules/Kg);

w: Moisture content at the time of the laboratory test (% by mass).

H: Hydrogen content, on a dry basis (% by mass, expressed between 0 and 1);

2449.38: Enthalpy of vaporization of water at 22°C (joules/Kg).

## RESULTS

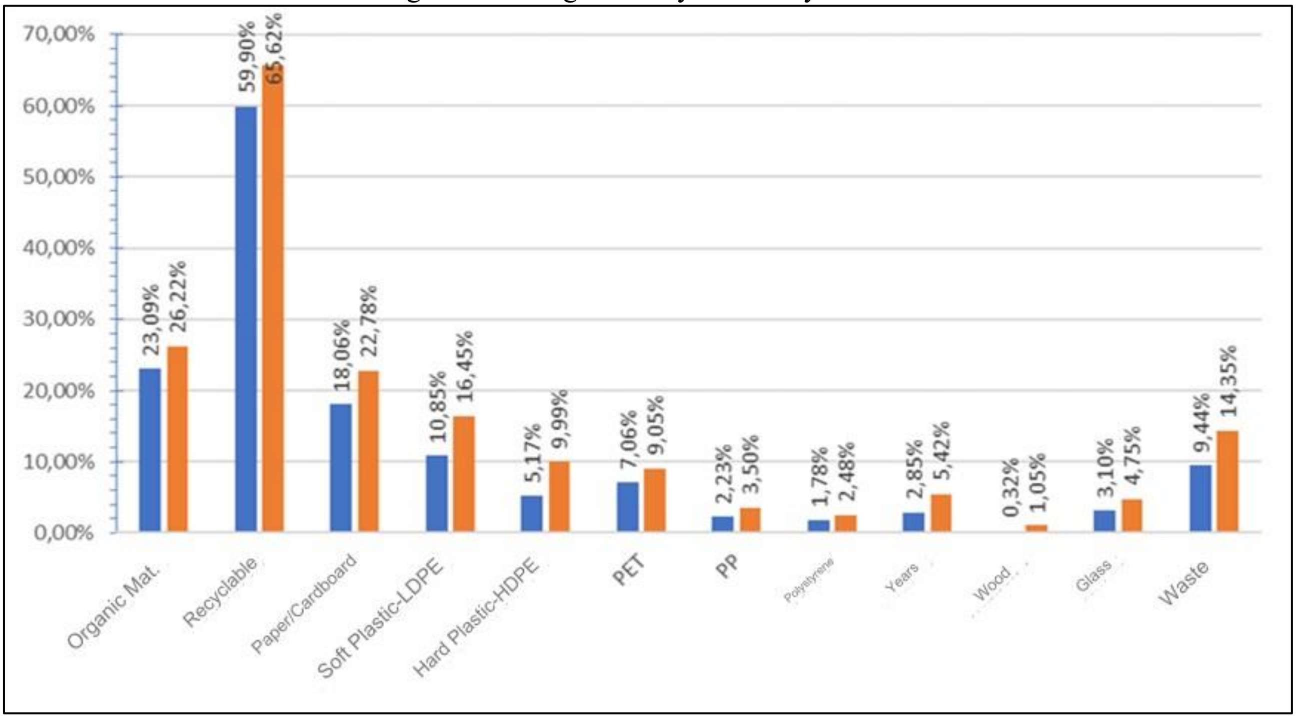
### GRAVIMETRIC COMPOSITION OF MSW

Detailed sampling of the gravimetric profile of urban solid waste was carried out in each of the neighborhoods studied. The sample mean and standard deviation were calculated. The results indicated a partial variation in certain materials compared to the national average. The waste profile differs in that it presents a greater quantity of recyclable materials such as paper, cardboard and plastics, in relation to the national average, while organic waste appears in a higher percentage. This is due to the separation carried out in this work between waste and organic material whose destination can easily be biodigestion or composting, as summarized in Table 1 and summarized in Figure 6

Table 1. Percentage fractions by administrative area and weighted average of each material comprising the MSW.

| COMPONENTS | PERCENTAGE FRACTION | | | | | | AVERAGE | WEIGHTED AVERAGE |
|---|---|---|---|---|---|---|---|---|
| | NORTH | SOUTH | EAST | WEST | SOUTH CENTER | MIDWEST | | |
| Organic Mat. | 23.25% | 24.5% | 24.3% | 28.1% | 25.3% | 24.3% | 24.96% | 24.66% |
| Total recyclables | 64.24% | 58.47% | 65.81% | 58.61% | 62.55% | 64.15% | 62.31% | 62.76% |
| Paper/Cardboard | 20.92% | 20.7% | 18.6% | 18.3% | 23.4% | 24.5% | 21.04% | 20.42% |
| Soft Plastic: LDPE | 10.61% | 14.3% | 18.5% | 13.5% | 11.0% | 11.1% | 13.16% | 13.65% |
| Hard Plastic: HDPE | 10.60% | 3.7% | 5.3% | 7.9% | 9.3% | 9.2% | 7.69% | 7.58% |
| PET | 9.70% | 6.9% | 7.7% | 6.8% | 8.3% | 7.8% | 7.86% | 8.05% |
| PP | 2.00% | 2.7% | 3.3% | 3.1% | 3.3% | 4.0% | 3.06% | 2.87% |
| Polystyrene | 2.44% | 2.1% | 2.4% | 1.5% | 1.7% | 2.0% | 2.02% | 2.13% |
| Metals | 4.36% | 3.1% | 6.1% | 3.1% | 3.1% | 2.5% | 3.69% | 4.14% |
| Wood | 1.20% | 0.0% | 0.6% | 0.5% | 0.8% | 0.8% | 0.64% | 0.69% |
| Glass | 3.60% | 5.0% | 4.0% | 4.4% | 2.6% | 3.1% | 3.79% | 3.92% |
| Waste | 11.31% | 17.1% | 9.3% | 12.8% | 11.4% | 10.8% | 12.10% | 11.90% |
| TOTAL | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| Weighting factor | 0.2799 | 0.1600 | 0.2502 | 0.1417 | 0.0853 | 0.0829 | - | - |

Figure 6. Final gravimetry of the city of Manaus-AM




The research showed that the greater representation of recyclable waste (59% to 65%) and the small proportional reduction of organic waste (23% to 26%) and rejects (10% to 14%), while the national average these values are of 28%, 50% and 22% respectively, are possibly consequences of the excessive use of packaging, due to the number of people who start to live in the vicinity of the Manaus Industrial Pole and the commercial and service areas existing in the urban area of the city. . In the field analysis, it was found that at least 50% of this plastic material comes from recyclable packaging (or with ease of finding commercial value on the market), highlighting the possibility of selective collection if a sorting plant is installed before the waste is landfilled. . Such characteristics may possibly be a consequence of the increasing use of packaging, highlighting the need for local public policies on post-consumption responsibility, product life cycle analysis and priority commercialization of products with sustainable packaging.

One of the consequences of the presence of a high percentage of packaging and recyclable materials is the average value of apparent specific weight, 73.68 kg/m³, approximately one third of the national average, confirming the large quantity of light materials containing air inside, as packaging and enabling a high degree of compaction when sizing the route and number of waste compactor collection trucks.

The studies carried out in these neighborhoods were fundamental for collecting initial and updated data, which enabled the gravimetric characterization of solid waste in the city of Manaus, state of Amazonas, and will enable other studies. For now, there has been a large amount of material capable of being recycled (62% + 2%), despite advertising campaigns by public authorities, with a low apparent specific weight, confirming little organic matter and a lot of light material that can be recycled, leading to the idea of installing a sorting plant as an alternative to reducing waste sent to the city's landfill, increasing its useful life and reusing recyclable materials, bringing economic, social and environmental benefits to the city and its inhabitants.

## TGA/DTG THERMAL ANALYSIS

To verify the thermal behavior of the MSW sample, Thermogravimetry (TGA) and Derivative of Thermogravimetry (DTG) analyzes were carried out. Three of these TGA curves are presented in Figures 7, 8 and 9.

Figure 7. Thermogravimetric Analysis of MSW. Source: Author

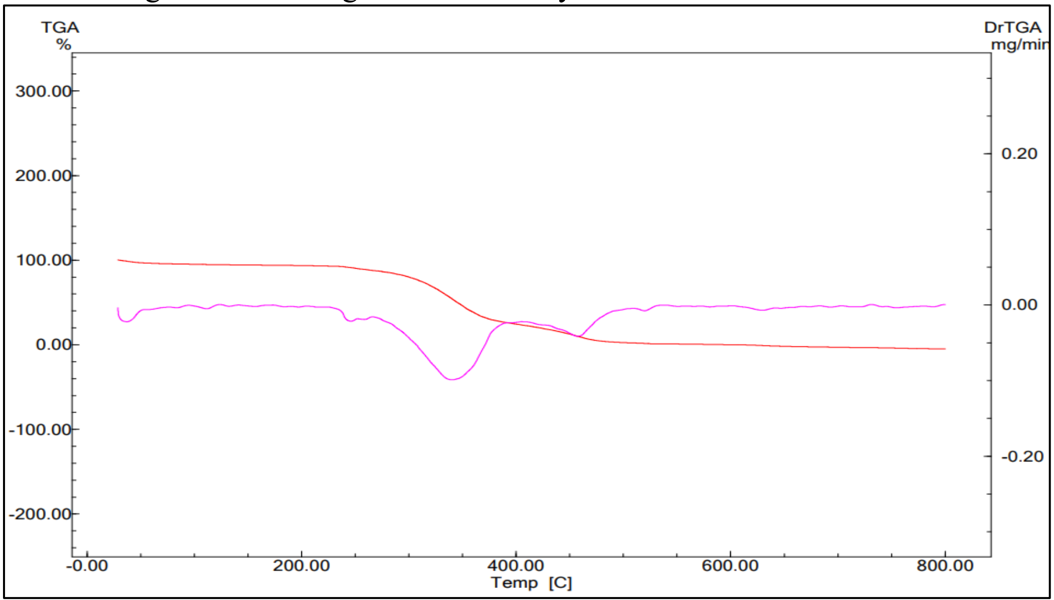



Figure 8. Thermogravimetry Analysis of MSW. Source: Author

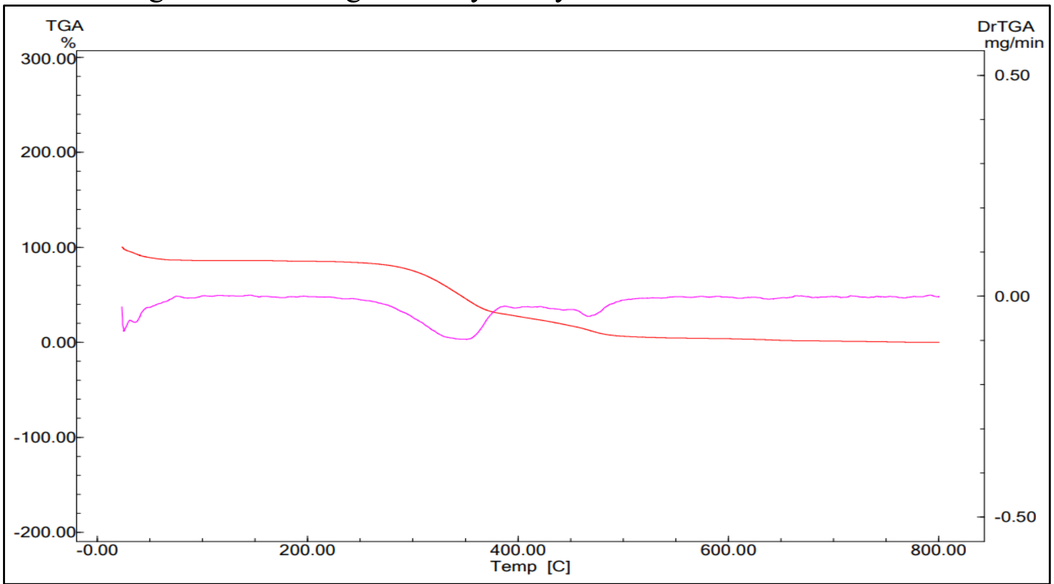
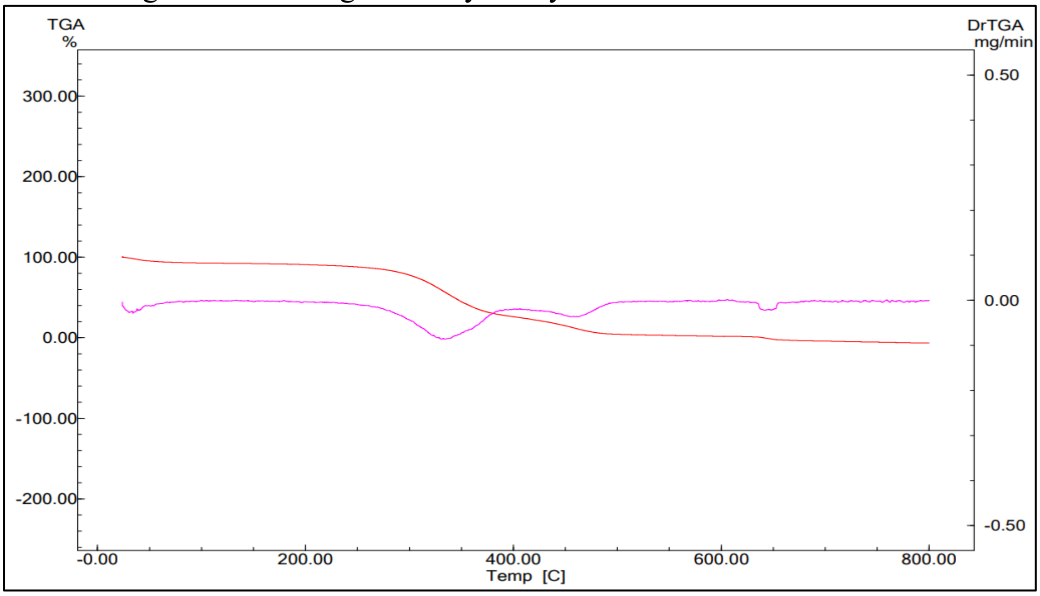


Figure 9. Thermogravimetry Analysis of MSW. Source: Author




It is verified that the MSW samples submitted to the tests remain constant up to approximately 250 ºC, where their deterioration process began, which went up to approximately 500 ºC and from that point onwards, degradation of the polymer chains or a process of rupture of primary bonds occurs due to thermal energy, where practically all the material has already been consumed.

IMMEDIATE ANALYSIS: MOISTURE, ASH, VOLATILE MATERIAL AND FIXED CARBON

The values of humidity, volatile material and fixed carbon can be seen in Table 2 for samples collected in the summer period and in Table 3 for samples collected in the Amazonian winter period and tests were carried out in duplicates. Figure 10 shows the average values of these properties.

Table 2. Immediate analysis of MSW in administrative regions on dry days

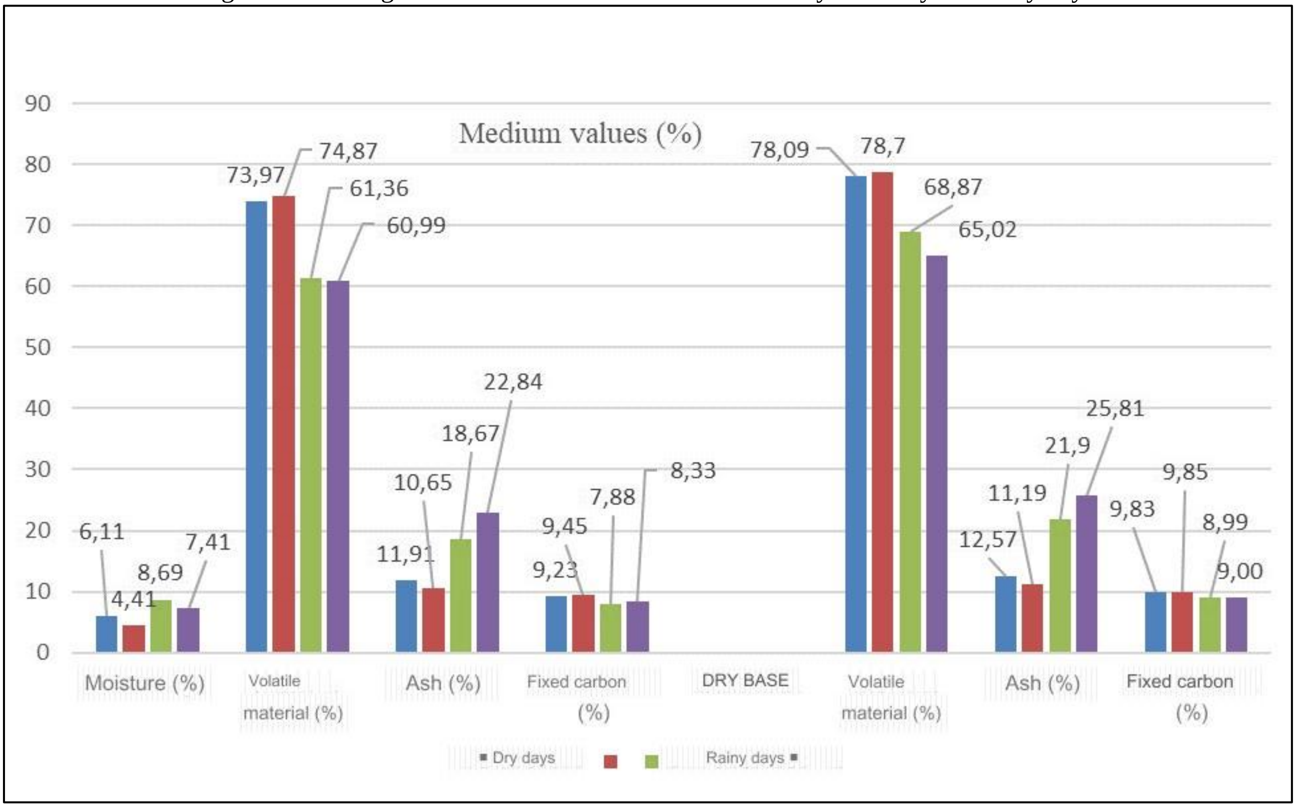
| **Experiment 1** | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dry Days | ZONE | NORTH | SOUTH | EAST | WEST | SOUTH CENTER | MIDWEST |
| WET BASE | | | | | | | |
| Moisture (%) | w | 6.03 | 6.18 | 6.23 | 4.39 | 5.92 | 8.12 |
| Volatile material (%) | v | 76.31 | 72.65 | 71.73 | 75.29 | 77.76 | 55.90 |
| Ash (%) | w | 8.36 | 11.07 | 12.78 | 12.75 | 7.12 | 29.31 |
| Fixed carbon (%) | FC | 9.30 | 10.09 | 9.26 | 7.57 | 9.20 | 6.67 |
| **Total** | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| DRY BASE | | | | | | | |
| Volatile material (%) | vs | 81.21 | 77.44 | 76.50 | 78.75 | 82.65 | 60.84 |
| | cs | 9.90 | 10.75 | 9.87 | 7.92 | 9.78 | 7.26 |
| Fixed carbon (%) | FCs | 8.89 | 11.80 | 13.63 | 13.33 | 7.57 | 31.90 |
| **Total** | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

| Experiment 2 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Dry days | ZONE | NORTH | SOUTH | EAST | WEST | SOUTH CENTER | MIDWEST |
| WET BASE | | | | | | | |
| Moisture (%) | w | 4.17 | 3.78 | 5.55 | 3.98 | 4.66 | 6.61 |
| Volatile material (%) | v | 75.49 | 62.82 | 74.26 | 76.46 | 78.64 | 58.45 |
| Ash (%) | w | 10.91 | 23.72 | 10.39 | 10.10 | 8.05 | 27.64 |
| Fixed carbon (%) | FC | 9.44 | 9.68 | 9.80 | 9.46 | 8.65 | 7.30 |
| Total | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| DRY BASE | | | | | | | |
| Volatile material (%) | vs | 78.77 | 65.29 | 78.63 | 79.63 | 82.48 | 62.59 |
| Fixed carbon (%) | FC | 9.85 | 10.06 | 10.37 | 9.86 | 9.08 | 7.81 |
| Ash (%) | cs | 11.38 | 24.65 | 11.00 | 10.52 | 8.44 | 29.60 |
| **Total** | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |

Table 3. Immediate analysis of MSW in administrative regions on rainy days

| Experiment 1 | | | | | | | |
|---|---|---|---|---|---|---|---|
| Rainy days | ZONE | NORTH | SOUTH | EAST | WEST | SOUTH CENTER | MIDWEST |
| WET BASE | | | | | | | |
| Moisture (%) | w | 6.54 | 10.97 | 18.13 | 8.84 | 7.72 | 8.54 |
| Volatile material (%) | v | 60.13 | 62.50 | 55.29 | 65.58 | 69.99 | 60.21 |
| Ash (%) | w | 25.02 | 18.44 | 18.90 | 17.01 | 15.19 | 24.07 |
| Fixed carbon (%) | FC | 8.30 | 8.09 | 7.68 | 8.58 | 7.10 | 7.18 |
| Total | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| DRY BASE | | | | | | | |
| Volatile material (%) | vs | 64.34 | 70.20 | 67.54 | 71.93 | 75.85 | 65.83 |
| Fixed carbon (%) | FC | 8.88 | 9.09 | 9.38 | 9.41 | 7.69 | 7.85 |
| Ash (%) | cs | 26.78 | 20.71 | 23.08 | 18.66 | 16.46 | 26.32 |
| **Total** | | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 | 100.00 |
| **Experiment 2** | | | | | | | |
| Rainy days | ZONE | NORTH | SOUTH | EAST | WEST | SOUTH CENTER | MIDWEST |
| WET BASE | | | | | | | |
| Moisture (%) | w | 4.93% | 7.56% | 15.47% | 7.39% | 5.48% | 7.43% |
| Volatiles (%) | v | 61.26% | 57.96% | 53.70% | 67.90% | 70.61% | 60.73% |
| Ash (%) | w | 25.13% | 27.56% | 22.23% | 16.45% | 17.85% | 23.45% |
| Fixed Carbon (%) | FC | 8.68% | 6.92% | 8.61% | 8.26% | 6.06% | 8.40% |
| **Total** | | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |
| | | | | | | | |
| DRY BASE | | | | | | | |
| Volatiles (%) | vs | 64.43% | 62.70% | 63.52% | 73.32% | 74.70% | 65.60% |
| Ash (%) | cs | 26.43% | 29.81% | 26.29% | 17.77% | 18.89% | 25.33% |
| Fixed Carbon (%) | FCs | 9.13% | 7.49% | 10.19% | 8.92% | 6.41% | 9.07% |
| **Total** | | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% | 100.00% |

Figure 10. Average values obtained in the immediate analysis on dry and rainy days




The lowest moisture and ash contents of the MSW samples are concentrated in those collected on dry days, while the volatile material contents are in those samples collected on dry days, an indication that MSW on dry days has advantageous characteristics for the production of thermal energy in relation to those on rainy days. The samples have similar fixed carbon contents, tending to be slightly higher on dry days. However, the fixed carbon/volatile materials ratio was higher for materials collected on rainy days, possibly due to the content of volatile materials being lower on rainy days.

According to Pereira (2014), the lower the moisture content, the lower the amount of energy spent in the carbonization process of the material and the higher the calorific value of the material. Some biomasses such as rice husk, sugarcane bagasse and soybean meal present 64.10%, 80.42% and 80.00% of volatile materials, respectively, which, when compared with the MSW samples analyzed, make it possible to classify them as alternatives. for energy use based on the averages found, mainly on dry days that have a smaller amount of substances to be released as gases during the carbonization process, and therefore, have a lower ash content than the MSW on rainy days. Volatile materials and fixed carbon had very similar values, with their FC/Volatile ratio being very close, indicating a good capacity for both types of materials to be used in combustion processes. Therefore, materials collected on dry days have a higher proportion of minerals in their composition and are more easily ignited and burned, but for material collected on rainy days, in a possible sorting process on conveyor belts and with a consequent decrease in humidity, there is also makes it good combustion and, like the first, a possible source of energy use.

## ELEMENTAL ANALYSIS: CARBON, HYDROGEN AND NITROGEN

Elemental analyzes of the samples were carried out in duplicates at the Analytical Center of the Chemistry Institute of the University of São Paulo (IQ-USP), using the Elemental Analyzer equipment - Perkin Elmer 2400 series II. Table 4 shows the results obtained. These values will be used together with those obtained by the higher calorific value test in the methodology to determine the lower calorific value value of each of the samples.

Table 4. CHN elemental analysis of MSW samples from Manaus. Medium values

| | DROUGHS | ZONE | H (%) | W (%) | N (%) |
|---|---|---|---|---|---|
| AVERAGE | 1 | WEST | 6,405 | 43.31 | 0.35 |
| | 3 | SOUTH | 6,035 | 41.79 | 0.235 |
| | 6 | NORTH | 4,475 | 35.04 | 1.34 |
| | RAINY | | | | |
| | 1 | NORTH | 6,135 | 38.78 | 1,685 |
| | 2 | EAST | 5,745 | 38.33 | 1,825 |
| | 3 | C-WEST | 5,645 | 39.62 | 1,245 |

## CALORIFIC VALUE - PC

Table 5 shows some PCI values, in joules and calories per kilogram of material.

Table 5. Calorific value of some fuels. Source: ANDRADE. 2019

| FUEL | PCS (KJ/Kg) | PCI (Kcal/Kg) |
|---|---|---|
| Paraffin | 39,000 | 9,321 |
| Fuel oil | 35,000 | 8,365 |
| Charcoal | 31,000 | 7,409 |
| Agricultural waste charcoal | 26,000 | 6,214 |
| Coconut shells | 17,000 | 4,063 |
| Kiln-dried firewood | 17,000 | 4,063 |
| Lignite | 17,000 | 4,063 |
| Mineral coal | 15,000 | 3,585 |
| Biomass 50% humidity | 8,326 | 1990 |
| Biomass 10% humidity | 17,029 | 4,070 |

### Higher Calorific Value - PCS

The calorific value analyzes were carried out in the Thermal Laboratory of the Faculty of Mechanical Engineering of the State University of Campinas (UNICAMP), with the aid of the IKA C-200 Calorimetric Pump equipment, which performs analyzes of gross calorific values of liquid and solid samples. To carry out the analysis, each sample must be weighed between 0.5 and 0.7g in a porcelain crucible, without a lid. The analytical balance used was PIONEER OHAUS.

The higher calorific value analyzes carried out in the Thermal Laboratory of the Faculty of Mechanical Engineering of the State University of Campinas (UNICAMP), with the aid of the IKA C-200 Calorimetric Pump equipment, resulted in the values described in Table 6 for rainy days and in Table 7 for samples collected in the administrative zones of Manaus on dry days.

Table 6. Determination of MSW PCS in administrative regions on rainy days

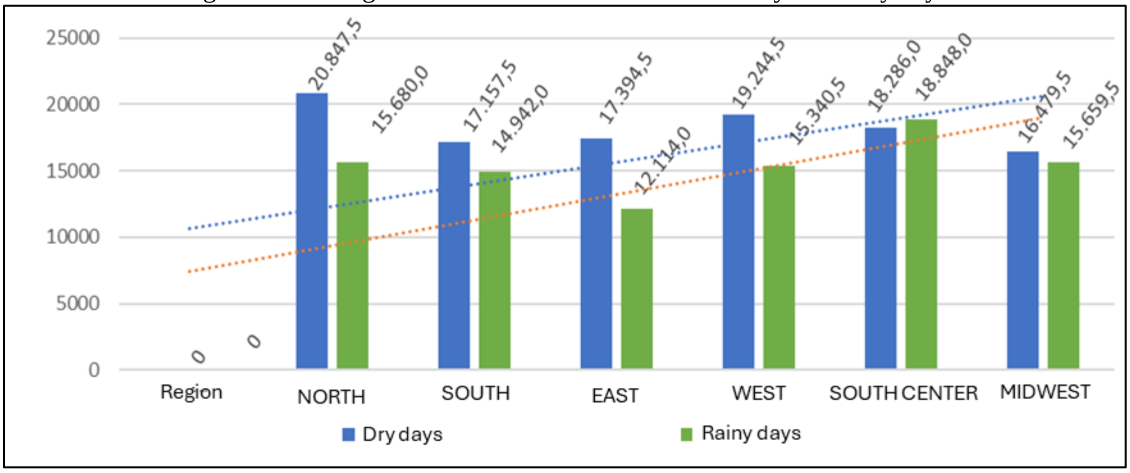
| Sample | PCS-1 | PCS-2 | Average | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| RSU-M07 | 15,243.0 | 15,438.0 | 15,340.5 | 2001.95 | 13,339 | 17,342 |
| RSU-M08 | 15,147.0 | 14,737.0 | 14,942.0 | | 12,940 | 16,944 |
| RSU-M09 | 15,690.0 | 15,670.0 | 15,680.0 | | 13,678 | 17,682 |
| RSU-M10 | 11,994.0 | 12,234.0 | 12,114.0 | | 10,112 | 14,116 |
| RSU-M11 | 17,885.0 | 19,811.0 | 18,848.0 | | 16,846 | 20,850 |
| RSU-M12 | 15,543.0 | 15,776.0 | 15,659.5 | | 13,658 | 17,661 |

Table 7. Determination of MSW PCS in administrative regions on dry days

| Sample | PCS-1 | PCS-2 | Average | Standard deviation | Minimum | Maximum |
|---|---|---|---|---|---|---|
| RSU-M01 | 20,086.0 | 21,609.0 | 20,847.5 | 1547.66 | 19,300 | 22,395 |
| RSU-M02 | 16,925.0 | 17,390.0 | 17,157.5 | | 15,610 | 18,705 |
| RSU-M03 | 16,955.0 | 17,834.0 | 17,394.5 | | 15,847 | 18,942 |
| RSU-M04 | 18,672.0 | 19,817.0 | 19,244.5 | | 17,697 | 20,792 |
| RSU-M05 | 17,685.0 | 18,887.0 | 18,286.0 | | 16,738 | 19,834 |
| RSU-M06 | 16,236.0 | 16,723.0 | 16,479.5 | | 14,932 | 18,027 |

Figure 11 shows the average PCS values of the MSW samples from the six zones on summer and winter days in the city. Possibly due to the naturally increased humidity due to the exposure of waste to rain that occurred on rainy days, the values will naturally be lower than on dry days, with the exception of the central-south area where there was probably no rain on the day of collection, making the average value similar to the average value resulting from dry days.

Figure 11. Average PCS of MSW in Manaus-AM on dry and rainy days




## Dry Higher Calorific Value - PCSdry

In the previous item, the sample was in thermal equilibrium with the environment and exposed to local humidity and the amount of additional water formed by the hydrogen in the fuel, as well as the water existing in the relative humidity of the combustion air, were not considered. In this case, it was necessary to obtain the dry PCS values, in joules/Kg, using equation 2 and obtaining the values in Table 8:

Table 8. Dry PCS of Manaus MSW samples on dry and rainy days

| ADMINIST REGION. | Dried | | Rainy | | Dry | Rain | Dried | | Rainy | |
|---|---|---|---|---|---|---|---|---|---|---|
| Region | PCS-1 | PCS-2 | PCS-1 | PCS-2 | w | w | $_{Dry}$ PCS-1 | $_{Dry}$ PCS-2 | $_{Dry}$ PCS-1 | $_{Dry}$ PCS-2 |
| NORTH | 20,086.0 | 21,609.0 | 15,690.0 | 15,670.0 | 6.02 | 6.54 | 21,372.63 | 22,993.19 | 16,787.93 | 16,766.53 |
| SOUTH | 16,925.0 | 17,390.0 | 15,147.0 | 14,737.0 | 6.18 | 10.97 | 18,039.86 | 18,535.49 | 17,013.37 | 16,552.85 |
| EAST | 16,955.0 | 17,834.0 | 11,994.0 | 12,234.0 | 6.23 | 18.13 | 18,081.48 | 19,018.88 | 14,650.05 | 14,943.20 |
| WEST | 18,672.0 | 19,817.0 | 15,243.0 | 15,438.0 | 4.38 | 8.84 | 19,527.30 | 20,724.74 | 16,721.15 | 16,935.06 |
| SOUTH CENTER | 17,685.0 | 18,887.0 | 17,885.0 | 19,811.0 | 5.92 | 7.72 | 18,797.83 | 20,075.47 | 19,381.23 | 21,468.36 |
| MIDWEST | 16,236.0 | 16,723.0 | 15,543.0 | 15,776.0 | 8.12 | 8.54 | 17,670.88 | 18,200.91 | 16,994.31 | 17,249.07 |

## Lower Calorific Value - PCI

After calculating the dry PCS, it was possible to determine the values for PCI, using Equation 3 and considering the hydrogen content extracted from the CHN elemental analyzes carried out on samples of urban solid waste. The calculated values for PCI, in joules/Kg, are described in Table 9. The mean PCI values and standard deviation are also presented.

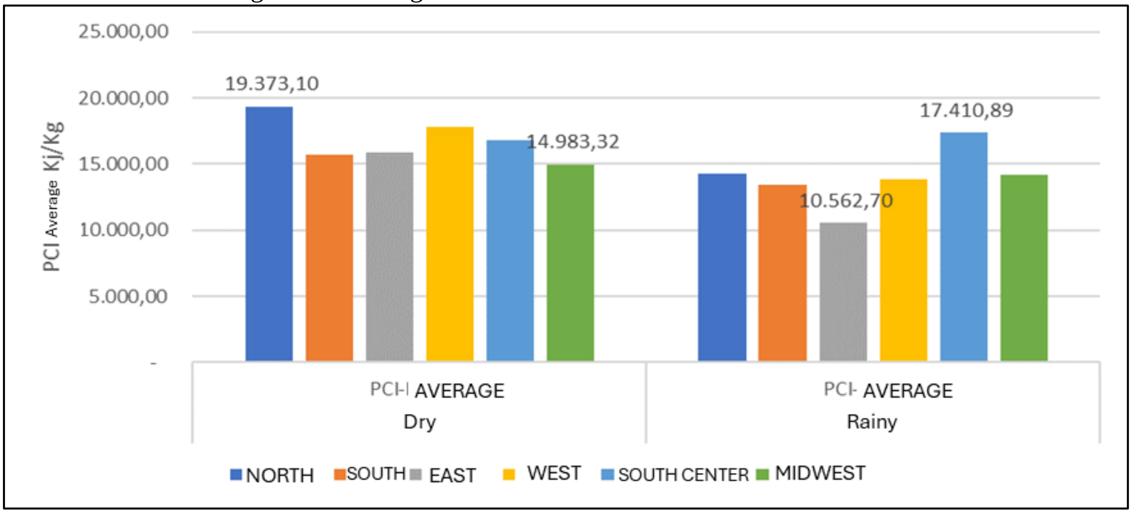
Table 9. PCI of Manaus MSW samples on dry and rainy days

| Region | Dry Days | | | Rainy days | | | DP | | Weighting | Weighted PCI – by region | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | H(%) | PCI-1 | PCI-2 | (%) | PCI-1 | PCI-2 | Dry | Rainy | % | Dry days | Rainy days |
| N | 6,405 | 18,611.60 | 20,134.60 | 6,135 | 14,265.83 | 14,245.83 | 761.5 | 10 | 0.2799 | 5,422.53 | 3,990.21 |
| S | 6,035 | 15,448.94 | 15,913.94 | 6,135 | 13,674.24 | 13,264.24 | 232.5 | 205 | 0.16 | 2,509.03 | 2,155.08 |
| L | 6,405 | 15,478.42 | 16,357.42 | 5,745 | 10,442.70 | 10,682.70 | 439.5 | 120 | 0.2502 | 3,982.66 | 2,642.79 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| O | 6,405 | 17,214.62 | 18,359.62 | 6,135 | 13,793.60 | 13,988.60 | 572.5 | 97.5 | 0.1417 | 2,520.43 | 1,968.37 |
| CS | 6,405 | 16,211.64 | 17,413.64 | 6,135 | 16,447.89 | 18,373.89 | 601 | 963 | 0.0953 | 1,602.24 | 1,659.26 |
| CO | 6,405 | 14,739.82 | 15,226.82 | 5,645 | 14,096.89 | 14,329.89 | 243.5 | 116.5 | 0.0829 | 1,242.12 | 1,178.29 |
| | | | | | | | | | Average | 17,279.02 | 13,593.99 |

The calorific value of MSW is immediately influenced by the increase in the material's moisture content, and any variation in this property in any sample changes the result. This is because the higher the moisture content, the greater the energy expenditure to evaporate the water present in the sample and the more water, the lower the other components, reducing the calorific value of the material present as fuel. Figure 12 explains the above.

Figure 12. Average PCI of MSW in the administrative zones of Manaus-AM




## CONCLUSION AND FUTURE WORK

The characterization of a city's waste is extremely important for government decision-making on the type of treatment to be carried out at that location. Knowing that there is Law 12,305 (PNRS) in the country, which requires a form of waste treatment before final disposal and knowing about thermal treatments, whose techniques are safer and more innovative, increases the range of options available on the market. The values obtained in the tests, such as apparent specific weight, 73.68 kg/m³, indicate the presence of a high percentage of packaging and recyclable materials, approximately one third of the national average, confirming the large quantity of light materials containing air in its interior, enabling a high degree of compaction when sizing the route and the number of waste compactor collection trucks. Gravimetric studies will enable other studies. For now, there has been a large amount of material capable of being recycled (62% + 2%), despite publicity campaigns, indicating little organic matter and a lot of material that can be recycled, leading to the idea of installing a plant sorting as an alternative to reducing waste sent to the city's landfill, increasing its useful life and reusing recyclable materials, bringing economic, social and environmental benefits to the city and its inhabitants. The high percentages of recyclable materials, combined with values of lower calorific value (PCI), presenting values between 15,000 and 19,000 KJ/Kg on dry days, calorific value equivalent to fuels cataloged in the bibliography as Lignite, Kiln-dried firewood and Coconut shells (17,000 KJ/Kg), Mineral coal, (15,000 KJ/Kg), showed promise in future decision-making for the treatment of MSW by incineration. Currently in the city of Manaus, approximately 83 thousand tons of MSW are generated per month. This waste is mostly (98%) landfilled, occupying a large area and causing environmental impacts. Research shows the feasibility of increasing recycling, composting part of these and the remainder undergoing thermal treatment by incineration and consequently generating electricity.

## FUTURE WORK

The proposed management plan for the city of Manaus-AM aims at adequate treatment and final disposal of MSW to reduce dependence on landfills and electricity generation. An economic analysis should be presented in the future considering some scenarios of recycling percentages, the quantity and cost of fuel used in incineration, the energy consumed in the process, as well as the gas emissions and financial impacts that may be caused. Finally, the calculation of the actual mass to be deposited in landfill, which includes the solid ash from incineration and the possible use of this in the composition of cementitious material to be used in civil construction.

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