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Original Research

Bibliometric analysis of technologies for municipal solid waste valorization and their potential in the colombian context

Análisis bibliométrico de tecnologías para la valorización de residuos sólidos urbanos y su potencial en el contexto colombiano

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Abstract

The constant growth in global urban waste generation has led to an increasing need to address its management sustainably. Despite the proven effectiveness of converting this waste into energy in various countries, its implementation in Colombia is still in its early stages. In this study, a bibliometric analysis and systematic review of the literature was conducted to assess urban solid waste valorization technologies and their potential integration into biorefineries in the Colombian context. Among the identified technologies, incineration, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery stand out.

Anaerobic Digestion emerges as an attractive option due to its versatility. However, there is a recognized imperative to dynamically choose technologies, considering the diversity of contexts and specific conditions in Colombia. Additionally, gasification and pyrolysis appear as viable options, each with its own advantages and challenges, reflecting the complexity and variability in waste management. Concerning landfill gas recovery, its significance as an essential installation in controlled landfills is emphasized, dismissing its consideration as an independent alternative. While the literature suggests that incineration is perceived as less favorable in social, economic, and environmental terms, it is crucial to recognize the dynamics and specificity of each situation.

The choice of technologies must be adaptive and guided by a contextual approach that considers the heterogeneity in waste composition, available infrastructure, and other factors that vary significantly from one scenario to another. This dynamic and adaptive approach is essential to address the complexity of urban waste management and find sustainable solutions in the Colombian context.

Resumen

El crecimiento constante en la generación de residuos urbanos a nivel global ha generado una creciente necesidad de abordar su gestión de manera sostenible. A pesar de que la conversión de estos residuos en energía ha demostrado ser efectiva en varios países, su implementación en Colombia aún se encuentra en una etapa incipiente. En este estudio, se llevó a cabo un análisis bibliométrico y una revisión sistemática exhaustiva de la literatura con el propósito de evaluar las tecnologías de valorización de los residuos sólidos urbanos, así como su potencial integración en biorrefinerías en el contexto colombiano. Entre las tecnologías más relevantes identificadas se encuentran la incineración, la gasificación, la pirólisis, la digestión anaeróbica y la recuperación de gas de vertedero.

La Digestión Anaerobia destaca como una opción atractiva debido a su versatilidad. No obstante, se reconoce la necesidad imperante de adoptar una elección dinámica de tecnologías, considerando la diversidad de contextos y condiciones específicas en Colombia. Además, la gasificación y la pirólisis emergen como opciones viables, cada una con sus propias ventajas y desafíos, reflejando la complejidad y variabilidad en la gestión de residuos. En relación con la recuperación de gas de vertedero, se subraya su importancia como instalación esencial en vertederos controlados, desestimando la consideración de una alternativa independiente. Si bien la literatura sugiere que la incineración se percibe como menos favorable en términos sociales, económicos y ambientales, es crucial reconocer la dinámica y especificidad de cada situación. La elección de tecnologías debe ser adaptativa y orientada por un enfoque contextual que considere la heterogeneidad en la composición de residuos, infraestructura disponible y otros factores que varían significativamente de un escenario a otro. Este enfoque dinámico y adaptativo es esencial para abordar la complejidad de la gestión de residuos urbanos y encontrar soluciones sostenibles en el contexto colombiano.

Keywords: urban Solid Waste, Waste Valorization, Renewable Energy, Biorefinery, Valorization Technologies.

Palabras clave: Residuos Sólidos Urbanos, Valorización de Residuos, Energía Renovable, Biorrefinería, Tecnologías de Valorización.

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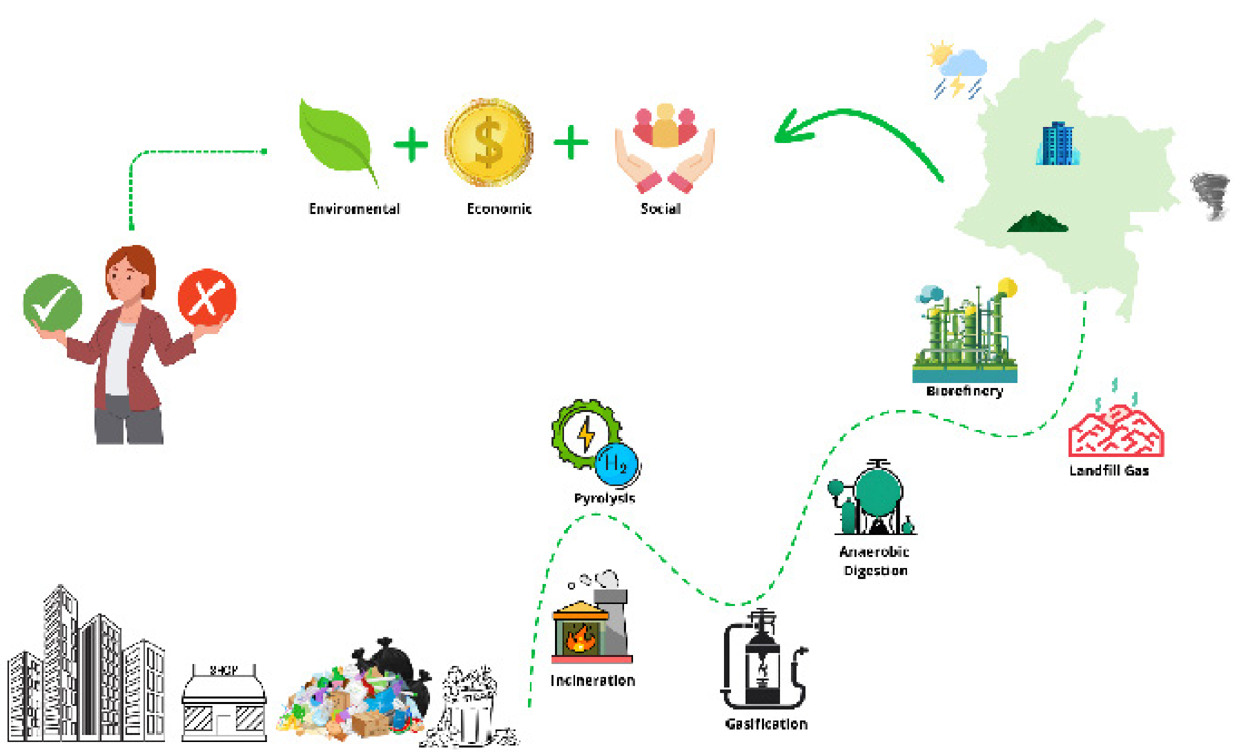
Why was it carried out?
This study was conducted in response to the growing concern over the increasing generation of urban waste globally and the need for sustainable waste management practices. Despite the effectiveness of waste-to-energy conversion technologies demonstrated in several countries, their implementation in Colombia is still in its early stages. Thus, this study aimed to conduct a comprehensive systematic literature review to evaluate solid urban waste valorization technologies and their potential integration into biorefineries within the Colombian context..

What were the most relevant results?
The study identified several key findings regarding solid urban waste valorization technologies in the Colombian context such as incineration, gasification, pyrolysis, anaerobic digestion, and landfill gas recovery.

What do these results provide?
This study sheds light on sustainable urban waste management practices in Colombia through a thorough examination of solid waste valorization technologies. It emphasizes the importance of evidence-based decision-making and the need for adaptable strategies that consider the diverse contexts and conditions within the country. Highlighting options such as anaerobic digestion, gasification, and pyrolysis, the study provides valuable insights for policymakers and industry stakeholders. By advocating for a holistic approach that integrates social, economic, and environmental considerations, it calls for concerted efforts to implement sustainable waste management solutions tailored to Colombia's unique circumstances, ultimately contributing to a cleaner and healthier environment for all.

Graphical Abstract



doi: 10.25100/iyc.v26i2 13225

Introduction

In recent decades, waste generation has become an increasingly significant challenge for humanity. It is estimated that the amount of waste produced will surpass population growth by more than double by the year 2050. Currently, approximately 2.24 billion tons of waste are generated annually, with a projected 73% increase in the next 30 years (1). This alarming trend poses a series of challenges for cities and urban centers, as waste management is costly and can impact other essential services. Moreover, improper waste management can have a significant adverse effect on public health and the ecosystem at large. (2)

Waste managed by or for municipalities as a public service, including waste generated by domestic, commercial, and institutional activities, is known as Municipal Solid Waste (MSW) (3–5). These often consist of significant fractions of paper, food scraps, wood, cotton, leather, plastic, rubber, textiles, glass, and metals (6) and they represent around 50% of all waste generated worldwide. In developing countries, MSW typically accounts for a lower percentage, but they are rapidly increasing as these countries urbanize and their economies grow. (1). The improper disposal of MSW leads to significant impacts, such as groundwater pollution, sewer blockages, flooding, disease spread, vector proliferation, uncontrolled burning of waste emitting particulate matter, damage to ecosystems, and economic repercussions, including reduced tourism. (2)

According to the World Bank, 33% of the total MSW is not environmentally safely disposed of. This means it is either burned in open fires or disposed of in some form of landfill. Most of these landfills lack leachate and gas collection systems, leading to soil and water pollution, as well as considerable emissions of greenhouse gases (GHGs) (7). Landfills contribute to more than 5% of the total carbon dioxide emissions (CO_2) globally, as well as 11% of the global methane emissions (CH_4), The latter has a heat-trapping capacity 25 times greater than that of CO_2 in the atmosphere (8,9). On the other hand, leachate from landfills poses a significant environmental risk due to its potential contamination of groundwater and surface water. This contamination can lead to oxygen depletion in parts of the surface water, alterations in the fauna and flora of the streambed, and toxicity from ammonia and heavy metals (10).

In Colombia, there are currently 281 final disposal sites where 11.6 million tons of waste are disposed of annually. Only 24% of these disposal sites have a remaining lifespan of more than 10 years (11). Therefore, the implementation of an integrated waste management system focused on source minimization and efficient methodologies for reuse, recycling, and valorization is essential for the country’s future.

The conversion of waste into energy has been an alternative applied since the 1980s to address the issue of MSW, especially in Europe. This practice allows for the reduction of waste volume and provides economic, social, and environmental benefits by generating energy, reducing the need for fossil fuels, and decreasing GHG emissions (6,12). This process is carried out through Waste-to-Energy (WtE) conversion technologies such as incineration, gasification, and anaerobic digestion. These techniques have proven to be effective in European Union countries, rapidly growing economies in Asia, and also in developing nations like Brazil.

In Colombia, research production on the topic is limited and in its early stages. It is crucial for academia to propose treatment and valorization alternatives to address the challenges of MSW management and energy supply in the country. Chemical engineering plays a significant role in this field, as it is responsible for process design and optimization. The development of efficient and safe systems that maximize energy production and minimize environmental impacts is required. Establishing the general context for implementing these processes in Colombia is essential for understanding the current state of knowledge, evaluating technologies and processes, identifying challenges and improvement opportunities, and laying the groundwork for future research in the area.

This article aims, through a systematic literature review, to determine the most relevant available WtE technologies for MSW valorization and their potential implementation in Colombia. Additionally, it seeks to identify alternatives for integrating WtE technologies into biorefineries for the conversion of solid waste into value-added chemical products. The goal is to provide a comprehensive overview of the most relevant existing technologies, as well as to identify

doi: 10.25100/iyc.v26i2 13225

opportunities and challenges, and to provide recommendations and perspectives for the effective valorization of MSW in Colombia. This contribution aims to promote sustainable practices and the generation of clean energy.

Methodology

A bibliometric analysis of the literature was conducted, and the results found were used to perform a systematic review. Inclusion and exclusion criteria were established to ensure the relevance and quality of the studies considered in the review. Additionally, data extraction and critical analysis of the findings were carried out to obtain solid conclusions supported by the available scientific evidence. This combination of bibliometric analysis and systematic review constitutes a robust approach to addressing the proposed research objectives and providing a comprehensive and up-to-date understanding of the study topic.

Bibliometric analysis

Scopus from Elsevier was utilized as the search engine due to its extensive literature coverage compared to other available databases. Scopus includes journals from over 5,000 publishers and encompasses more than 200 million publications. With over 230 million keywords (however, it is important to note that some of these keywords may be repeated), it facilitates the search for relevant literature. Additionally, it provides abstracts for all indexed publications, offering an overview before detailed reading. Scopus also offers citation analysis tools that allow tracking the impact of publications, identifying the most influential ones, and observing how they are cited by other researchers.

Search equations were formulated using concepts and key terms related to MSW, such as *Municipal Solid Waste* and *Urban Solid Waste*. Additionally, related terms such as *Waste to Energy* and *Waste Biorefinery* were included to address specific valorization approaches. Tests were conducted with different combinations of terms and operators. The results obtained, presented in Table 1, reflect the number of documents found in each search. As terms and operators were adjusted, a variation in the number of results was observed, indicating the specificity and breadth of the searches. Finally, number 6 was selected as the final search equation.

Table 1. Formulation of the search equation

Search	Equation	No. of results
1	“Municipal Solid Waste” OR “Urban Solid Waste”	29,100
2	(“Municipal Solid Waste” OR “Urban Solid Waste”) AND (“Waste to Energy”)	1,730
3	(“Municipal Solid Waste” OR “Urban Solid Waste”) AND Energy	7,315
4	(“Municipal Solid Waste” OR “Urban Solid Waste”) AND (“Waste Biorefinery” OR “technology”)	4,813
5	(“Municipal Solid Waste” OR “Urban Solid Waste”) AND (“Waste Biorefinery” OR “technology” or “Waste to Energy”)	5,789
6	(“Municipal Solid Waste” OR “Urban Solid Waste”) AND (“Waste Biorefinery” OR “technology” or “Waste to Energy”) AND NOT (“Wastewater” OR “Sewage”)	5,174

Results

Of the 5,174 documents found, more than 60% belong to the article type, as shown in Figure 1. It was decided to restrict the search to this type of research documents to optimize the quality and relevance of the gathered information. This decision is based on the premise that research

doi: 10.25100/iyc.v26i2 13225

articles tend to be the primary source of reliable and up-to-date data in the field of study, which will facilitate a more precise and effective investigation.

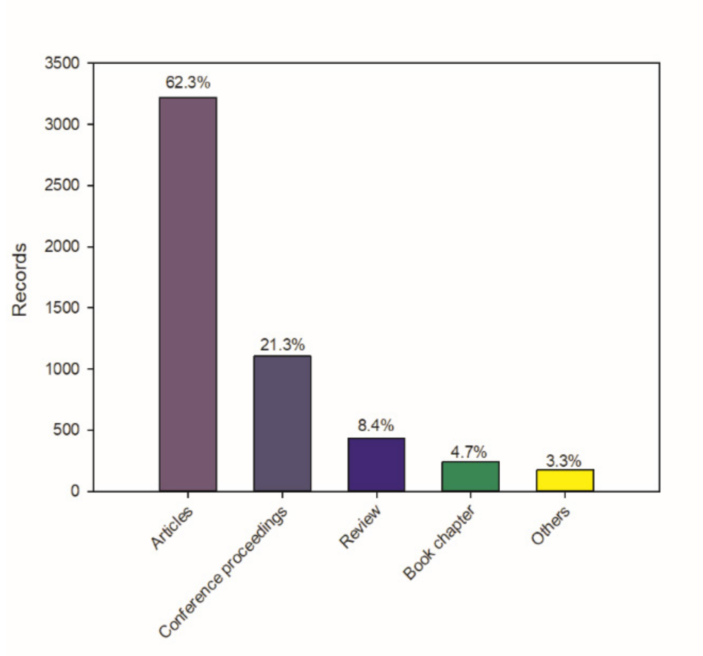


Figure 1. Distribution by document type in search results of the base equation.

The database records articles published since 1971, but it is observed that 70% of the publications are concentrated in the period from 2012 to the present, as shown in Figure 2. Therefore, it was decided to restrict the search to this time interval to obtain a sample of 2,326 articles highly focused on the most recent and relevant information in the field.

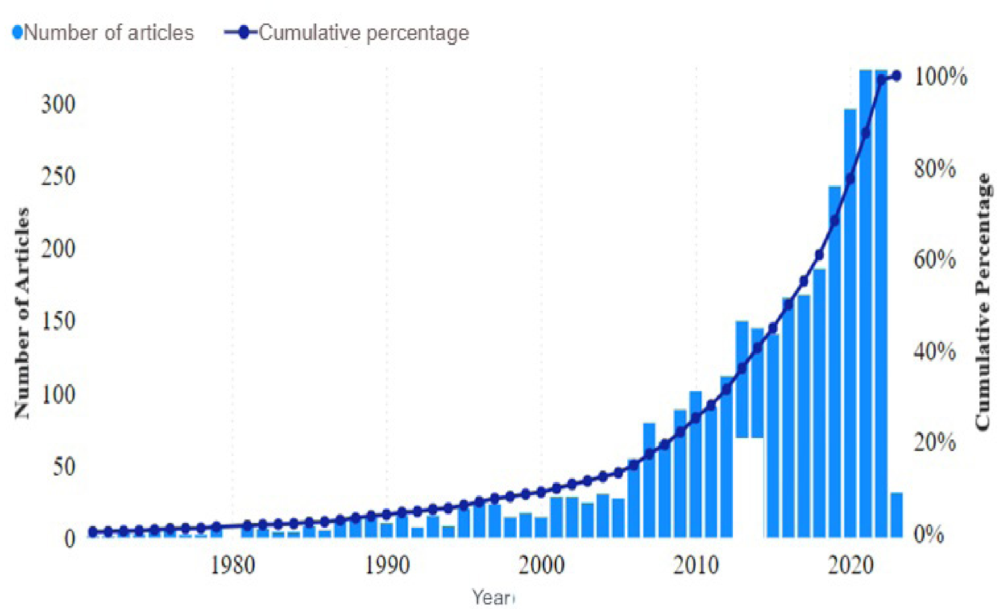


Figure 2: Number of articles published per year and their cumulative percentage.

The areas of study with the highest number of published articles for this search are Environmental Sciences (33%), Energy (17%), Engineering (13%), and Chemical Engineering (8%). These results, shown in Figure 3, indicate a significant interest in the development of these technologies due to their potential to address the problem of MSW management, provide an alternative renewable

doi: 10.25100/iyc.v26i2 13225

energy source, and require complex chemical and physical processes that engineering is responsible for designing, building, and optimizing.

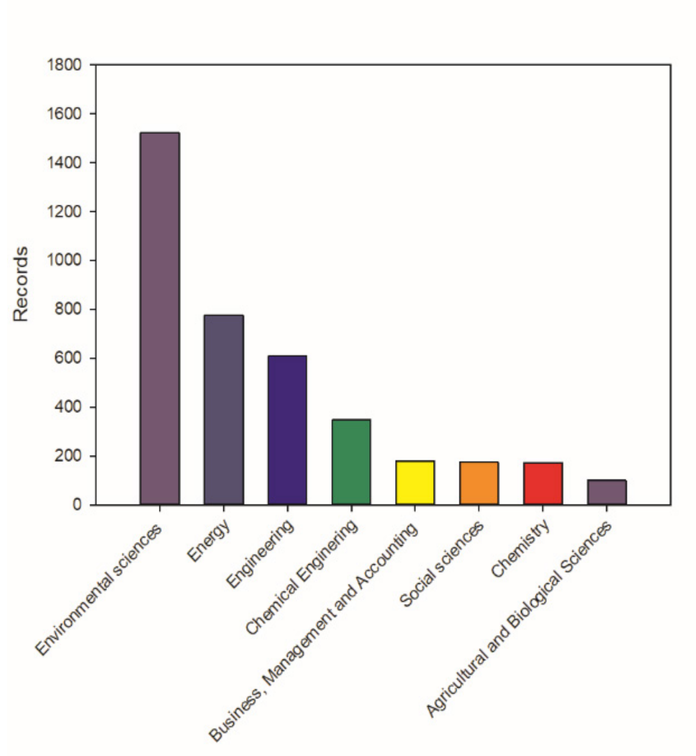


Figure 3. Number of articles per area of study

An analysis of the contribution of countries or regions was conducted through the extraction of correspondence information in the publications. Authors from 69 different countries were identified. Table 2 presents the 20 most productive countries in terms of the number of published articles. For each country, the number of publications, the percentage contribution in this search, the average number of citations received per article, the number of publications with international collaboration, and the h-index are provided. The latter is a measure used to assess the productivity and impact of a researcher based on the number of publications that have been cited at least h times. (13). The rankings corresponding to each category are indicated in parentheses.

China, the United States, and Italy lead the research in converting MSW into energy. These countries stand out due to their population, government investment, renowned academic institutions, and strong industrial interest in these technologies. Their main objective is to develop efficient and sustainable methods for MSW management, with the purpose of reducing environmental impact and generating business and employment opportunities. Globally, there is a significant momentum in energy generation from waste, with notable cases in the United States, China, and European Union countries. Italy has implemented anaerobic codigestion to harness organic waste. Additionally, there is a growing interest in countries like India, Vietnam, and Malaysia, which are starting to recover energy from organic waste. However, many developing countries have not fully recognized the potential of these technologies, representing an opportunity for future research and development in this area (14).

doi: 10.25100/iyc.v26i2 13225

Table 2. Scientific publications by country in the field of waste-to-energy conversion

Country	No. of publications	Percentage (%)	Average citations per article	Publications with international collaboration	h-index
China	563 (1)	18.1%	18 (14)	284 (1)	50 (1)
United States	216 (2)	6.9%	21 (12)	160 (2)	40 (3)
Italy	210 (3)	6.7%	32 (1)	97 (5)	44 (2)
India	208 (4)	6.7%	17 (18)	97 (6)	35 (4)
United Kingdom	108 (5)	3.5%	26 (4)	122 (3)	29 (5)
Brazil	99 (6)	3.2%	17 (19)	35 (17)	23 (10)
Spain	95 (7)	3.0%	24 (6)	58 (11)	26 (6)
Malaysia	86 (8)	2.8%	27 (3)	108 (4)	24 (7)
Germany	80 (9)	2.6%	18 (15)	95 (7)	23 (8)
Iran	75 (10)	2.4%	18 (16)	47 (13)	23 (9)
Japan	61 (11)	2.0%	22 (11)	51 (12)	21 (12)
Australia	59 (12)	1.9%	24 (7)	59 (10)	22 (11)
Poland	53 (13)	1.7%	18 (17)	39 (16)	14 (19)
Sweden	51 (14)	1.6%	24 (8)	45 (14)	18 (15)
Canada	50 (15)	1.6%	19 (13)	30 (19)	15 (18)
France	46 (16)	1.5%	25 (5)	59 (9)	18 (14)
Saudi Arabia	45 (17)	1.4%	31 (2)	59 (8)	20 (13)
Taiwan	45 (18)	1.4%	24 (9)	32 (18)	18 (16)
Russia	45 (19)	1.4%	7 (40)	26 (20)	11 (20)
Greece	44 (20)	1.4%	17 (20)	40 (15)	16 (17)

Network Analysis

Network analysis is a quantitative method for studying the relationships between actors in a network. It is used to identify and visualize connections between authors, institutions, and keywords, as well as to detect emerging research trends (15). With VOSviewer software, network analyses were conducted between countries and keywords to identify the most relevant WtE technologies in current literature. VOSviewer enables graphical representation of bibliometric information structure and analysis of relationship patterns among key terms in literature.

Figure 4 shows the collaboration network among the 46 most productive countries. Six distinct groups, represented by different colors, were identified. It can be observed that countries tend to collaborate mainly with other countries from the same region, which is consistent with expectations.

Colombia has published a total of 20 articles, 12 of which were conducted in collaboration with 9 different countries, such as Brazil, Spain, United Kingdom, Australia, China, Cuba, United States, Switzerland, and Taiwan. Although the number of publications is relatively low compared to other countries, there is a growing interest in the development of sustainable solutions for waste management and energy generation. Among the highlighted research are those evaluating

doi: 10.25100/iyc.v26i2 13225

incineration systems, predictive analyses on MSW generation in Bogotá, and exploration of electricity production from food waste in microbial fuel cells. However, there is still a gap in detailed and comprehensive research on the possibility of energy generation from MSW in different regions of Colombia, as well as in social and community participation aspects. More focus is required on emerging and alternative technologies, as well as long-term research on the environmental effects of these technologies in the country.

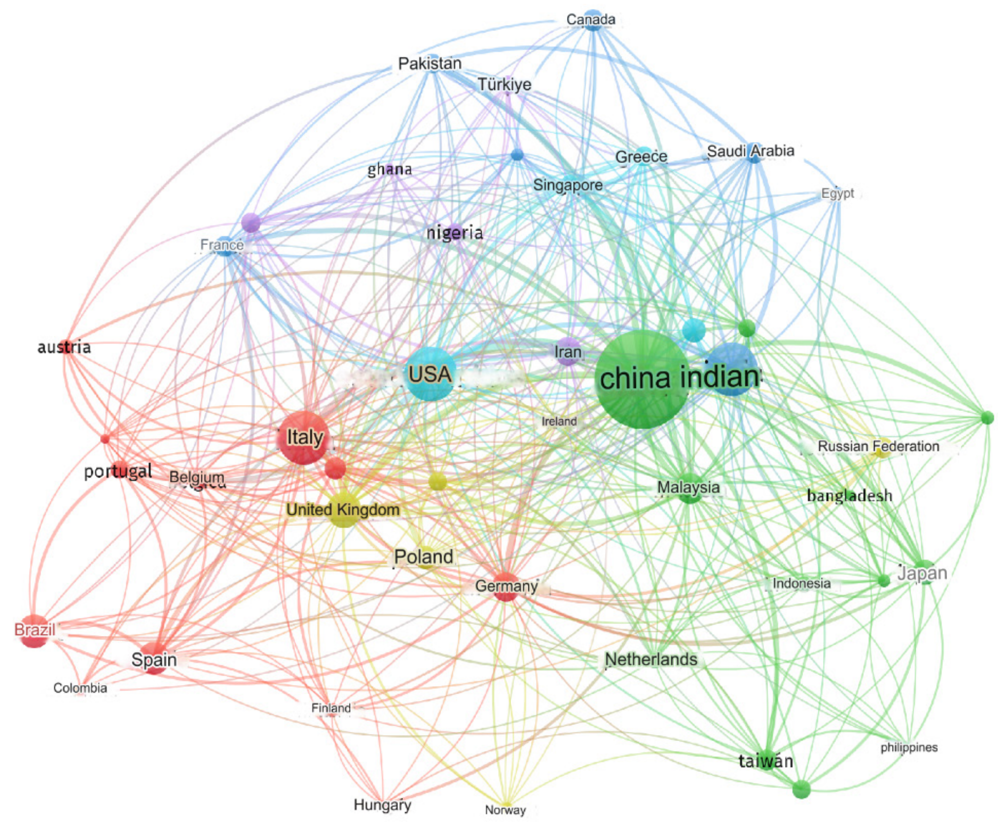


Figure 4**:** Network map of co-authorship among the 46 most productive countries

In Figure 5, the co-occurrence of author keywords that repeat more than 15 times in the results is presented. 6 distinct groups differentiated by colors are observed, which have been numbered and named according to the relationship between the terms. Among the technologies with the highest keyword co-occurrence in the analyzed publications, incineration (253), gasification (142), Anaerobic Digestion (121), landfill gas recovery (119), and pyrolysis (63) stand out. Additionally, other technologies with a lower number of mentions were identified, such as Refuse Derived Fuel (RDF), mechanical-biological treatment, plasma gasification, and hydrothermal carbonization.

Based on these results, the 5 most popular technologies in the research were identified, which will be the subject of analysis in the systematic review. This selection indicates that these technologies are relatively well developed in the waste management sector globally.

doi: 10.25100/iyc.v26i2 13225

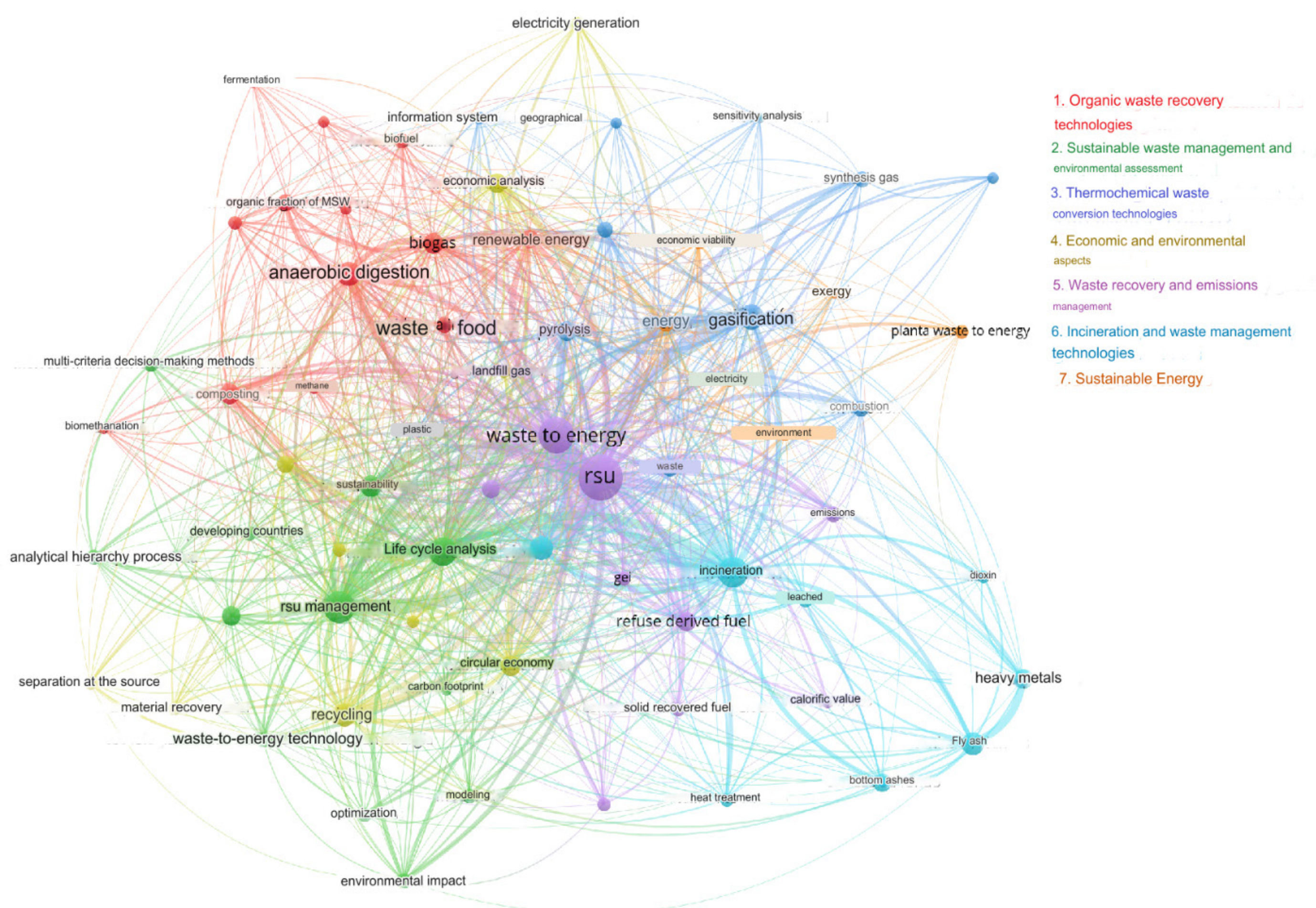


Figure 5: Co-occurrence of author keywords

Selection of Scientific Articles

After conducting the search, the titles and abstracts of the most relevant publications were evaluated based on citations, relevance to search terms, and Colombian origin. Additionally, specific searches were conducted within the initial results for each area of interest, selecting the most relevant articles in each category. This ensured the objectivity and quality of the review, providing a solid base of scientific evidence to support the conclusions and recommendations. Furthermore, complementary sources such as government reports and theses were included to supplement the research and provide a more comprehensive and contextualized perspective. This inclusion strengthened the validity and justification of the findings.

Analysis of Patent S-curves

An analysis of the technological development of the 5 most relevant technologies previously selected was conducted using an innovative approach based on S-curves generated from patent data. This methodology is employed to understand technological growth over time, identifying key phases such as emergence, growth, maturity, and saturation (Figure 6). However, it is relevant to highlight that the interpretation of these data may be influenced by various factors, such as political considerations, which could impact the actual development of a technology and not accurately reflect its maturity level. The 'S' curve allows estimating the level of technological growth in each stage and predicting when a technology will reach a particular state. It is especially used in patent data-based studies to predict the evolution of technologies and their impact on different industries.

doi: 10.25100/iyc.v26i2 13225

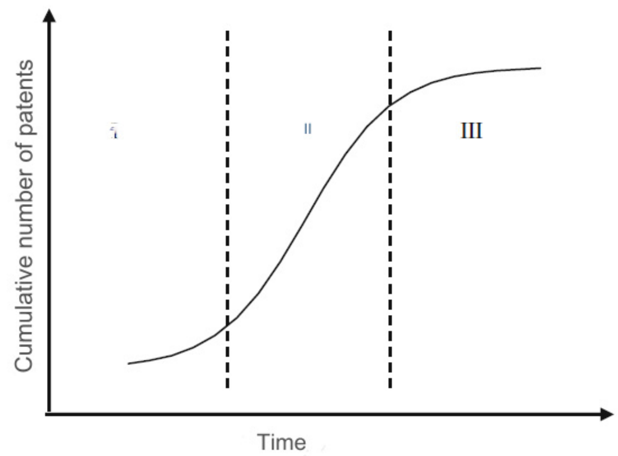


Figure 6. S-curve depicting the trend of technological development where I, II, and III represent the stages of emergence, growth, and saturation, respectively.

The patent data was collected from the Patentscope database of the World Intellectual Property Organization (WIPO) within the timeframe from 1971 to 2022. This is one of the largest and most comprehensive patent databases in the world, containing over 100 million patent documents from more than 190 countries. To fit the collected data, the online curve fitting system Loglet Lab 4 was used, which utilizes the logistic model described in detail by Liu & Wang (16) y Meyer (17). The input data consists of the cumulative quantities of patents granted up to each year. The Loglet Lab 4 system processes the curve fitting and automatically generates an 'S' curve. Figures 7, 8, 9, 10, and 11 respectively show the S-curves for the technologies of incineration, gasification, anaerobic digestion, landfill gas, and pyrolysis.

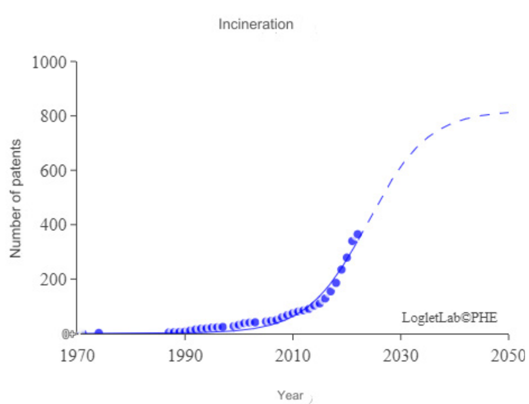


Figure 7. S-curve for Incineration

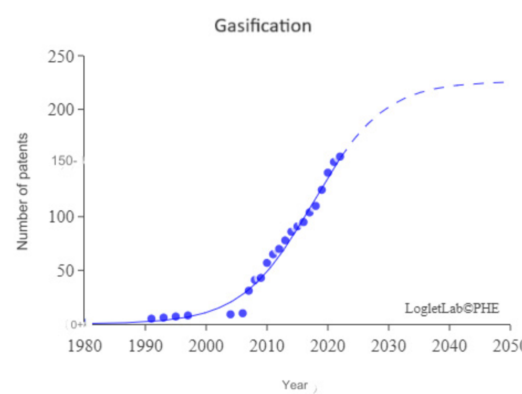


Figure 8. S-curve for Gasification

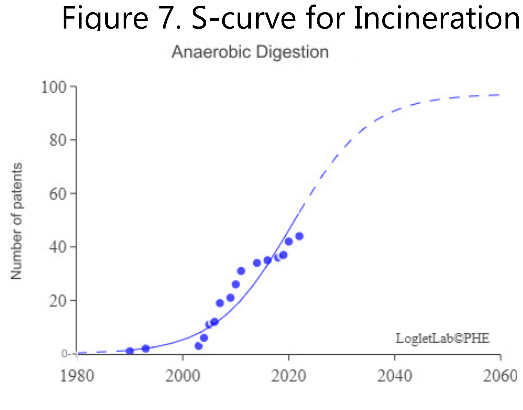


Figure 9. S-curve for Anaerobic Digestion

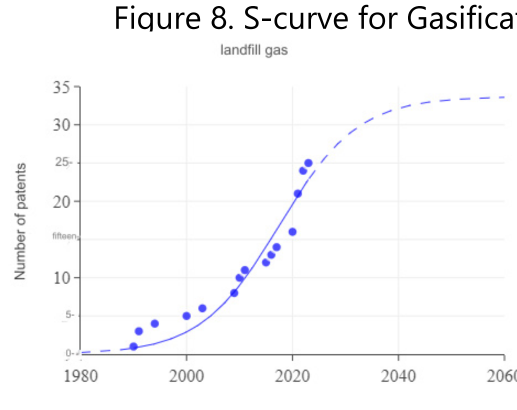


Figure 10. S-curve for Landfill Gas

doi: 10.25100/iyc.v26i2 13225

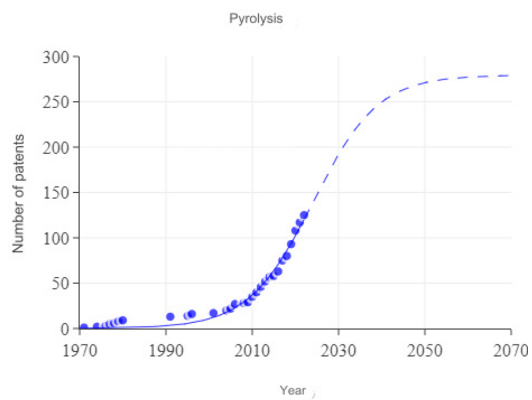


Figure 11. S-curve for Pyrolysis

The S-curve for incineration shows a period of steady growth in the number of patents until the inflection point in 2024. However, the curve reaches a patent saturation point at 820, which could indicate a slowdown in innovation after maturity. This could be due to the consolidation of established solutions in the incineration industry, but it could also indicate the emergence of more restrictive regulations limiting the focus of this technology. According to this curve, incineration is in a growth phase with significant industrial adoption, but possibly reaching maturity. Saturation is projected for 2050.

Unlike the incineration curve, the gasification curve shows a lower total number of patents. The inflection point in 2023 (with 1,745 patents) suggests a more moderate growth compared to incineration. The proximity of the patent limit value at 349 could indicate that gasification is reaching maturity earlier, which could be due to a greater concentration of research efforts in this specific technology. According to the curve, gasification is in a growth phase with a more specific focus, closer to maturity, and possibly more adopted in specialized industries.

The anaerobic digestion curve shows a similar trend to the previous ones in terms of growth and maturity, albeit with an even lower number of patents. Despite its inflection point in 2021, indicating an increase in research and development investment, the technology seems to have a patent limit at 97.3. This could reflect lower industrial adoption compared to other technologies. According to the curve, Anaerobic Digestion is in a growth phase but with more limited adoption and a relatively low patent limit value, indicating lower industrial adoption.

The pyrolysis curve shows a similar trend in terms of growth and saturation, with an inflection point in 2024 and a patent limit value of 280. However, the curve extends to saturation point in 2070, which could indicate slower or more limited adoption compared to other technologies. This could be due to specific technical or economic challenges associated with pyrolysis. According to the curve, pyrolysis is in a growth phase with moderate adoption, but the projected saturation in 2070 suggests a slower pace compared to other technologies.

The landfill gas curve shows one of the lowest patent growth rates, with an inflection point in 2024 and a patent limit value of 34.5. This suggests that landfill gas technology may be in an earlier stage of development or experiencing challenges in terms of industrial adoption. According to the curve, landfill gas recovery is in the early stages of growth with a slow adoption rate and a low patent limit value, indicating early development.

Systematic Review: Technologies for MSW to Energy Conversion

WtE technologies harness waste to generate energy through various techniques. Their advantages include waste mass and volume reduction, preservation of landfill space, degradation of pollutants, use of recyclable materials, and reduction of GHG emissions (18,19). Globally, there are over 1700 waste-to-energy conversion plants, with a higher presence in the Asia Pacific region (62%), followed by Europe (33%), and North America (4.5%) (20).

doi: 10.25100/iyc.v26i2 13225

Thermochemical technologies

Thermochemical technologies for converting MSW to energy involve the thermal treatment of organic matter to produce highly oxygenated fuel, biochar, or gas (21,22). Thermochemical technologies utilize dry waste with a high content of non-biodegradable organic matter. These processes, such as incineration, gasification, and pyrolysis, are characterized by high temperatures and rapid conversion rates compared to biochemical processes (23).

Incineration

Incineration is a widely used technology in thermochemical conversion. It involves the oxidation of combustible materials present in MSW, generating high-temperature heat that can be utilized for electricity production (24). Additionally, it significantly reduces the weight and volume of MSW, by approximately 80-85% and 90-95%, respectively, reducing the need for landfills (25–27). However, it presents challenges due to the variable composition of waste and the presence of hazardous components (28). Figure 12 outlines the process.

During incineration, byproducts such as fly ash, combustion gases, and solid residues are generated. Therefore, strict emission control is necessary, and advanced exhaust gas treatment technologies should be employed to minimize environmental and health impacts (19,29).

According to the composition of MSW and operating conditions, MSW incineration can generate compounds such as particles, dioxins, furans, NOx, SOx, VOCs, and heavy metal compounds, which pose a threat to the ecosystem and living organisms (24,30). Therefore, emission control measures and stabilization are required before the final disposal of ashes. Technologies such as filters, electrostatic precipitators, wet cleaning, and chemical reactions are employed to remove pollutants from combustion gases (24).

The objective of the process is to achieve complete combustion by supplying an excess amount of air, between 40% and 150% above the stoichiometric value, to ensure sufficient oxygen in the combustion zone (31). Additionally, it is necessary to maintain a temperature of at least 1070°C (32). Waste input into the combustion chamber only occurs when the required minimum temperature is reached (24). However, it is essential to avoid the temperature exceeding 1200 – 1250°C to prevent ash fusion. Modern plants operate at controlled temperatures of 1050-1150°C (19), and are efficient in destroying these hazardous organic substances while recovering energy (18).

The composition of the waste and the design of the combustion equipment are key factors to consider. Types of incinerators include moving/fixed grate, rotary kiln, and fluidized bed. Grate technology is considered mature and stable, while fluidized bed offers advantages in complete combustion and adaptability to low-quality waste (20,28). Energy generation is achieved through a steam generator integrated with the incinerator. It can be thermal, electrical, or combined. Combined heat and power (CHP) production is considered the best technique for energy recovery, with superior results in energy efficiency and life cycle assessments compared to electricity-only generation (33).

The net efficiency of energy production from current incineration facilities reaches values of up to 26% (30). CHP facilities typically have higher efficiencies, although exclusive electricity generation can be an option if there are no nearby thermal users (33). In order to improve efficiency in energy generation from MSW, strategies such as increasing the pressure and temperature of the steam used, minimizing heat losses by recirculating exhaust gases, CHP production, pretreatment of MSW through mechanical sorting plants, and integration of combined steam and gas cycles can be implemented (33).

This technology is more favorable in developed countries due to stricter environmental regulations and greater economic resources available. On the other hand, in developing countries, it faces challenges due to economic limitations, unfavorable composition of MSW, lack of technical expertise, and availability of suitable land. Incineration plants offer benefits such as continuous feed, rapid treatment, and emission reduction, but they also have limitations in small volumes, dioxin production, and treatment of waste with high moisture and low calorific value (34).

The largest capacity incineration plants in the world are located in countries such as China, Germany, the United States, Japan, Spain, the Netherlands, and France. With the exception of China, the MSW

doi: 10.25100/iyc.v26i2 13225

in these countries mainly consists of paper and cardboard, plastics, and metals, which gives them a higher energy content compared to MSW produced in developing countries, where organic waste with high moisture content predominates (30). China faces challenges in its MSW incineration processes due to poor waste quality and air pollution.

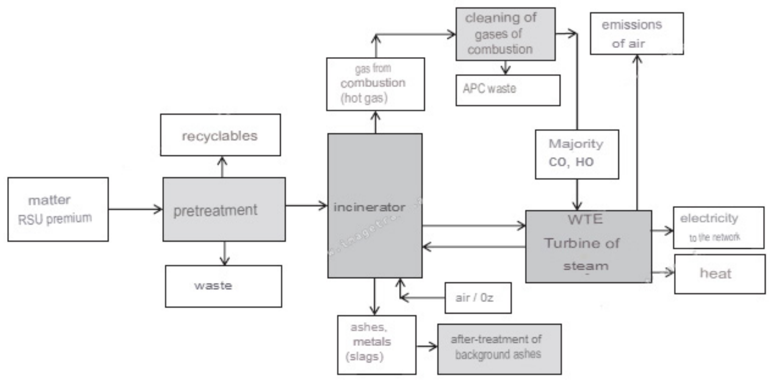


Figure 12. WtE: from MSW to energy (and heat) through incineration (APC stands for air pollution control) (30).

Gasification

Gasification is a process of transforming MSW into syngas, a gaseous fuel that can be used for energy generation as well as to produce chemicals and liquid fuels (19,35). Additionally, coke (charcoal), a combustible byproduct, is generated during the process. Syngas is composed of a mixture of H_2, CO, CO_2, CH_4 and traces of other compounds (19,25) and can be employed as a raw material in the chemical industry through various reforming processes, as well as a fuel source for efficient electricity and/or heat generation (24,30). This conversion involves the partial oxidation of carbon contained in MSW at high temperatures, typically between 600 and 1,800°C, using air, oxygen, steam, or plasma as gasification agents in quantities less than required for stoichiometric combustion (26,32,33). During the process, traces of other compounds such as ethane and propane, inert gases originating from the gasification agent, and various contaminants like small carbon particles are generated (33). Various factors such as waste type, gasifier type, and operating conditions like temperature, residence time, and oxidant used, affect the characteristics of the produced syngas (34,36). The resulting gas can be used to generate electricity in highly efficient cycles, such as gas turbines, combined gas and steam turbine cycles, or internal combustion engines (33,34). Figure 13 outlines the gasification process.

Generally, some form of pre-treatment of MSW is required before gasification can occur because it is necessary for the waste to maintain size and consistency within certain predefined limits, although this depends on the design and configuration of the gasification reactor (26). There are different types of gasification reactors, such as fixed bed, fluidized bed, entrained flow, rotary kiln, and plasma reactor, each with specific operating conditions and applications (30). Gasification processes are classified based on the oxidation medium used: partial oxidation with air, air enriched with oxygen, or pure oxygen; steam gasification; and plasma gasification. The heating value of the obtained syngas increases in that same order (37).

The overall conversion efficiencies of MSW to electricity using a conventional steam cycle are comparable to those of incineration, around 18-22%; however, they can increase up to 26-28% with the use of a gas engine or up to 30% with a gas turbine (33). This type of plants tends to be more expensive than incineration ones, but they present some advantages such as a volume reduction of over 95% (24,27), lower requirements for cleaning combustion gases, lower CO2 emissions, and the generation of H2 as a carrier of clean energy, with a high calorific value and a low exergy rate (24,26,30). Plasma gasification offers higher efficiency in electricity generation and lower formation of unwanted byproducts, such as tars, which can cause blockages in pipelines and downstream equipment (23,29,30). The primary application of thermal plasma is focused on hazardous waste destruction rather than energy recovery (33). Di Matteo et al. (2017) found that plasma arc gasification has superior thermal efficiency compared to other conventional gasification

doi: 10.25100/iyc.v26i2 13225

technologies, in addition to having the highest annual net income. This process produces vitrified slag, which is an environmentally acceptable byproduct that can generate additional revenue as a construction material.

Gasification technology faces technical, economic, and feasibility challenges for wider adoption, as it is still under development and the number of commercial plants is limited (23). Despite its technical reliability and good environmental performance, gasification faces high operating and capital costs that hinder its market penetration. There is a need to reduce the cost of syngas cleaning and improve the efficiency of electricity conversion. Research and experience gained from plants in commercial operation will be crucial in determining its competitiveness with conventional combustion systems in the future.

Asia has experienced significant advancement in recent years and can be considered one of the most favorable markets for this technology, followed by Europe, Africa, and the United States (38). Canada has shown a preference for gasification and plasma gasification facilities in its most recent WtE installations (32). Currently, there are 33 operational gasification plants in the United States, mainly using carbon-based fuels with a smaller amount of MSW. Most of them are in the demonstration or experimental validation stages for industrial and pilot-scale use (29).

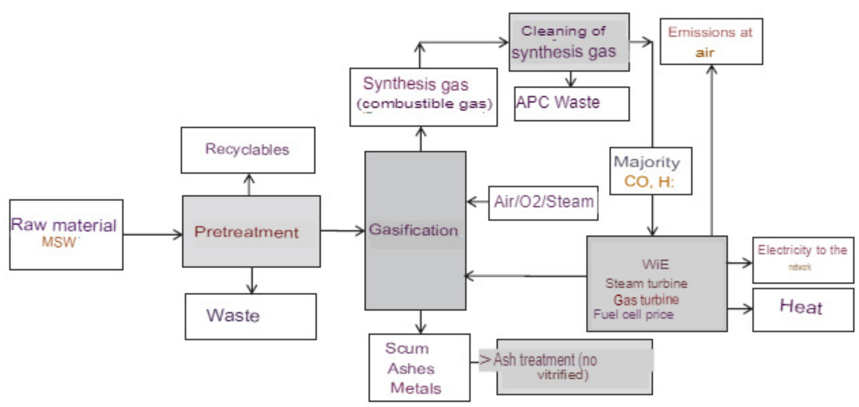


Figura 13. WtE: from MSW to energy (and heat) through gasification (APC stands for air pollution control) (30).

Pyrolysis

Pyrolysis is a thermochemical process in which MSW is thermally degraded at high temperatures in an inert environment. It is carried out at temperatures of 400-900°C, typically below 700°C (19,30), and has the ability to reduce the volume of waste by 50-90% (27). Through this process, products such as biochar and bio-oil are obtained, along with minor gases such as CH4, CO, H2, and CO2 (39). The relative proportions of these products depend on the characteristics of the raw material, the method of the process, and the reactor parameters. While biomass pyrolysis has been widely studied, MSW pyrolysis is still in the research stages. Studies have been conducted on the pyrolysis of various types of waste, such as plastics, tires, wood, and electrical and electronic equipment (33). Among the drawbacks of the process is the need for physical separation of non-combustible elements before the process, and the use of catalysts, although they enhance efficiency and increase costs. Figure 14 schematizes the general pyrolysis process.

The condensed liquid derived from volatile compounds has versatile applications, either as combustible bio-oil after further enhanced processes or as an essential precursor in the synthesis of chemical products (23). Pyrolysis, an essential process for obtaining this liquid, encompasses various variants, each contributing to the formation of a wide variety of products. These variants include carbonization (up to 400 °C), which focuses on the primary production of charcoal; slow pyrolysis (5-30 minutes, up to 600 °C), which provides both charcoal and pyrolysis oil; fast pyrolysis (0.5-5 seconds, up to 650 °C), aimed at efficiently obtaining pyrolysis oil and pyrolysis gas; flash pyrolysis (less than 1 second, less than 650 °C), oriented towards obtaining liquid pyrolysis oil and pyrolysis gas; ultra-pyrolysis (less than 0.5 seconds, up to 1000 °C), for the purpose of generating gas and fuel

doi: 10.25100/iyc.v26i2 13225

in the form of chemical products; low-pressure vacuum pyrolysis for the production of pyrolysis oil; hydropyrolysis (less than 10 seconds, less than 500 °C), aimed at obtaining pyrolysis oil and chemicals; and methanopyrolysis (less than 10 seconds, over 700 °C), which seeks the formation of gas chemical products (36,39). In particular, variants with extraordinarily short pyrolysis times, such as fast pyrolysis, flash pyrolysis, and ultra-pyrolysis, stand out for their effectiveness in the specific production of oils, gases, and chemicals. These processes minimize the exposure of organic matter to conditions conducive to unwanted secondary reactions, thereby maximizing the selectivity of the final products and optimizing the overall efficiency of the pyrolysis process.

There are different types of reactors used to treat MSW, such as rotary kilns and large-scale tubular reactors, as well as fixed-bed and fluidized-bed reactors in laboratory-scale studies (25). These conventional reactors can be combined with gasification or combustion systems for operation (7)(40). The yields and composition of products resulting from pyrolysis are affected by factors such as temperature, heating rate, and residence time. As temperature increases, gas and aromatic compound production increases. A longer residence time may increase gas production but reduce MSW treatment capacity. Additionally, high heating rates favor the formation of volatile products (14,41). Pyrolysis temperature also affects the stability and properties of pyrolytic carbon, and the use of catalysts reduces the formation of undesirable byproducts. Compared to incineration, pyrolysis shows advantages in reducing the release of heavy metals and volatile organic pollutants. For the control of pollutant emissions, exhaust gas scrubbing is considered the most efficient method (23).

Studies on the application of pyrolysis to MSW have mainly focused on technological development and system design, with little research on its feasibility and commercial use. In Europe, the MSW pyrolysis plant in Burgau, Germany, has been generating electricity since 1986, but no new large-scale facilities of this kind are currently being constructed (23). There are other successful plants operating in Germany, the United Kingdom, France, and Japan. In the latter, pyrolysis of waste tires for the production of gas, oil, steel, and carbon is popular (27). Plants with a capacity of 10 tons/day operate successfully in countries like India (29). Although these plants are small, they represent an important source of energy. However, implementing these plants in developing countries faces challenges due to the lack of infrastructure, technical expertise, and public acceptance.

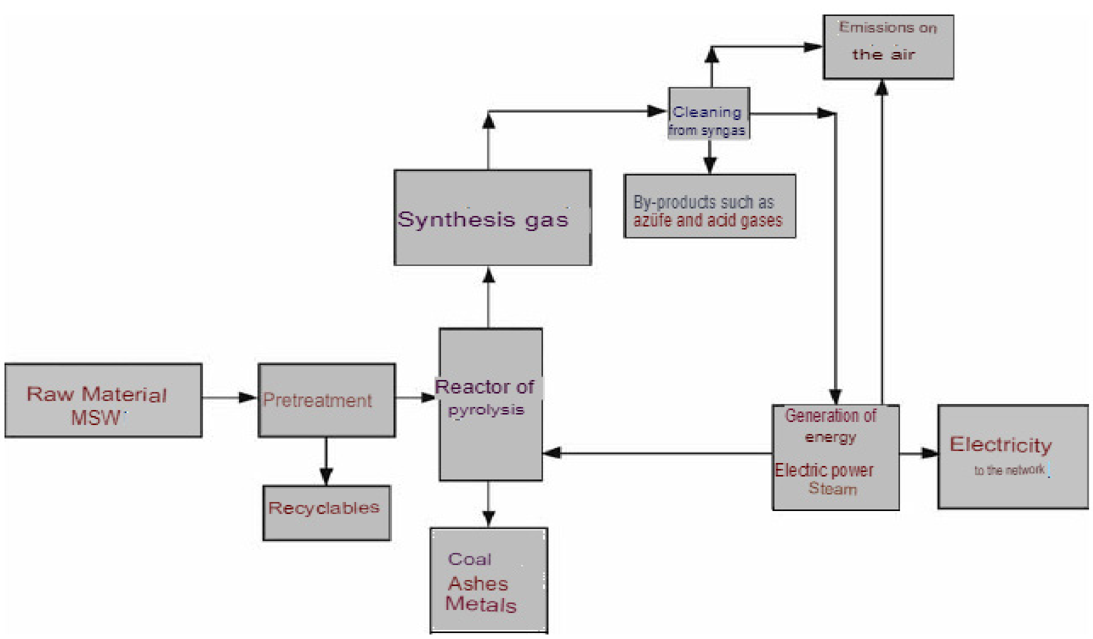


Figure 14. WtE: from MSW to energy through pyrolysis (25)

doi: 10.25100/iyc.v26i2 13225

Biochemical technologies

Biochemical techniques used in the treatment of organic waste for energy generation are based on the decomposition of organic matter through microbial and enzymatic activity, resulting in the production of biogas and digestate (22). AD is the main process, along with other technologies such as landfill gas recovery, composting, vermicomposting, and microbial fuel cells (29). These technologies offer environmental advantages, producing less air pollution and generating renewable energy. However, they can also be more expensive, require more complex operation, and generate emissions with unpleasant odors.

Anerobic digestion

AD is a microbial process that degrades organic matter in the absence of oxygen, resulting in the production of biogas and the formation of stabilized digestate (24). Biogas contains approximately 55-60% CH_4 and 30-45% CO_2, with traces of other gases (42). Biogas can be used as direct fuel or upgraded to obtain biomethane similar to natural gas, while digestate can be used as organic fertilizer (36). Figure 15 schematizes the AD process.

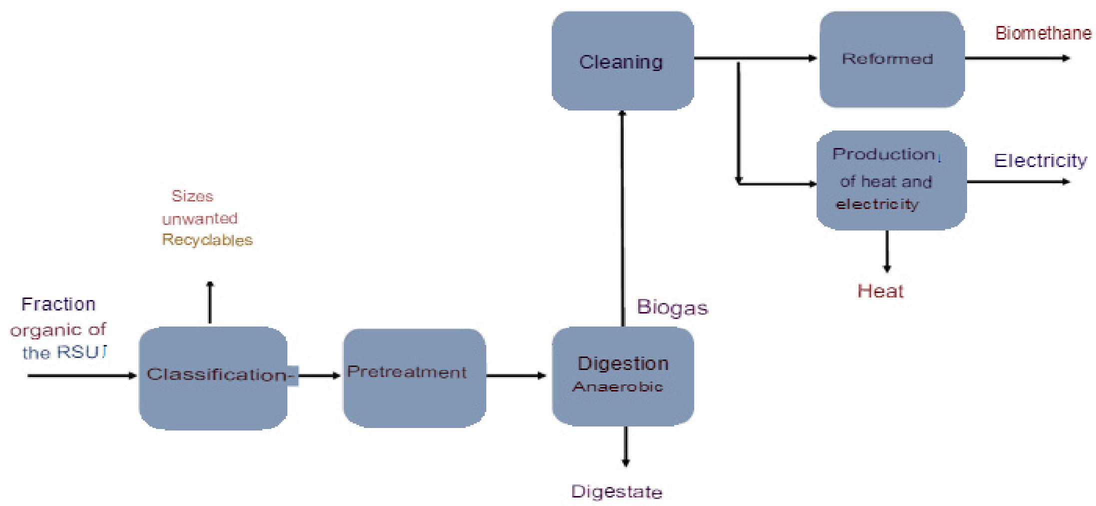


Figure 15. WtE: from MSW to energy through AD (43)

This methodology is especially useful for waste with a high moisture content (>50%). During the process, the total volume of the waste is reduced by around 35%, with a reduction of approximately 70% in the organic fraction (42). The density of the substrate influences the performance, with denser substrates being more biodegradable and containing fewer unwanted materials (44). Parameters such as total solids, volatile solids, Kjeldahl nitrogen, and pH are related to biogas production (43). The optimal pH for MSW AD is 6.8-7.2 (27,29). The recommended percentages of total solids and volatile solids in the substrate range from 11.4-27% and 15-46.3%, respectively (45). Temperature, typically mesophilic (20-40°C), is critical in the process, although thermophilic temperature (50-65°C) can be more efficient. Loading rate and retention time are important in reactor design to maximize efficiency and digester loading (39).

AD in wet processes is more efficient in terms of reactor volume (46). Compared to a landfill, AD can produce 2 to 4 times more methane in less time. It is reported that 2.04 kWh of electricity is generated per m^3 of biogas (39). Approximately, 150 kg of methane are obtained from 1 ton of MSW with an organic matter content of 60% and 40% moisture (27,43). The produced biogas is purified to remove CO_2, water, and other trace elements (29), and can be used directly for domestic purposes or to generate electricity. Biogas has a high energy content of 20-25 MJ/m^3 and emits around 0.2 kg of CO_2/kWh in electricity generation, indicating a low global warming potential compared to incineration (42). The digestate recovers nutrients and can be used as fertilizer, but its quality depends on the feedstock and there may be limitations on its use due to regulations and possible undesirable materials (21). Disposing of digestate in a landfill has advantages, as it reduces

doi: 10.25100/iyc.v26i2 13225

the mass and volume of waste, inactivates organic and biochemical substances, reduces emitted gases, prevents settlements, and eliminates toxins that could contaminate leachate (27).

AD consists of four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. During hydrolysis, complex organic compounds break down into basic molecules. Acidogenesis breaks down the remaining components, generating CH_4, CO_2, and ammonia (NH_3). In acetogenesis, simple molecules are further broken down to produce acetic acid (CH_3COOH), CO_2, and H_2. Finally, in methanogenesis, methanogenic bacteria convert intermediate products into CH_4, CO_2, and water (Figure 16). The process and its stages are described in greater detail by Barkha Vaish et al., 2016.

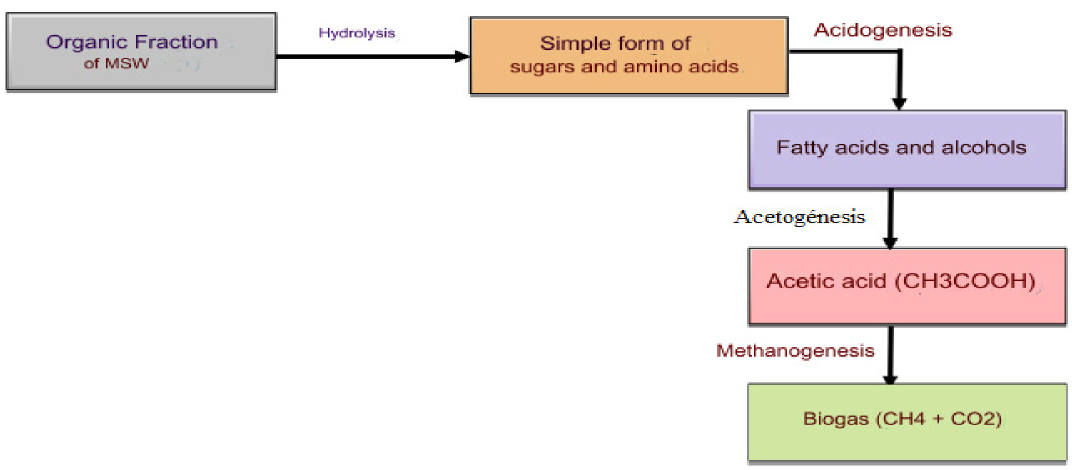


Figure 16. Stages of the AD process (39)

Landfill with gas recovery

Landfill gas recovery is carried out in modern landfills that comply with health and environmental standards. They require large land areas, potentially occupying up to 36 hectares. The United Kingdom leads in this technology, with over 435 plants and a total installed capacity of 1GWe. GHG emissions are higher compared to other WtE technologies, measuring at 1-1.2 kg CO_2/kWh. In developing countries like Colombia, most waste is disposed of in uncontrolled landfills, but there are opportunities to capture gas in large, older landfills (26).

The degradation of organic matter into landfill gas occurs in five phases: hydrolysis, fermentation, acidogenesis, acetogenesis, and methanogenesis (34). The gas is extracted from landfills and burned to produce electricity. The average biogas recovery rate ranges between 120 and 150 m^3/ton, with a calorific value of 2.5 MJ/kg. Although capital costs are low, landfill gas recovery receives less government support. Challenges are presented, such as the requirement for large land areas, referring to the need for extensive landfills. Compared to other technologies, the land area required is significantly larger, considering both the space for the power generation plant and the landfill. This requirement for more space becomes a factor to consider, adding logistical complexity and possibly affecting the viability of the technology compared to more compact alternatives. Additionally, other challenges are noted, such as the risk of spontaneous combustion and leachate contamination. Studies indicate that it is the least sustainable waste-to-energy treatment technique (29,34,41).

In North America, landfill gas recovery is the most commonly used technique among biochemical treatments. Improvements have been implemented in systems such as waste conversion into activated carbons and the combined treatment of leachate with sequential persulfate oxidation and Fenton oxidation (29). To maximize gas utilization, combined heat and power (CHP) systems are used to convert gas into electricity and heat. In Colombia, approximately 640 kWh is generated from biogas recovered at the Doña Juana landfill in Bogotá. Additionally, this technology is being implemented in Cúcuta to generate 2MW from 851 tons of MSW daily at the Guayabal landfill (11).

doi: 10.25100/iyc.v26i2 13225

Integrated MSW biorefineries

The biorefineries mentioned in the third section are based on a single conversion process to primarily produce fuels. However, there are applications for MSW in the generation of chemical products and biological materials, such as bioplastics, to address concerns about environmental impact, availability, and the high cost of oil and its derivatives (47). Biorefineries are considered a key instrument for achieving the goals of the bioeconomy and promoting the transition from linear to circular. The fundamental contribution of integrated biorefineries to the concept of the circular economy is based on their ability to transform biomass into different end products with high added value (48–50).

MSW biorefineries are facilities that integrate various WtE technologies. The organic fraction of MSW (OFMSW) is mainly composed of carbohydrates, proteins, and lipids, which represent high-potential raw materials for creating valuable products (48These facilities use a combination of specific biological, chemical, and physical processes and treatments to treat different fractions of MSW and obtain different products (21,50,51). However, there are technical, financial, and social awareness barriers that must be overcome. This requires greater investment in infrastructure, incentives to foster technological innovation, and the promotion of industrialization (49). Waste biorefineries should aim for a versatile exploitation of OFMSW as a raw material according to its nature and composition. Therefore, it is necessary to identify the most important industrial demands as well as the necessary synergies to allow for the design of a versatile and efficient facility (52).

The integration of various WtE technologies in biorefineries reduces costs. The pyrolysis technique to produce liquid oil is especially advantageous in existing oil refineries. By leveraging their infrastructure and available resources, the production of liquid oil is optimized, and the conversion process efficiency in biorefineries is maximized (53).

The world's first integrated biorefinery, initiated in 2003 in collaboration between the National Renewable Energy Laboratory (NREL, USA) and DuPont, marked the beginning of numerous similar projects in different parts of the world to obtain value-added products (54). One of the current milestones is the URBIOFIN biorefinery, which demonstrates the technical, economic, and environmental viability of converting MSW into various valuable products (52).

URBIOFIN integrated plant

The Urban Biorefinery for Innovative Fuels (URBIOFIN) plant is a semi-industrial scale demonstration biorefinery developed as a joint public-private research initiative in the European Union. Its main goal is to transform the OFMSW into various bio-based products, thus contributing to the transition towards a circular economy (48).

The URBIOFIN plant is a collaboration between 16 European companies, universities, and research centers, with a budget of 15 million euros. It uses physicochemical and biological processes in three main stages. In the first stage, MSW is sorted into OFMSW and recyclable non-organic components. In the second stage, part of the OFMSW is converted into bioethanol, which can be transformed into bioethylene for fruit ripening. Another fraction of OFMSW is converted into volatile fatty acids (VFAs) used to produce biopolymers called polyhydroxyalkanoates (PHAs) with applications in packaging and agriculture. In the third stage, the digestate undergoes anaerobic biotransformation to produce biogas, which is upgraded to obtain biomethane. During this process, microalgae are also generated and used as biofertilizers.

The URBIOFIN plant transforms 10 tons of OFMSW daily, validating the technical, environmental, and economic sustainability of these technologies. It involves all stakeholders in the value chain and exemplifies how an urban waste biorefinery can improve solid waste management by harnessing its potential as a raw material for high-value bio-based products. Additionally, it contributes to the implementation of a circular economy in the European Union and responds to the growing demand for biomass-based products instead of petroleum derivatives (48).

On the other hand, studies have been conducted in developing countries on the implementation of integrated biorefineries. Nizami, Shahzad, et al., (2017) evaluated the potential of an integrated waste biorefinery in the city of Makkah, Saudi Arabia. During Ramadan and Hajj, approximately

doi: 10.25100/iyc.v26i2 13225

20,000 and 70,000 tons of municipal solid waste are generated per day, respectively. The proposed biorefinery could treat approximately 87.8% of the waste generated, with 12.2% destined for recycling. In addition to the recovery of valuable products, the biorefinery is estimated to generate significant economic and environmental savings, landfill diversion, and electricity generation worth $141.4 million, and save 1.95 million barrels of oil and 11.2 million m^3 of natural gas.

Integrated MSW biorefineries face economic and technical challenges in developing countries. Economic profitability is affected by waste variability and high implementation costs. Lack of infrastructure and financial resources also limit the capacity to build and operate these facilities. Additionally, a shortage of technical knowledge makes it difficult to select efficient processes. Increased investment in research and development activities, as well as favorable policies and collaboration among academic, industrial, and governmental sectors, are required to overcome these challenges in countries like Colombia.

To consider waste biorefining, it's essential to have a solid understanding of the origin and quantity of waste generated, as well as recycling and reuse capacity. Factors related to waste management and valorization, proper transportation, and associated risks should also be considered. Other important factors include water management, city involvement, bridging research and development, and establishing a flexible regulatory framework (55).

Colombian context

Colombia has a remarkable potential for energy production from its municipal solid waste (MSW). The population annually generates 14 million tons of residential waste, averaging 0.77 kg per person per day (56). Despite only 15% of the waste being recycled, few efforts have been made to fully harness MSW in the country. A comprehensive and collaborative approach among the government, industry, and civil society is necessary to effectively address this issue and move towards a more sustainable management (57).

83% of MSW in Colombia is disposed of in landfills, posing challenges due to the lack of availability of new disposal sites (58). On the other hand, diversification of the energy matrix is crucial, as currently 81% relies on hydroelectric power, 17% on fossil fuels, and only 1% on biomass. Climate phenomena like "El Niño" affect the capacity for hydroelectric power generation, increasing electricity prices during dry seasons (59). Additionally, the scarcity of natural gas and oil reserves jeopardizes the country's economy. It is imperative to explore alternatives for waste management and energy generation in Colombia to address these challenges and ensure greater energy security (60).

In Colombia, MSW has an average composition of 61.5% organic waste, 10.39% cardboard and paper, 1.41% metals, 4.05% glass, 10.67% plastics, and 12.67% other waste and inert materials. The moisture content of MSW is generally over 50%, with a C/N ratio between 25-30 in the organic fraction and a calorific value of 700-1600 kcal/kg (43, 56, 61). These characteristics vary by region due to factors such as climate, level of economic development, and waste management practices. In countries like Peru, Suriname, Guatemala, and Brazil, technologies such as incineration, AD, and landfill gas recovery are employed (Margallo et al., 2019). However, in Colombia, the high moisture content of MSW hinders the efficiency of thermochemical technologies, such as incineration, due to the energy consumption required for water evaporation. Therefore, site-specific studies are required to determine the best waste management option in each case (43).

The Island of San Andrés faces issues due to the depletion of the Magic Garden landfill. To address this situation, the RSU Plant was constructed in 2012, which utilizes a grab crane and a conveyor belt to transport the MSW to two rotary combustion chambers, where they are incinerated at 850°C. The resulting gases are directed to a boiler system designed to produce steam, which is then fed into turbines to generate electricity. After this process, the gases are cooled and filtered through bag filters. The plant has a capacity of 52.5 tons per day, with an expected generation of 1.2 MW. However, the plant has encountered challenges in infrastructure, financing, technical expertise, and socio-economic and cultural aspects, which have hindered its operation. Significant investments have been made, but there are still obstacles to overcome (11, 62). Incineration as a waste management option requires careful technical and economic evaluation (63, 64).

doi: 10.25100/iyc.v26i2 13225

Recently, a project in the bidding stage for the construction of a waste-to-energy plant using incineration to transform 1,800 tons of waste per day into approximately 8.5 MW of electrical energy was canceled in Bogotá. The cancellation was due to changing financial and economic conditions, such as the increase in the dollar exchange rate, interest rates, and the rise in the cost of raw materials (65,66).

Except for landfill gas recovery at two sites mentioned in section 3, there are no operational plants in the country for energy recovery from MSW.

Discussion

In this section, the outstanding findings derived from the comprehensive review of literature related to MSW valorization technologies in the Colombian context are examined. The economic, social, and environmental factors emerging from these studies are addressed, and conclusions are presented to provide an overview and guidance in the sustainable waste management in the country.

Prioritized strategies for waste valorization in the Colombian context

Economic factors:

Incineration emerges as an option with significant capital investment, attributed to the prevalence of organic MSW and its low calorific value. Although it promises a higher net income compared to other technologies, challenges arise in the initial investment and sustained maintenance costs in the Colombian context. Conversely, gasification stands out in some studies compared to incineration, as synthesis gas offers versatile applications and contributes to the reduction of atmospheric pollutants (67). However, it is essential to note that gasification entails considerable investment to achieve efficient energy recovery through gas cleaning.

In another vein, pyrolysis presents a suitable net calorific value for the production of liquid fuel but demands an additional heat source to maintain the process temperature, resulting in higher investment and operational costs compared to AD (68). From an economic perspective, AD stands out among the mentioned technologies due to its lower capital and operational costs, besides operating at a more moderate temperature. AD not only generates biogas with substantial calorific value but also transforms by-products into fertilizers, increasing their added value. Recent feasibility studies conducted in Colombia support the adoption of AD as a preferable alternative in MSW treatment (43). It is crucial to note that, although landfill gas recovery may reduce CH_4 emissions, it is not considered the most cost-effective option in the long run due to its large land requirements for operation (69).

Social factors

Waste-to-energy conversion technologies can have varied impacts on local communities, with varying levels of acceptance. Incineration, for example, might be perceived positively due to the reduction in waste volume and job creation in areas surrounding incineration plants. However, it faces substantial concerns in terms of health and the environment due to emissions of atmospheric pollutants and fine particles, which commonly elicit opposition from local communities (70). Similarly, gasification, like incineration, could be well received due to waste reduction and job creation. However, the initial investment required to establish gasification facilities may limit their adoption and social acceptance in some communities.

Pyrolysis, by generating employment in surrounding areas, could be viewed positively in social terms. However, its higher operating costs compared to some other technologies may affect its viability and social acceptance. Regarding anaerobic digestion (AD), having a lesser impact on public health and producing fertilizers as a byproduct, it could be positively accepted by local communities. However, the need for precise control and management may increase costs and operational complexity, which could influence its social acceptance.

It is essential to highlight that landfill are often considered sources of pollution and environmental issues, and landfill gas recovery plants can generate visual and olfactory impacts in nearby areas, causing concern and opposition from local communities (71). The social acceptance of waste-to-

doi: 10.25100/iyc.v26i2 13225

energy conversion technologies varies depending on the location and local conditions. Although this study does not aim to select a specific technology, it provides valuable insights for general prioritization and offers essential considerations for the development of waste management-related projects.

Environmental factors

The various waste-to-energy conversion technologies present diverse environmental impacts. For example, incineration significantly reduces waste volume but emits air pollutants such as SO_x, NO_x, and CO_x, contributing to global warming and air pollution. The resulting ash may contain heavy metals and other contaminants that require proper management. Additionally, incineration generates carcinogenic dioxins and higher noise levels compared to other technologies (72).

In contrast, pyrolysis, when implemented correctly, tends to generate fewer harmful emissions to air quality. However, harmful volatile compounds and combustion gases with chlorine and sulfur may still be produced, requiring proper management. Gasification offers advantages such as greater waste volume reduction, but it can generate gases containing tars, particles, halogens, heavy metals, and alkaline compounds, potentially impacting the environment and human health (45).

On the other hand, Anaerobic Digestion emits less CO_2 and requires less space. It can also reduce environmental impacts such as Global Warming Potential and Freshwater Eutrophication more than other technologies (73). However, Anaerobic Digestion faces challenges related to the variability in the composition of MSW and the need for precise control and management to maintain optimal digestion conditions, which can influence its efficiency and environmental performance.

Regarding landfill gas recovery, it presents an environmental benefit by reducing methane emissions into the atmosphere. However, the efficiency of gas capture can vary depending on the age and composition of landfills, affecting its performance in emission reduction. Additionally, proper management of by-products such as leachate and ashes are essential to prevent soil and surrounding water contamination. Although landfill gas recovery requires large land areas to operate, making it less desirable in environmental terms.

Concluding remarks in the literature

The analyses presented in the scientific literature provide valuable insights into the waste-to-energy technologies in Colombia. By critically reviewing these studies, key considerations affecting local applicability and specific decision-making emerge. Alzate et al. found that all technologies generate positive revenues, but high investment costs and revenues per ton of waste and electricity sales affect the outcomes. They concluded that special energy sales prices and tax incentives are needed to ensure competitiveness in the electricity market. Montiel-Bohórquez et al. evaluated the implementation of a plasma gasification plant combined with a steam cycle and found that high plasma temperatures and low reactor temperatures improve plant efficiency, which can generate 67.8 MW of mechanical power and 56 MW of net electrical power. They concluded that strategies such as higher fees for waste entry and sales of by-products are required. I. Khan & Kabir assessed the sustainability of 4 technologies in the context of developing countries and found that anaerobic digestion (AD) and incineration are the most and least sustainable options, respectively, while gasification and pyrolysis rank second and third. AD was found to be the most economical and socially sustainable, followed by pyrolysis (74). studied incineration and landfill gas recovery and found that incineration has higher potential for electricity generation and greenhouse gas emissions reduction. Afanador et al., in 2022, conducted simulations of three thermal conversion processes for plastic waste and concluded that gasification and pyrolysis are promising technologies for waste management in Bucaramanga, Colombia.

Recommendations

In the complex scenario of MSW management in Colombia, the choice of technologies for energy conversion must be addressed with a comprehensive and objective perspective. While Anaerobic Digestion emerges as a potentially suitable alternative, it is acknowledged that this technology is primarily designed for the biodegradable organic fraction of MSW.

It is crucial to emphasize that the choice of technologies must be based on specific studies that consider the variability of Colombian MSW. The heterogeneous composition of MSW collected

doi: 10.25100/iyc.v26i2 13225

in mixed form implies that certain technologies, such as incineration, are applicable, while others, such as gasification, pyrolysis, and direct application of AD, are not viable in their raw state. Here, the existence of intermediate treatments is highlighted, such as mechanical treatment plants, which separate organic matter for composting or biomethanization, in addition to selecting other materials for recycling.

AD emerges as an attractive option not because it is the only one, but because of its versatility and ability to integrate into different scales of operation. It is essential to consider that the MSW management process does not follow a single path, and AD can effectively fit into this flow, contributing to progress towards more sustainable systems. The variability in MSW and the need for adaptive treatments make the choice of technologies dynamic and specific to each case. This discussion does not seek to establish AD as the only viable option but rather to highlight its suitability in the Colombian context.

Conclusions

Based on the systematic review and bibliometric analysis of WtE technologies, with a focus on the Colombian context, the following conclusions are drawn:

The variability in the composition of MSW in Colombia presents a significant challenge, requiring flexible approaches and adaptive technologies for its treatment. The selection of technologies must consider the heterogeneous nature of waste collected in a mixed manner.

Despite the technical feasibility of alternatives such as incineration, gasification, and pyrolysis, Anaerobic Digestion emerges as an attractive option in the Colombian context. Its applicability at different scales and the ability to manage waste with high moisture content and low quality are highlighted aspects.

The lack of specific information on the composition and characteristics of MSW in Colombia underscores the need for further research. Specific studies addressing the peculiarities of waste in the region are essential for informed decision-making.

The transition to advanced landfills, coupled with the elimination of open dumps, is perceived as a valuable strategy. However, the importance of implementing incentives and subsidies to address the costs associated with these technologies is emphasized.

The choice of valorization technologies must be dynamic and adaptive, considering the variability in the composition of MSW and the need for specific treatments. Source separation and waste hierarchy should be central aspects of management strategies.

Integrated MSW biorefineries show potential for MSW treatment, but they are still in an early stage of development in Colombia. However, it is essential to promote research and multidisciplinary collaboration to assess the feasibility of integrating multiple technologies into MSW biorefineries.

Ultimately, promoting more sustainable waste management systems in Colombia relies on a careful evaluation of available options and a balanced approach considering technical, economic, social, and environmental aspects. The path towards a more sustainable future in waste management involves ongoing commitment to research, innovation, and multidisciplinary collaboration in pursuit of optimal solutions for the Colombian context.

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