International Journal for Innovation Education and Research www.ijier.net Vol:-9 No-9, 2021

Waste-to-energy technology for the brazilian context: a review article

Natália Dadario (Corresponding author)
Doctoral student of the Program in Agribusiness and Development, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/0000-0002-5614-747X
Email: natalia.dadario@unesp.br

Mário Mollo Neto
Associate Professor, Dept. of Biosystems Engineering, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/0000-0002-8341-4190
Email: mario.mollo@unesp.br

Cristiane Hengler Corrêa Bernardo
School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/0000-0002-9957-7437
Email: cristiane.bernardo@unesp.br

Roberto Bernardo
Post-graduate of the Program in Agribusiness and Development, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/ 0000-0002-3140-9138
Email: roberto.bernardo@unesp.br

Luís Roberto Almeida Gabriel Filho
Associate Professor, Dept. of Management, Development and Technology, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/ 0000-0002-7269-2806
Email: gabriel.filho@unesp.br

Camila Pires Cremasco
Associate Professor, Dept. of Biosystems Engineering, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/ 0000-0003-2465-1361
Email: camila.cremasco@unesp.br

Felipe André dos Santos
Associate Professor, Dept. of Biosystems Engineering, School of Sciences and Engineering, São Paulo State University (UNESP),
Tupã/SP, Brazil.
ORCID: https://orcid.org/ 0000-0001-7264-3396
Email: felipe.andre@unesp.br

Abstract

Waste-to-Energy Technologies (WtE) have been widely used in European countries, in Japan, in some US cities, and have been growing in China. Currently, in Brazil, there are no WtE power plants in operation, but there are studies on the feasibility of this technology. The Systematic Bibliographic Review (SBR) presented in this mini-review article appears as a result of a process of prospecting documents in the following databases: Science Direct, Web of Science and Scopus. The purpose was to map the articles of the last five years on the applications of WtE technologies in Brazil. From the selection of articles relevant to the research, these documents were registered and cataloged, as well as their qualitative and quantitative analyses. During the systematization process, it was possible to raise hypotheses about which professionals have been working the most on this topic, the journals in which these researches are being published and the keywords most addressed for these case studies. In addition, it was possible to identify the characteristics of the publications related to the theme, the central axes of analysis of the studies and the primary techniques studied for the Brazilian reality. It was also considered part of the results of the present work, the systematization of the main definitions of WtE, the presentation of the main WtE technologies operations, and the exposition of the benefits and impacts of each of these technologies.

Keywords: waste-to-energy; incineration; gasification; pyrolysis; municipal solid waste; energy recovery.

1. Introduction

The generation of municipal solid waste (MSW) in the world has increased over the past few years. According to estimates by the World Bank (Hoornweg and Bhada-Tata, 2012), approximately 1.3,109 tons of waste are generated per day, with the prospect that, in 2025, this number will reach 2.2,109 tons per day.

In emerging economies, such as Brazil, China and India, the volume generated tends to grow more dramatically due to rapid urbanization, population growth and economic development (Saraiva et al., 2017). According to Waste Atlas (2017), China is the country that generates more MSW in the world, while India and Brazil occupy the third and fourth positions, respectively. The generation of waste in these countries is likely to double by 2025, which increases the need to implement effective MSW management strategies in these countries (Veloso, 2013).

Although Brazil has advanced in the management of MSW, mainly with the implementation of the National Solid Waste Policy (PNRS), Law No. 12,305 (Brasil, 2010), there are still many challenges for the country to reduce the environmental impacts related to waste management.

One of these obstacles is the inappropriate final disposition of the MSW which remains at a high percentage in the nation. According to data from the Brazilian Association of Public Cleaning and Special Waste Companies (ABRELPE, 2019), the inappropriate destination of MSW in controlled dumps or landfills still represents 40.5% of the destinations of waste in Brazil. Therefore, efforts are needed to develop this last stage of the waste chain, in order to avoid environmental damage and protect the health of the population (Tisi, 2019).

One of the alternatives used to treat MSW is Waste-to-Energy Plants (WtE), widely used in northern Europe, Japan, in several cities in the USA, and increasingly in China (Themelis et al., 2013). These plants perform heat treatment of domestic and similar wastes in order to produce energy. The generation of energy can occur in the form of electricity, water heating, or steam. Electricity is fed into the grid and distributed to end users. Hot water, depending on the local infrastructure, can be sent to a heating (or cooling) network to heat (or cool) houses, hospitals, offices, among others. Steam can be used by a nearby industry in its production processes (Cewep, 2020).

The main advantages of WtE technology are: (a) the possibility of energy recovery with an average value of 10 megajoule per kilogram (MJ / kg) in each plant (THEMELIS et al., 2013); (b) the reduction of up to 90% in the volume of MSW, reducing the need to allocate municipal areas for this purpose, which is a major problem for metropolitan regions (Tabasová et al., 2012; Lino and Ismail, 2017); (c) it takes less time for the treatment of waste than biological processes do (Chhabra et al., 2016); (d) the simplicity of the operation (almost the whole process is automated) (Themelis et al., 2013); (e) lower volume of liquid and gaseous emissions to the environment in relation to the landfill (Tisi, 2019), and (f) products resulting from the process are stable, odorless and free of pathogens (Chhabra et al., 2016).

However, the process also has drawbacks such as: (a) the high cost of implementation and operation (Tabasová et al., 2012); (b) the generation of potentially toxic emissions, such as dioxins and furans, due to the chlorine present in the MSW composition (Zhao et al., 2016; Nordi et al., 2017); (c) negative public perception regarding the emission of pollutants and the possible reduction in the recycling rate, especially in developing countries with high population density (Themelis et al.; 2013; Kalyani and Pandey, 2014; Ren et al., 2016); (d) heterogeneous composition of waste that makes combustion difficult, especially in countries with an emerging economy where the organic fraction represents the majority of the total mass of waste (between 50% and 70%) (Nuss et al., 2012), and (e) from a social perspective, little absorption of labor in the process, since WtE technology requires relatively few specialized operators (Lima et al., 2019).

According to Themelis (2013), in Japan, there are 310 WtE plants in operation. In Europe, this number is even higher, with 514 WtE plants in operation and a processing of 263,314 tons of waste per day (Cewep, 2020). In the USA, about 13% of MSW is destined for its 86 WtE plants, representing a production capacity of 2,720 megawatts (MW) of energy per year, processing more than 28 million tons of waste (Swana, 2018; Trindade et al., 2018).

China currently has the largest installed capacity of WtE plants in the world. In 2017, 339 plants were registered in operation with an installed capacity of 7.3 gigawatts (GW) (IEA, 2019). According to Tisi (2019), in the forecast of the 13th Five-Year Plan of China, the country will have 10 GW of installed power from WtE plants for this year, 2020, and growth forecasts for more than 13 GW by 2023. This means that by then, China will have the capacity to generate waste energy similar to the Itaipu Dam, a hydroelectric plant located on the Paraná River, on the border between Brazil and Paraguay.

In Brazil, until now, there are no WtE plants in operation (Tolmasquim, 2016). There are only two Energy Recovery Unit (ERU) projects in the cities of Barueri and Mauá, both in São Paulo State. For the first ERU, 825 tons of MSW with 25 MW of installed capacity are expected to be processed per day. While for the second, is is calculated that 3,000 tons of waste are to be transformed into 80 MW of power per day (Tisi, 2019).

It is worth mentioning that, in the researched literature, there are some differences regarding which technologies are part of the concept of WtE. For some authors, such as Mayer, Bhandari and Gäth (2019), WtE technology includes both biological conversion and thermochemical systems, so the authors include anaerobic digestion, hydrothermal carbonization, pyrolysis, gasification and incineration as being WtE technologies. Other authors, such as Soares, Miyamaru and Martins (2017), consider that WtE plants are those that use only the MSW incineration process, probably due to the fact that, in practice, the incineration plant, also called ‘mass burning’, is the dominant technology in the market. According to data from the Intergovernmental Panel on Climate Change (IPCC, 2014), 90% of the world's WtE plants are mass burning combustion types, with a mobile grid, as it is the most cost-effective method today. Other treatment technologies, such as gasification and pyrolysis, are still very incipient because they are complex technologies. The first, for example, needs a pre-treatment for drying MSW (Abrelpe and Plasvida, 2012), and the second needs an external source of energy (Themelis et al., 2013). These additional costs decrease its competitiveness in face of the mass burning technology.

For this work, the WtE technologies studied were: incineration (operation with excess oxygen); gasification (in which combustion occurs partially), and pyrolysis (process with total absence of oxygen).

The Brazilian National Solid Waste Policy (Brasil, 2010) states that the municipal government agencies must find adequate solutions for the final disposition of MSW, considering the particularities of each city (Tisi, 2019). Therefore, it is of utmost importance that the research be directed to the management of MSW and, therefore, also include studies related to their thermal treatment, especially for metropolitan regions where there is a greater generation of MSW, and difficulty in providing proper waste grounding.

Thus, the present article seeks to identify the most relevant and recent researches on the application of WtE technology in the Brazilian context. The systematization of the study allowed us to understand the characteristics of publications related to this theme, such as, for example, the journals that most concentrate this type of study, the authors who have been most dedicated to the theme, the most used keywords, the heat treatment of MSW most studied for the Brazilian reality and the main axes of analysis of these studies. In addition, the work also brought together the main concepts adopted by the authors to define Waste-to-Energy, the operation of the main technologies adopted (incineration, gasification and pyrolysis), and the benefits and impacts caused by these energy recovery techniques.

The article is divided into sections, the first being this introduction. The following section presents the methodology used, including all the steps used to perform the searches, definition of the strings, design of the research and form of data analysis. The third section presents the research results and discussions. And finally, the fourth section contains the final remarks and conclusions.

2. Methodology

In this article, a Systematic Bibliographic Review (SBR) was carried out, adapted from Levy and Ellis (2006) and Conforto, Amaral e Silva (2011). According to these authors, the application of this system allows for greater scientific rigor, being able to achieve better search results for the theme.

Initially, a model was adopted, adapted from Levy and Ellis (2006), divided in steps, for the bibliographic review to happen more effectively. In the first stage, 'Input of preliminary information', some elementary parameters will be determined, such as, for example: the selection and collection criteria for the study subjects, the databases to be used, the search strings, and the inclusion and exclusion criteria. This is done in order to constitute the strategy by which the SBR will be conducted. The 'Application of the processing method' step consists of the application of the methodology already proposed in the previous step, in which searches are carried out on the bases defined with the pre-established criteria. The last step, 'Output of results and reports', corresponds to the analysis carried out of the articles selected for the research. The analysis may be a quantitative approach, aiming to translate the information found into numbers, so that they can be compiled and classified, facilitating the investigation. It may also be qualitative, describing the proposed theme without the need for metric, giving the author more freedom. Finally, it can still have both styles, being qualitative and quantitative.

For this research, in the 'Input of preliminary information' step, the choice of scientific bases, languages, search steps and applied filters was made, as explained in the following paragraphs.

Initially, the choice of three relevant scientific bases was made, Web of Science, Scopus and Science Direct, to bring to this article a context of how the heat treatment of MSW for energy use has been studied in Brazil in the last five years. For this, documents were selected in Portuguese, English and Spanish.

In the 'Application of the processing method' step, the first search was carried out, surveying the number of searches that these words alone had in the three chosen databases. Subsequently, a combined search for these words was performed, using the Boolean operators 'AND' and 'OR', in order to converge the topics of interest. Searches, both isolated and combined, were carried out in the period of 2 and a half months (from February 3rd to April 17th, 2020). It is important to note that this research was used as an inclusion criterion: (a) Documents classified only as 'Article'; (b) Articles published in the last 5 years (2015 to 2020); (c) Articles in Portuguese, English and Spanish.

After identifying the publications that had the subjects in question, those that appeared in duplicate in two or in the three chosen databases were removed. The next step was to remove the files that were unavailable for download.

Subsequently, some filtering steps were performed to select only the materials that actually portrayed the desired context. Three filters were made, adapted from the work of Conforto, Amaral and Silva (2011). The first was the reading of the title, summary and keywords of the pre-selected materials. The second regarded the reading of the introduction and conclusion of the articles. Lastly, the complete reading was performed. Figure 1, clearly shows the steps taken in the entire process of selecting and filtering articles.

After each filter was applied, it was verified the number of documents that were being discarded and the number of articles that were left, in order to generate the quantitative synthesis of the results, to the 'Output of results and reports' step. Still, in relation to the quantitative analysis, in possession of the selected final documents, an attempt was made to carry out a general classification of the articles through their attributes. In addition, it was sought to perform a descriptive analysis, with graphs and comparative table, with other relevant data.

In addition to that, a qualitative analysis was carried out in order to provide a greater understanding of the topic, such as, the main concepts used for Waste-to-Energy; the main existing technologies for burning MSW with the aim of generating energy and their respective definitions, and the benefits and impacts caused by these energy recovery plants.

The next section presents the results obtained.

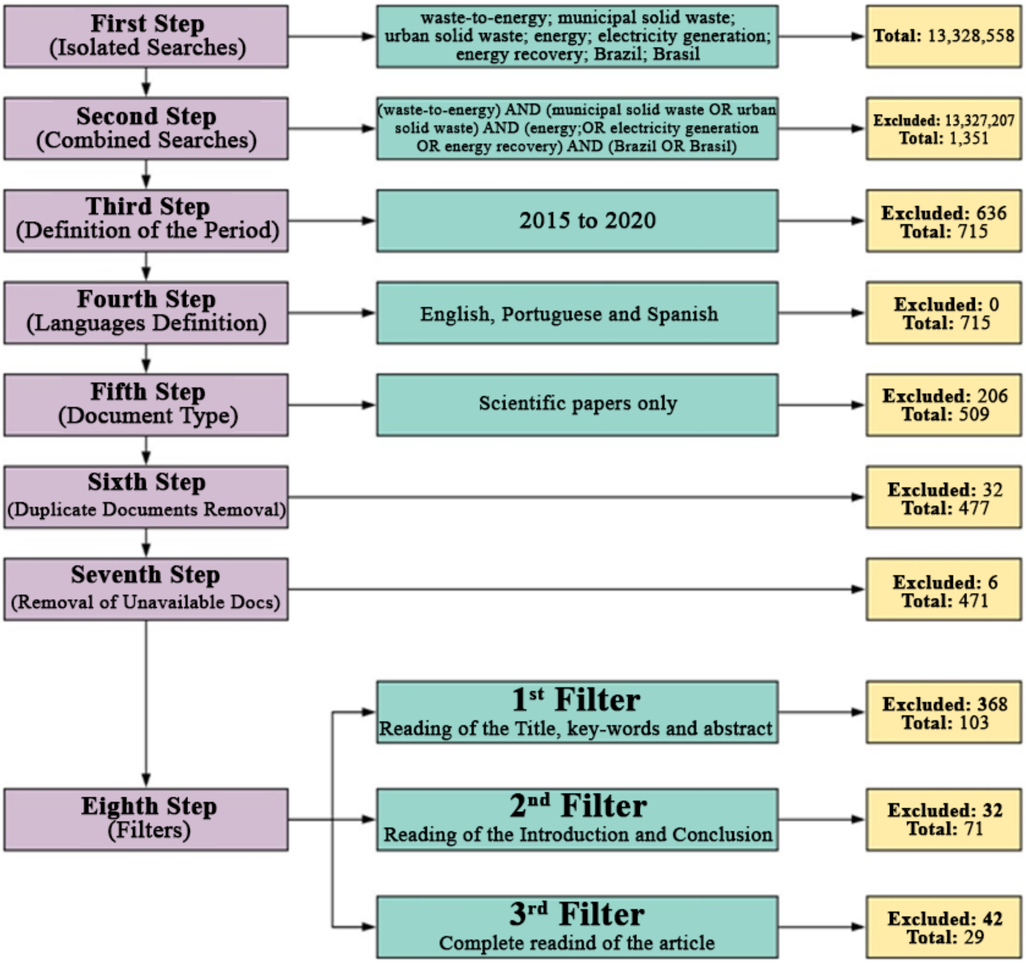

Figure 1. Stages of the document selection and filtering process

3. Results and Discussion

3.1 Quantitative Analysis

Considering twenty-nine (29) articles selected for final analysis, Figure 2 illustrates the percentage of publications related to the theme in each of the presented journals.

From Figure 2, it can be seen that the journal Waste Management & Research is the one that concentrates the biggest number of publications with the field of WtE application technology in Brazil, representing 20.7% of the selected articles.

In this work, the most frequent keywords in the studies were also analyzed, in order to understand which expressions are most used to indicate research in the field of WtE technology in Brazil. Thus, for the 29 analyzed articles, 80 keywords were considered for insertion in the software Tagul Word Cloud. Later, a composition of the word cloud is shown in Figure 3.

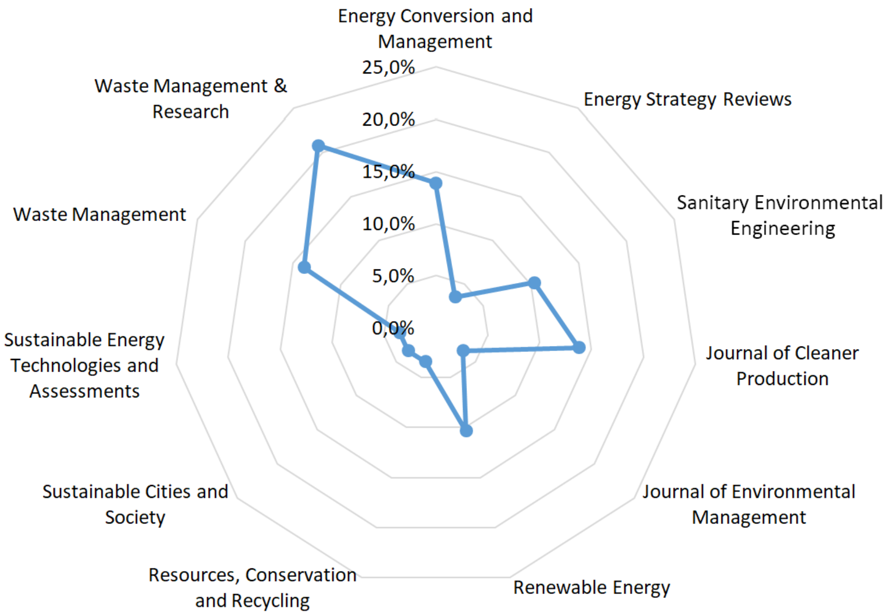

Figure 2. Journals that concentrate more publications within the studied area

Figure 3. Keyword cloud
Source: Prepared by the authors using the software Tagul Word Cloud.

The word cloud construction brings together the main terms used to portray the central theme of the article, highlighting the words that appear most frequently in larger letters, while the terms with less frequency are presented in smaller letters. This visualization makes it easier for the reader to carry out a broader and more practical evaluation of the main terminologies that are being used to designate the themes treated throughout the article, allowing for a more comprehensive understanding of the research structure, in relation to the technology used, the object of study and approach to work.

In Figure 4, only the heat treatments most discussed in the analyzed articles are presented. It is important to highlight that several researches did not only address a specific treatment, but made a comparison between them in different scenarios, contrasting or even associating them with techniques other than thermal ones, such as recycling, composting, disposal in landfills (with or without power generation), anaerobic digestion, among others.

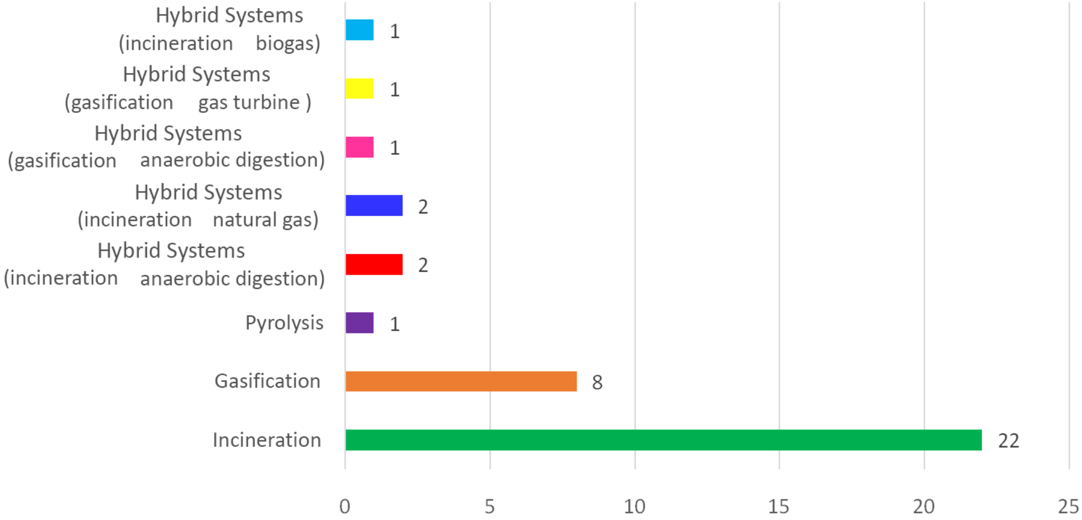

Figure 4. Most addressed heat treatments

Based on Figure 4, it is possible to see that the most studied heat treatment was incineration. This is due to the fact that this technology is the most economically and energetically viable, as pointed out by the Intergovernmental Panel on Climate Change (Ipcc, 2018). It can also be seen, in the studies, that gasification and pyrolysis were researched for regions with a lower number of inhabitants, due to the pre-treatment of waste that must be done in these processes, making them even more expensive and impracticable for large-scale operations, as mentioned by Themelis et al. (2013) and Abrelpe and Plasvida (2012).

Still in Figure 4, it can be seen that seven scenarios were based on hybrid systems, that is, that incorporate more than one treatment. These associated systems aim to obtain the best cost-benefit ratio, as they relate the best in each of the techniques, for example, greater economic viability of one and less atmospheric emission of another.

Finally, the main aspects approached by the researches were verified (Figure 5). For this, the analyses were classified as: economic, environmental, social, energetic and exergetic analysis.

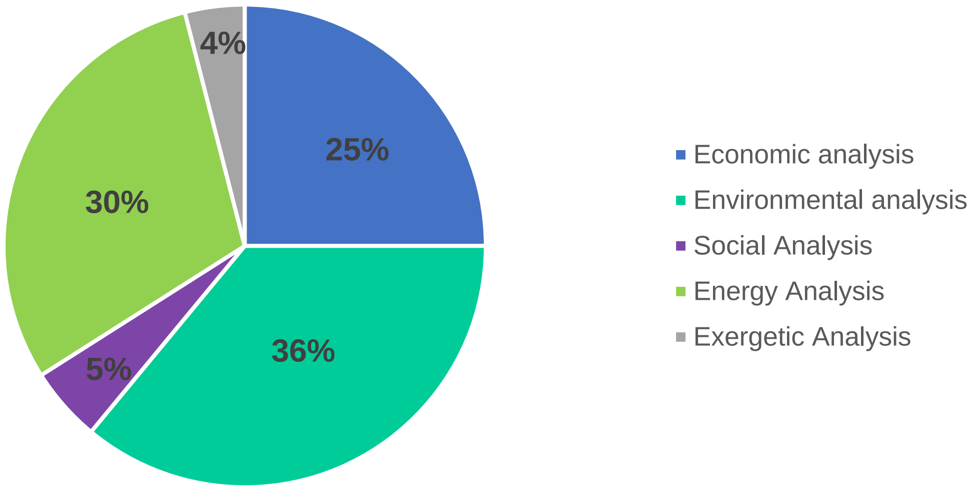

Figure 5. Main analyses performed in the studies

It should be considered that, in several studies that contained an economic analysis, sensitivity analyses were also performed. Life cycle analyses (LCA), atmospheric emission analyses and specific analyses for greenhouse gas emissions (GHG) were included within the category of environmental analysis. The analysis of ecological and energy efficiency (EE) was categorized both in the environmental and in the economic aspects.

In the social scope, only two articles were included: one that considered the inclusion of scavengers in the process, and another that quantified the toxicity of emissions to human health through an indicator. From this cataloging, it was possible to verify that few studies on the application of WtE for the Brazilian context take into account social aspects.

The social pillar, and especially its potential influence on decision-making, can be decisive for the Brazilian context depending on the region. Although a technology can be presented as more economically viable, in practice there is considerable resistance against this alternative, since the number of jobs to be created (social sustainability) would be minimal. So it is important to think about what would be the alternatives for social inclusion for these people (Lima et al., 2019).

Regarding the analysis of energy and exergy, 15 of the 29 articles carried out such investigations, demonstrating the relevance of these pillars for this type of study, since the greater the energy efficiency, the greater the sale of energy, and the more viable the implementation of these plants will become.

Finally, it should be noted that no article has considered political and cultural analyses. Some cited that cultural barriers need to be overcome and others made recommendations for political incentives to deploy the technology, but no study aimed to explore these perspectives.

Thus, the quantitative analysis fulfills the objective of describing the aspects of the studies regarding the progress of the applications of WtE technology in Brazil on the last five years. A qualitative analysis was also performed from the selected articles and is presented on the next topic.

3.2 Qualitative Analysis

The WtE technologies researched by the articles were mainly focused on the thermochemical conversion technique, which includes the process of incineration, pyrolysis and gasification (Lopes et al., 2018). Some of the studies compared these thermal technologies for the final destination of MSW with more conventional treatments used in Brazil, such as landfill and recycling. Other research carried out comparisons of heat treatments with methods still little used for the Brazilian reality, such as composting and anaerobic digestion.

Another aspect that should be highlighted in the analysis of the articles is that there was a prevalence of research that did not consider the recycling process prior to the thermal process. Thus, the calculated energy power of these treatments was relatively high, since all MSW were considered for energy transformation, including those with high calorific potential, such as paper and plastic, which would go to the recycling process if there was a previous segregation to the thermal process. In the study by Silva Filho et al. (2019) to further increase the energy content of MSW, the authors added wood to the raw material of the process.

This consideration of including all residues in the thermal process, common to articles, is not intended to disqualify them, but rather to have in mind the readers who might use these researches to support heat treatment studies with prior segregation. On this case, this aspect should be considered.

It is also worth discussing that some processes were considered unfeasible for one article, but viable in others. This discrepancy is due to the conditions considered to be different in each study (different realities), and also because the analyses have been diversified, as some studies have carried out analyses from an energetic and / or exergetic point of view, others considered economic viability, or environmental aspects and social issues, as previously mentioned in Figure 5. An example of different results for the same process was the article by Santos et al. (2019), in which the authors concluded that incineration was the most unlikely scenario from the point of view of economic viability, although it was the one with the greatest potential for energy recovery.

There was also a predominance of the quantitative approach in the analyzed articles, and many of them use commercial softwares to perform the calculations, such as to quantify the atmospheric emissions of each technology.

Finally, a common recommendation from several studies is that, for WtE technologies to become viable in Brazil, there must be a political incentive from the Brazilian government to encourage these techniques so that in the medium and long term they bring benefits in the management of MSW, as previously mentioned.

After reading these articles, the contents were selected and grouped according to three proposed subtopics: (a) Main definitions of Waste-to-Energy (WtE); (b) WtE Technologies: Incineration, Gasification and Pyrolysis, and (c) Advantages and disadvantages of WtE technologies. These groupings with the perspectives of the articles are presented below.

3.2.1 Main definitions of Waste-to-Energy (WtE)

In all the analyzed articles, none clearly defined the concept of Waste-to-Energy. The term is more used as a keyword to indicate the research to the reader when portraying the main theme of the article, than to serve properly as a theoretic support to the study.

It may be that, due to the lack of a consensus regarding this definition in the literature, the articles used it as an artifice to include the process studied as being a 'thermal processing of MSW'. They included, in this terminology, the treatments by incineration, gasification, pyrolysis and plasma (Jimenez et al., 2017; Lino and Ismail, 2017; 2018), although there are some differences, as the article by Carneiro and Gomes (2019) does not consider plasma treatment as a heat treatment process.

Still other articles, consider the incineration, gasification and pyrolysis process as a 'thermochemical conversion process' (Luz et al., 2015; Lopes et al., 2018), and in addition to these individual methods, there may be combinations with other treatments, which would be the case for plasma gasification, fusion, distillation, etc. (Luz et al., 2015).

The study by Nordi et al. (2017) also considers that the energy routes can be divided into biochemical (spontaneous or controlled digestion) and thermal (incineration, gasification and pyrolysis).

Finally, there are surveys (Soares et al., 2017) that consider that WtE plants are those that use only the MSW incineration technique.

Thus, it is clear that there is no consensus among the authors for a consistent definition of Waste-to-Energy. What most have done is to circumvent it, using other terminologies to include the treatments proposed in the studies

3.2.2 WtE Technologies: Incineration, Gasification and Pyrolysis

This topic presents the functioning of the WtE technologies researched in this study: incineration, gasification and pyrolysis.

Incineration, as already mentioned, is the technique that has been most studied for the Brazilian reality over the past five years. This fact is mainly due to the fact that the technology is already very traditional and well established in several countries around the world, as it presents the best cost-benefit ratio (Ipcc, 2014; Lino and Ismail, 2018; Santos et al., 2019).

This method can be defined as a thermochemical process that, through complete oxidation, aims to decrease the volume and mass of the waste, prolonging the useful life of landfills (Santos et al., 2019; Dalmo et al., 2019a; Dalmo et al., 2019b). According to Silva et al. (2019), in this process, oxygen reacts with combustible elements present in the waste (at temperatures above 800 °C), such as carbon, oxygen and sulfur, converting chemical energy into heat.

Colvero et al. (2020) add that in addition to the production of heat, it is possible to produce electricity through the heating energy of materials. In this process, the generation of energy occurs after the generation of steam in boilers, which is sent to the turbines, resulting in electrical energy (Dalmo et al., 2019a; Dalmo et al., 2019b).

The generation of electrical energy by incinerating MSW is similar to the process of conventional thermal plants of the Rankine cycle, in which the steam generated in the boilers is conducted by means of turbines that activate electric generators that produce electrical energy (Soares et al., 2017; Dalmo et al., 2019b;). According to Soares et al. (2017), the generation capacity will depend on the efficiency of the process of transforming heat into electric energy, and on the calorific value of the incinerated material. According to Silva et al. (2019), the plastic, paper and rubber components have the highest calorific values.

On average, the technology can generate between 0.3 and 0.7 megawatt-hours (MWh) of electricity per ton of waste, depending on the lower heating value (LHV) of the waste and the size of the plant (Dalmo et al., 2019b). The process yield is around 20 to 25%, values that are relatively low, which reflect the limitation of the system in operating at very high temperatures (Soares et al., 2017).

Incineration, like any conversion process, generates by-products. Among the solid emissions are ash and slag, from which ferrous and non-ferrous alloys can be extracted for recycling (Colvero et al., 2020). As gaseous emissions, there is CO_2, water steam and volatile ash (Lino and Ismail, 2018), in addition to carcinogenic emissions such as benzene, dioxins and furans (Silva Filho et al., 2019).

For Brazil, Soares, Miyamaru and Martins (2017) considered that if the entire volume of MSW (192,000 tons / day) were incinerated, it would be possible to obtain 35 terawatt-hours (TWh) per year, considering the average of 0, 5 MWh per ton. In a more optimistic view, this value could reach 50 TWh per year, with 700 kilowatt-hours (kWh) per ton.

Finally, it should be noted that incineration is a well-established method worldwide and has the main advantage of recovering non-biodegradable and low moisture content energetically (Trindade et al., 2018) without the need for any treatment process or prior processing (Soares et al., 2017).

After incineration, gasification was the second most studied method for the Brazilian context. According to Dalmo et al. (2019b), this technique has been widely studied over the past few years, with commercial plants operating in Japan and in some countries in Europe. The technology consists of a thermal process with partial oxidation of MSW operating at an elevated temperature (600 ºC to 1700 ºC) which converts organic compounds into a fuel gas called ‘syngas’, with a lowest heating value ranging from 4.0 to 6.0 MJ / Nm^3 (Luz et al., 2015; Jimenez et al., 2019).

Syngas basically consists of CO, H_2, small amounts of CH_4 and different hydrocarbons (tars), inorganic impurities (H_2S, HCl, NH_3, HCN, HF, alkalis) and particles. It can be burned as a combustible gas in a burner with an efficiency of 20 to 40% of heat generation. Also, it can be used for electricity generation, in a conventional Rankine Cycle (with efficiency of 17 to 28%), in a gas turbine (24 to 33%), in an ICE (25 to 37%), or in a SOFC (41 to 60%) (LUZ et al., 2015).

In the gasification process, the fuel must meet different characteristics before entering the reactor. Among them, there are the particle size and moisture content. That is why it is important to study a pre-treatment for this technology (Dalmo et al., 2019b). Lopes et al. (2018b) explain that the gasification process is usually preceded by drying (endothermic vaporization at low temperatures, from 25 to 110 ºC, of compounds with low boiling point, such as water) and pyrolysis (endothermic decomposition of low density polymers and volatilization of other compounds with low molecular weight, operating from 110 to 550º C). For drying and pyrolysis reactions, the gasifier must be built with subdivisions that have areas of heat exchange by convection or radiation.

The treatment of gas purification and subsequent burning allows for to prolongation of the useful life of the equipment, minimizing the emissions of atmospheric pollutants and contributing to the production of electrical energy. However, the purification process also increases the operational cost of the technique, so another possibility is to burn the syngas without any previous treatment, making the process more financially viable, but in return, generating more pollutants (Lopes et al., 2018).

From the analyzed studies, it can be concluded that gasification may emerge as a promising technology in the near future, as the burning of syngas is easier to handle than that of solid waste. It also has the great advantage of minimizing environmental and public health damage by emitting less polluting gases.

Unlike other thermal processes, in pyrolysis, combustion occurs in the absence of oxygen or with a significantly lower amount of oxygen than is necessary for incineration or gasification. According to Silva Filho et al. (2019), pyrolysis reactions generally occur at moderately high temperatures (< 500º C) and break down biomass into non-condensable gases, liquids (condensable gases) and solids (residual solids or biochar), which are used as energy sources.

According to the authors, the use of biomass associated with MSW can promote a reduction in the generation of greenhouse gases and in the diversification of energy sources in the energy matrix.

Another promising option is the combination of pyrolysis, and combustion processes to eliminate the chlorine problem in combustion emissions. The presence of polyvinyl chloride (PVC) in MSW, which represents 38 to 66% of the chlorine content, reduces combustion efficiency and can lead to carcinogenic compounds, such as benzene. In addition, the presence of chlorine in the MSW during thermal conversion can generate the emission of hydrochloric acid (HCl) in the form of particles that contribute to the formation of dibenzo-p-polychlorinated dioxins (Polychlorinated dibenzo-p-dioxins, PCDD) and of polychlorinated dibenzofurans (polychlorinated-p-dibenzofurans, PCDF) (Silva Filho et al., 2019), which are also carcinogenic emissions.

3.2.3 Advantages and disadvantages of WtE technologies

In order to better visualize the advantages and disadvantages of energy generation technologies from MSW studied in this research, the data obtained from the articles in this Systematic Bibliographic Review.

The incineration has been the most studied in the explored articles (as already seen in Figure 4 as well), the technique has the greatest number of advantages and disadvantages, when compared to the others.

It is worth mentioning, that for incineration, there is the advantage of reducing volume and mass, which is one of the main reasons for the larger amount of studies in this subject. The generation of energy during incineration is also widely cited among the authors. The main disadvantages are the high cost of implantation and operation, in addition to the emission of pollutants harmful to human health and, therefore, the need for strict control in relation to these emissions.

Table 1. Advantages and disadvantages of technologies for generating energy from MSW.

Incineration	
Advantages	**Disadvantages**
• Reduction in volume and mass by 90 and 75%, respectively, without long periods of residence (Jimenez et al., 2017; Nordi et al., 2017; Lino and Ismail, 2017; 2018; Pin et al., 2018; Colvero et al., 2020).	• Not viable for small power plants (Carneiro and Gomes, 2019). • High capital costs of the power plant (Jimenez et al., 2017; Nordi et al., 2017).

• Can be incinerated on the spot (Nordi et al., 2017). • Elimination of pathogens (Lino and Ismail, 2017; 2018; Colvero et al., 2020). • Generates heat that can be used for heating water or transformed into electricity (Lino and Ismail, 2017; 2018). • Electricity can be sold to the grid (Jimenez et al., 2017; Colvero et al., 2020). • Generates more energy than other treatments (Silva et al., 2019). • Ashes are sterile (Nordi et al., 2017). • Smaller area required when compared to landfill disposal (Jimenez et al., 2017; Nordi et al., 2017). • Increase in the useful life of landfills, since they would only receive ashes (Dalmo et al., 2019a). • Controlled incineration has less environmental impact than landfills (Santos et al., 2019), as it has a lower emission of greenhouse gases (GHG) when compared to landfills (Colvero et al., 2020). • Incineration has less CO_2 emissions compared to landfill, in absolute terms (t / y) (Carneiro and Gomes, 2019). • The cost of the process can be offset by selling the energy generated (Nordi et al., 2017). • Most reliable and economical method when used to generate electricity through mass burning without pre-treatment of MSW (Carneiro and Gomes, 2019).	• High cost of operation and management (Pin et al., 2018; Santos et al., 2019). • Need for qualified personnel (Nordi et al., 2017). • Not all materials are combustible (Nordi et al., 2017). • MSW has a low energy content and high humidity, that is, relatively low heating value (LHV), especially in developing countries (Carneiro and Gomes, 2019). • Need for additional fuel to start and sometimes sustain combustion (Nordi et al., 2017). • The combustion of waste results in the emission of pollutants and the production of solid particles and waste rich in metals (Santos et al., 2019). • Need for strict environmental control of gaseous emissions (Silva et al., 2019; Santos et al., 2019) and ash, as they are considered hazardous solid waste (Pin et al., 2018). • Flue gas cleaning residues can contaminate the environment if not treated properly (Nordi et al., 2017). • Still strongly criticized for the emission of pollutants (Souza et al., 2019). • Some incineration plants suffer high loss of ignition, due to the high excess of air necessary to obtain acceptable abrasion (Trindade et al., 2018). • Low efficiency induced by high internal energy consumption caused by waste handling (Trindade et al., 2018).

• The amount of secondary waste, such as vitrified slag, is reduced (Jimenez et al., 2017).	• The burning of MSW generates acidic gases that require careful combustion control to contain the boiler corrosion and reduce maintenance costs (Carneiro and Gomes, 2019).
Gasification	
• Application on small and medium scales (Luz et al., 2015). • Possibility of using syngas in high efficiency thermal devices (gas turbines or for biofuel synthesis) (Luz et al., 2015; Dalmo et al., 2019b). • Waste gasification presents more favorable environmental results than incineration (Luz et al., 2015; Jimenez et al., 2017; Ferreira and Balestieri, 2018; Lopes et al., 2018a; Dalmo et al., 2019b), as a limited formation of dioxins, furans, nitrous oxides, sulfur oxides and ash (Jimenez et al., 2017; 2019). • Less secondary waste which, in some cases, is produced in a less dangerous way, such as vitrified slag (Jimenez et al., 2017).	• High operating cost (Lopes et al., 2018a). • Need for pre-treatment to adjust the humidity (Lopes et al., 2018a; 2018b) and the particle size (Jimenez et al., 2019). • Still in the research phase (Carneiro and Gomes, 2019). • It is not viable for large-scale commercial purposes (Carneiro and Gomes, 2019).
Pyrolysis	
• Reduction in the volume of waste from 70 to 90% (Silva Filho et al., 2019). • Treatment time shorter than in biological processes (Silva Filho et al., 2019). • Generation of more stable products; free of odor and pathogens (Silva Filho et al., 2019).	• Still in the research phase (Carneiro and Gomes, 2019). • It is not viable for large-scale commercial purposes (Carneiro and Gomes, 2019).

Source: Compiled by the authors based on the works studied on this SBR

The advantages and disadvantages of pyrolysis and gasification are very similar. As disadvantages, both techniques are still in the research phase, as there are few plants operating in the world with these methods. In addition, these technologies are not yet feasible to operate on a large scale. They work very well in the laboratory but, in practice, there are many other issues involved that still make them impractical.

In addition, it is mentioned that, in gasification, there is a need to pre-treat the MSW, and the cost of operation is still considered to be very high.

These last two techniques, when compared to incineration, have greater environmental benefits, such as the limited emission of pollutants (dioxins, furans, nitrous oxides, sulfur oxides and ash) and greater stability. Gasification also allows the use of syngas, a fuel derived from the process, in high efficiency thermal devices.

Thus, it can be seen that every technique will have advantages and disadvantages. It will be up to the manager to analyze the particularities of the region and to see which technique is more viable to be applied, as already predicted by Tisi (2019).

4. Conclusion

The Systematic Bibliographic Review presented in the present article allowed for the summarization of the current research scenario on WtE sectors throughout Brazil. Through that, it was possible to verify: the main techniques involved; the central analyses and approaches produced; the most common regions studied; the main authors and universities that have been working to evaluate the method as a possible solution for the destination of MSW, especially for large centers in Brazil; the main journals interested in this type of publication, and the central keywords used to designate the theme of the article in the field of WtE technology for the Brazilian context.

With 29 journal articles reviewed, it was also possible to synthesize the main concepts attributed to WtE technology, explain the most studied technologies (incineration, gasification and pyrolysis), and categorize the main advantages and disadvantages of the methods.

From the results found, it is noted that the verification of the best technology for a given region was at the heart of most articles. There was an effort in these studies to analyze the energy potential of the method, economic feasibility, or even to perform a Life cycle analysis involving environmental variables. Some studies also brought together more than one approach, but a fact that called attention was that few studies involved social aspects as a way of analyzing the use of technology.

In Brazil, the social pillar can influence and be decisive in making decisions about whether or not to deploy technology, depending on each context. Although the WtE technology may be economically viable and have some environmental advantage, there is still a problem with the minimal creation of jobs; therefore, there is resistance from the population that should be considered as a criterion for the analysis. One should also think about what the alternatives for social inclusion would be, as a way to mitigate the impact that the process would bring to people.

In addition to the problem of job creation, there is also the reluctance of the population to introduce this technology due to the toxicity of atmospheric emissions that it can generate, affecting human health of the surroundings communities. Although European levels are lower than those established by legislation, opponents of this method have stated that, in Brazil, in addition to legislation being more lenient, enforcement may be inefficient. Thus, it is also necessary that the studies include these political issues of regulation of the process aiming for the least impact on the population. It is necessary to envision the study of cultural and communication issues, so that there is a better dialogue with society, in order to reduce the disinformation about this technique, clarifying doubts and considering anxieties.

This review then fulfills its objective of helping the reader to understand how research on WtE technologies is configured in Brazil over the past five years, and reiterates the importance of advancing studies on the subject, still incipient in the country. Studies in the area of government policies and regulations, financial support, technologies customized for each context, and processes that minimize environmental and public health impacts are possibilities for future researches on the sector in the country.

5. Acknowledgement

The authors wish to acknowledge the Postgraduate Program **in Agribusiness and Development (PGAD) of School of Sciences and Engineering of São Paulo State University (UNESP), the Brazilian National Council for Scientific and Technological Development (CNPq), the São Paulo Research Foundation (FAPESP)** and also by the Personnel Improvement Coordination of High Level (CAPES) for financial support.

6. References

Associação Brasileira De Empresas De Limpeza Pública e Resíduos Especiais – ABRELPE. (2019). *Panorama dos Resíduos Sólidos no Brasil* - 2018/2019. (Accessed October 07, 2020) at: https://abrelpe.org.br/download-panorama-2018-2019.

Associação Brasileira De Empresas De Limpeza Pública e Resíduos Especiais – ABRELPE. (2012). *Caderno Informativo:* Recuperação Energética de Resíduos Sólidos Urbanos. (Accessed May 01, 2020) at: http://abrelpe.org.br/download-caderno.

BRASIL. Lei n. 12.305, de 02 de agosto de 2010. *Institui a Política Nacional de Resíduos Sólidos*; altera a Lei n. 9.605, de 12 de fevereiro de 1998; e dá outras providencias. Diário Oficial da União, Brasília.

Carneiro, M. L. N. M.; Gomes, M. S. P. (2019). Energy, exergy, environmental and economic analysis of hybrid waste-toenergy plants. *Energy Conversion and Management*, v. 179, 397-417. http://dx.doi.org/10.1016/j.enconman.2018.10.007.

CEWEP, 2018. *Waste-to-Energy:* Energising your waste. (Accessed April 29, 2020) at: http://www.cewep.eu/wp-content/uploads/2018/07/Interactive-presentation-2018-New-slides.pdf.

Chhabra, V.; Shastri, Y.; Bhattacharya, S, (2016). Kinetics of pyrolysis of mixed municipal solid waste-A review. *Procedia environmental sciences*, v. 35, 513-527. https://doi.org/10.1016/j.proenv.2016.07.036.

Colvero, D. A.; Ramalho, J.; Gomes, A. P. D.; Matos, M. A. A.; Tarelho, L. A. C. (2020). Economic analysis of a shared municipal solid waste management facility in a metropolitan region. *Waste Management*, v. 102, 823-837. https://doi.org/10.1016/j.wasman.2019.11.033.

Conforto, E. C.; Amaral, D. C.; Silva, S. L. (2011). Roteiro para revisão bibliográfica sistemática: aplicação no desenvolvimento de produtos e gerenciamento de projetos. In: *Anais do 8 Congresso Brasileiro de Gestão de Desenvolvimento de Produto–CBGDP*, Porto Alegre, RS. (Accessed October 07, 2020) at: http://www.ufrgs.br/cbgdp2011/downloads/9149.pdf.

Dalmo, F. C.; Simão, N. M; Nebra, S.; Sant'ana, P. H. M. (2019a). Energy recovery from municipal solid waste of intermunicipal public consortia identified in São Paulo State. *Waste Management & Research*, v. 37, (3), 301-310. https://doi.org/10.1177%2F0734242X18815953.

Dalmo, F. C.; Simão, N. M; Lima, H. Q.; Jimenez, A, C, M.; Nebra, S.; Martins, G.; Palacios-Bereche, R.; Sant'ana, P. H. M. (2019b). Energy recovery overview of municipal solid waste in São Paulo State, *Brazil. Journal of Cleaner Production*, v. 212, 461-474. https://doi.org/10.1016/j.rser.2018.11.007.

Ferreira, E. T. F.; Balestieri, J. A. P. (2018). Comparative analysis of waste-to-energy alternatives for a low-capacity power plant in Brazil. *Waste Management & Research*, v. 36, (3), 247-258. https://doi.org/10.1177%2F0734242X17751849.

Hoornweg, D., Bhada-Tata, P. (2012). What a waste: a global review of solid waste management. Urban development series; knowledge papers no. 15. *World Bank*, Washington, DC. World Bank. (Accessed May 01, 2020) at: https://openknowledge.worldbank.org/handle/10986/17388

International Energy Agency - IEA, (2019). *Will energy from waste become the key form of bioenergy in Asia?* Analysis from Renewables 2018. (Accessed April 30, 2020) at: https://www.iea.org/newsroom/news/2019/january/will-energy-from-waste-become-the-key-form-of-bioenergy-in-asia.html.

Intergovernmental Panel on Climate Change - IPCC (2014). *AR 5 Climate Change 2014. Mitigation of Climate Change. Chapter 10 – Industry*. (Accessed May 01, 2020) at: https:// www.ipcc.ch/site/assets/uploads/2018/02/ipcc_wg3_ar5_chapter10.pdf.

Jimenez, A. C. M.; Nordi, G. H.; Bereche, M. C. P.; Bereche, R. P.; Gallego, A. G.; Nebra. S. A., (2017). Evaluation of two different alternatives of energy recovery from municipal solid waste in Brazil. *Waste Management & Research*, v. 35, (11), 1137-1148. https://doi.org/10.1177/0734242x17728123.

Jimenez, A. C. M; Bereche, R. P.; Nebra. S. A. (2019). Three municipal solid waste gasification technologies analysis for electrical energy generation in Brazil. *Waste Management & Research*, v.

37, (6), 631-642. https://doi.org/10.1177%2F0734242X19841126.

Kalyani, K. A., Pandey, K. K. (2014). Waste to energy status in India: a short review. *Renewable and Sustainable Energy Reviews*, v. 31, 113-120. https://doi.org/10.1016/j.rser.2013.11.020.

Levy, Y.; Ellis, T. J. (2006). A system approach to conduct an effective literature review in support of information systems research. *Informing Science Journal*, v. 9, 181-212. https://doi.org/10.28945/479.

Lima, P. M.; Olivo, F.; Paulo, P. L.; Schalch, V. Cimpan, C. (2019). Life Cycle Assessment of prospective MSW management based on integrated management planning in Campo Grande, Brazil. J. *Waste Management*, v. 90, 59-71. https://doi.org/10.1016/j.wasman.2019.04.035.

Lino, F. A. M; Ismail, K. A. R. (2017). Incineration and recycling for MSW treatment: Case study of Campinas, Brazil. *Sustainable Cities and Society*, v. 35, 752-757. http://dx.doi.org/10.11648/j.ijepe.20150404.12.

Lino, F. A. M; Ismail, K. A. R. (2018). Evaluation of the treatment of municipal solid waste as renewable energy resource in Campinas, Brazil. *Sustainable Energy Technologies and Assessments*, v. 29, 19-25. https://doi.org/10.1016/j.seta.2018.06.011.

Lopes, E. J., Queiroz, N.; Yamamoto, C. I.; Costa Neto, P. R. (2018a). Evaluating the emissions from the gasification processing of municipal solid waste followed by combustion. J. *Waste Management*, v. 73, 504-510. https://doi.org/10.1016/j.wasman.2017.12.019.

Lopes, E. J.; Okamura, L. A.; Maruyama, S. A.; Yamamoto, C. I., (2018b). Evaluation of energy gain from the segregation of organic materials from municipal solid waste in gasification processes. *Renewable Energy*, v. 116, 623-629. https://doi.org/10.1016/j.renene.2017.10.018.

Luz, F. C.; Rocha, M. H.; Lora, E. E. S.; Venturini, O. J.; Andrade, R. V.; Leme, M. M. V.; Olmo, O. A. (2015). Techno-economic analysis of municipal solid waste gasification for electricity generation in Brazil. *Energy Conversion and Management*, v. 103, 321-337. https://doi.org/10.1016/j.enconman.2015.06.074.

Mayer, F.;Bhandari, R.; Gäth, S. (2019). Critical review on life cycle assessment of conventional and innovative waste-to-energy technologies. *Science of the Total Environment*, v. 672, 708-721. http://dx.doi.org/10.1016/j.scitotenv.2020.137731.

Nordi, G. H.; Palacios-Bereche, R., Gallego, A. G.; Nebra, S. A. (2017). Electricity production from municipal solid waste in Brazil. J. *Waste Management & Research*, v. 35, (7), 709-720.

https://doi.org/10.1177%2F0734242X17705721.

Nuss, P.; Bringezu, S.; Gardner, K. H. (2012). Waste-To-Materials: the long term option. In: Karagiannidis, A. (Ed.), *Waste to Energy*. Springer, London, pp. 1–26.

Pin, B. V. R.; Barros, R. M.; Lora, E. E. S.; Santos, I. F. S. (2018). Waste management studies in a Brazilian microregion: GHG emissions balance and LFG energy project economic feasibility analysis. *Energy Strategy Reviews*, v. 19, 31-43.

Ren, X.; Che, Y.; Yang, K.; Tao, Y. (2016). Risk perception and public acceptance towards a highly protested Waste-to-Energy facility. *Waste Management*, v. 48, 528-539. https://doi.org/10.1016/j.wasman.2015.10.036.

Santos, R. E.; Santos, I. F. S.; Barros, R. M.; Bernal, A. P.; Tiago Filho, G. L.; Silva, F. G. B. (2019). Generating electrical energy through urban solid waste in Brazil: An economic and energy comparative analysis. *Journal of Environmental Management*, v. 231, 198-206. https://doi.org/10.1016/j.jenvman.2018.10.015.

Saraiva, A. B.; Souza, R. G.; Valle, R. A. B. (2017). Comparative lifecycle assessment of alternatives for waste management in Rio de Janeiro – Investigating the influence of an attributional or consequential approach. *Waste Management*, v. 68, 701-710. http://dx.doi.org/10.1016/j.wasman.2017.07.002.

Science Direct. (1997). (Accessed February 03, 2020) at: http://www.sciencedirect.com.

Scopus. (2004). (Accessed February 03, 2020) at: http://www.elsevier.com/scopus.

Silva,L. J. V. B.; Santos, I. F. S.; Mensah, J. H. R.; Gonçalves, A. T. T.; Barros, R. M. (2020). Incineration of municipal solid waste in Brazil: An analysis of the economically viable energy potential. *Renewable Energy*, v. 149, 1386-1394.

Silva Filho, V. F.; Batistella, L.; Alves, J. L. F.; Silva, J. C. G.; Althoff, C. A.; Moreira, R. F. P. M.; José, H. J. (2019). Evaluation of gaseous emissions from thermal conversion of a mixture of solid municipal waste and wood chips in a pilot-scale heat generator. *Renewable Energy*, v. 141, 402-410. https://doi.org/10.1016/j.renene.2019.04.032.

Soares, R. R.; Miyamaru, E. S.; Martins, G. (2017). Environmental performance of the allocation and urban solid waste treatment with energetic reuse through life cycle assessment at CTR – Caieiras. *Engenharia Sanitária e Ambiental*, v. 22, (5), 993-1003.

Souza, A. R.; Silva, A. T. Y. L.; Trindade, A. B.; Freitas, F. F.; Anselmo, J. A. (2019). Analysis of the potential use of landfill biogas energy and simulation of greenhouse gas emissions of different municipal solid waste management scenarios in Varginha, MG, Brazil. *Engenharia Sanitária e Ambiental*, v. 24, (5), 887-896. https://doi.org/10.1590/s1413-41522019187066.

Solid Waste Association of North America – SWANA. (2018). *Solid Waste Management to Resource Efficiency and Energy Recovery in The United States.* (Accessed April 30, 2020) at: http://www.foroenres2018.mx/presentaciones/13_10%20de%20oct%20Sara%20Bixby.pdf.

Tabasová, A.; Kropá, J.; Kermes, V.; Nemet, A.; Stehlík, P. (2012). Waste-to-energy technologies: impact on environment. *Energy*, v. 44, (1), 146 – 155. https://doi.org/10.3390/en6010045

Tagul Word Cloud. (2017). (Accessed April 21, 2020) at: https://wordart.com/create.

Themelis, N. J.; Barriga, M. E. D.; Estevez, P.; Velasco, M. G. (2013). *Guidebook for the Application of WTE Technologies in Latin America and The Caribbean*. Earth Engineering Center, Columbia University - EEC/IDB. (Accessed May 05, 2020) at: http://www.seas.columbia.edu/earth/wtert/pressreleases/Guidebook_WTE_v5_July25_2013.pdf.

Tisi, Y. S. A. B. (2019). *Waste-to-Energy:* recuperação energética como forma ambientalmente adequada de destinação dos resíduos sólidos urbanos. Synergia, Rio de Janeiro, 240 pp.

Tolmasquim, M., T. (2016). *Renewable energy:* hydraulics, biomass, wind, solar, ocean (in Portuguese). Rio de Janeiro (BR): Empresa de Pesquisa Energética,. pp. 452. (Accessed May 05, 2020) at: http://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-172/Energia%20Renov%C3%A1vel%20-%20Online%2016maio2016.pdf.

Trindade; A. B.; Palácio, J. C. E.; González, A. M.; Orozco, D. J. R.; Lora, E. E. S.; Renó, M. L. G.; Olmo, O. A. (2018). Advanced exergy analysis and environmental assessment of the steam cycle of an incineration system of municipal solid waste with energy recovery. *Energy Conversion and Management*, v. 157, 195-214. https://doi.org/10.3390/en12122378.

Veloso, S. (2013). *BRICS and the Challenges in Fighting Inequality*. Oxfam, Rio de Janeiro.

Waste Atlas. (2013). (Accessed April 09, 2020) at: http://www.atlas.d-waste.com.

Web of Science. (1997). (Accessed February 03, 2020) at: http://www.webofknowledge.com.

Zhao, X. G., Jiang, G. W., Li, A., Wang, L. (2016). Economic analysis of waste-to-energy industry in China.

J. *Waste management*, v. 48, 604-618. https://doi.org/10.1016/j.wasman.2015.10.014.

Copyright Disclaimer