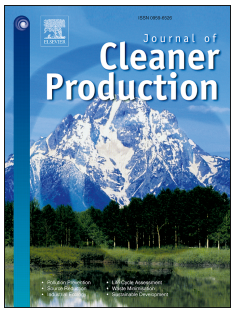
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Waste-to-Energy technologies for municipal solid waste management: Bibliometric review, life cycle assessment, and energy potential case study

Cristhian Chicaiza-Ortiz, Pedro Peñafiel-Arcos, Robinson J. Herrera-Feijoo, Wenchao Ma, Washington Logroño, Hailin Tian, Wang Yuan

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Waste-to-Energy technologies for municipal solid waste management: Bibliometric review, life cycle assessment, and energy potential case study

Cristhian Chicaiza-Ortiz [1,2,12,13], Pedro Peñafiel-Arcos[3], Robinson J. Herrera-Feijoo[4], Wenchao Ma[5,12*], Washington Logroño[6,7,8,9], Hailin Tian[10,11], Wang Yuan[12]

[1] China-UK Low Carbon College, Environmental Science and Engineering School, Shanghai Jiao Tong University, Shanghai 200240, China.
[2] Biomass to Resources Group, Universidad Regional Amazónica Ikiam, Tena, Napo 150150, Ecuador.
[3] Escuela Superior Politécnica de Chimborazo (ESPOCH), Sede Orellana, El Coca 220150, Ecuador.
[4] State Technical University of Quevedo (UTEQ), Faculty of Agricultural and Forestry Sciences, Quevedo Ecuador.
[5] Key Laboratory of Agro-Forestry Environmental Processes and Ecological Regulation, School of Ecology and Environment, Hainan University, Haikou,570228, China
[6] Department of Environmental Microbiology, Helmholtz Centre for Environmental Research–UFZ, 04318 Leipzig, Germany.
[7] Department of Environmental Science and Bioeconomy, Sustainable Environment Research Division, ECARI–Ecuadorian Centre for Advanced Research and Innovation, Ecuador
[8] DBFZ Deutsches Biomasseforschungszentrum gemeinnützige GmbH, Biochemical Conversion Department, Torgauer Strasse 116, Leipzig, 04347, Germany
[9] Grupo de Investigación y Desarrollo para el Ambiente y Cambio Climático (GIDAC-CEAA), Facultad de Ciencias, Escuela Superior Politécnica de Chimborazo, 060155 Riobamba, Ecuador.
[10] Energy and Environmental Sustainability for Megacities (E2S2) Phase II, Campus for Research Excellence and Technological Enterprise (CREATE), 1 Create Way, Singapore 138602, Singapore.
[11] School of Ecology, Environment and Resources, University of Technology, Guangzhou 510006, China.
[12] School of Environmental Science and Engineering, Tianjin University, Tianjin 300072, China
[13] Sustainable Environmental Biotechnology (biotecambiental.com), Consulting and Services, Shanghai, 200240, China.

Keywords: Municipal Solid Waste, Waste Management, Life Cycle Assessment, Incineration, Gasification, Waste-to-Energy, Network analysis.

Corresponding author: Wenchao Ma (mawc916@tju.edu.cn)

Abstract

Inadequate municipal solid waste (MSW) management threatens public health and the environment. The waste-to-energy (WtE) route allows the production of electricity, heat, and other valuable chemical products. WtE consists of incineration, gasification, pyrolysis, and some emerging technologies. This study applies the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to conduct a bibliometric analysis of WtE technologies for MSW management research. Scopus-indexed articles were examined between 1971 and 2023. Four periods were determined and analyzed in terms of their most significant results. In addition, the most pertinent journals, Waste Management, Chemosphere, and Waste Management & Research, were ranked first, second, and third, respectively. Moreover, the top contributor countries are one in America (the United States), three in Asia (China, Japan, and India), and five in Europe (Spain, Italy, Germany, Sweden, and the United Kingdom). Throughout a Life Cycle Assessment (LCA) case study, the environmental performance of gasification and incineration as relevant technologies for treating MSW were contrasted. Gasification excelled in seven environmental parameters, suggesting that developing strategies for MSW gasification on a commercial scale should prioritize this aspect. Finally, the energy potential was assessed, which provided valuable information on the societal

benefits of WtE technologies in various sectors, such as education, health, and electromobility. Under their respective contexts, stakeholders should enhance MSW sorting policies, pretreatment methods, and emerging valorization options. Increasing global interest in WtE requires a social, environmental, and economic evaluation before implementation.

Abbreviations

AD: Anaerobic Digestion
AOP: Advanced Oxidation Processes
BEV: Battery Electric Vehicle
CCUS: Carbon Capture, Utilization, and Storage
EAE: Enzyme-Assisted Extraction
EIA: Environmental Impact Assessment
ELFM: Enhanced Landfill Mining
EEA: European Economic Area
EU: European Union
GHGs: Greenhouse Gases
HTC: Hydrothermal Carbonization
HTL: Hydrothermal Liquefaction
IFA: Incinerator Fly Ash
ISO: International Organization for Standardization
ISWM: Integrated Solid Waste Management
IVOC: Intermediate Volatility Organic Compound
LCA: Life Cycle Assessment
LHV: Lower Heating Value
MAE: Microwave-Assisted Extraction
MFA: Material Flow and Analysis
MFC: Microbial Fuel Cell
MJ: Megajoule
MJ/Nm^3: Megajoule per normal cubic meter
MSW: Municipal Solid Waste
MSWI: Municipal Solid Waste Incineration
PLE: Pressurized Liquid Extraction
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PV: Photovoltaic
Scopus: Science Citation Indexing Probability and Coverage Database
SDG: Sustainable Development Goals
SJR: Scimago Journal Rank
SFE: Supercritical Fluid Extraction
SVOC: Semi-Volatile Organic Compound
TJ: Terajoule
USD: US Dollar
UAE: Ultrasonic-Assisted Extraction
WOS: Web of Science
WtE: Waste-to-energy

Chemical Compounds and Elements:

As: Arsenic
Ca: Calcium
Cd: Cadmium

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Cl: Chlorine
CO_2: Carbon Dioxide
Cr: Chromium
Cu: Copper
Na: Sodium
NO_x: Nitrogen Oxides
Pb: Lead
PCDD/PCDF: Polychlorinated Dibenzo-p-Dioxins/Polychlorinated Dibenzofurans
S: Sulfur
Si: Silicon
Zn: Zinc

1 Introduction

Municipal solid waste (MSW) is a significant environmental challenge affecting cities and communities worldwide. Rising MSW generation poses a grave threat to public health and the environment (Di Maria et al., 2021). MSW management is a complex challenge to governments and citizens due to the lag of technology and limited resources in developing countries (Kumar, 2016). Practices of Integrated Solid Waste Management (ISWM) represent the incorporation of different waste materials, sources of waste, collection practices, and various treatment techniques. ISWM performances can be validated by economic assessment, Material Flow and Analysis (MFA) (Guo et al., 2019), and Life Cycle Assessment (LCA), among other indicators (Muralikrishna and Manickam, 2017). LCA is based on a long-term evaluation to guide the decisions to reduce environmental loads, selecting the most suitable alternative (Bastianoni et al., 2023; Cremer et al., 2020; Schaubroeck et al., 2022). LCA has been extensively used for evaluating the environmental impacts in traditional MSW management (Avellán et al., 2017; Chicaiza-Ortiz et al., 2020; De Morais Lima et al., 2019; Nhubu et al., 2020; Shrestha et al., 2023; Tutunchian and Altınbaş, 2023); however, the number of articles in respect of Waste-to-energy (WtE) under the LCA approach is limited.

WtE is one of the promising approaches for MSW management; while significantly reducing the volume of MSW, it generates renewable energy and some valuable chemical products (Dong et al., 2018a; Kumar et al., 2023; Naveenkumar et al., 2023). In addition, WtE technologies can recover valuable materials like precious metals in urban mining (Funari et al., 2023) and circular economy (Gatto, 2023). WtE can support specific value chains such as raw material production, valorization of new waste flows in recycling, and an option for fossil fuels within a small land occupation (Lausselet et al., 2016a). Several WtE technologies are available to treat MSW, including incineration, gasification, and pyrolysis (Oakey, 2016a). WtE technology facilities are robust technology (Vaish et al., 2017). WtE uses a combination of post-recycled MSW and industrial residues, frequently the first one in a higher proportion; there is a pretreatment that enhances the low heating value (LHV) of MSW (Yong-Chil et al., 2018). The inability to recycle significant quantities of hazardous organic materials necessitates the adoption of WtE technologies as the most viable option for attaining a sustainable solution. Nevertheless, public acceptability is not given (Brunner and Rechberger, 2015; Yang et al., 2021).

Among the available options, gasification has promising results because of its robustness for energy conversion from biomass and coal (Dai et al., 2023; Tanigaki et al., 2012a). Gasification allows the conversion of MSW into gaseous fuel (syngas) that can be used in gas engines, combined cycle gas turbines, and solid oxide fuel cells (Ma et al., 2020a). Frequently, the syngas go through some stages, such as wet gas cleaning and induced draught fan; then, the syngas can have two

pathways. It could be directed to a gas engine, generating power, or run to a thermal oxidizer for complete oxidation (Materazzi, 2016a). Moreover, reaching high-quality syngas depends on the MSW composition and other aspects such as the pretreatment (particle size reduction and drying of the feedstock), operating parameters (gasifying agent, reaction temperature), and catalysts. The gasification process works with as little thermal energy as possible to convert the feedstock to valuable fuels, but the actual reactions involved with gasification are highly complicated and vary with the properties of the feedstock (Wang and Stiegel, 2017). As a result of the higher temperature and reduction conditions, the gasification of MSW could decrease the dioxin formation and gas emission (Bei et al., 2022; Xu et al., 2017a). Utilizing waste as co-gasification feedstocks can significantly reduce carbon emissions (Qin et al., 2023). In the same way, cleaner biomass materials are renewable fuels and can be linked with reasonable prices in electricity generation (Oakey, 2016b; Shahabuddin and Alam, 2022). Gasification requires security procedures and control equipment to handle syngas due to its toxicity and explosivity; the plants tend to be more expensive and difficult to operate and maintain, and another disadvantage may be the connection between the production of pollutants and the processing of syngas downstream from the gasifier (Consonni and Viganò, 2012).

On the other hand, the incineration of MSW has certain benefits, which include reducing MSW sent to landfills, producing renewable energy, lowering emissions, and fostering a circular economy (Zhang et al., 2021), even some potential economic benefits in developing under an adequate policy (Silva et al., 2020). MSW Incineration has developed actively within the last 50 years; contrarily, pyrolysis and gasification are relatively new technologies available for MSW, not coal (Xi et al., 2016). Nonetheless, additional research and enhanced practices are required to maximize these benefits and minimize potential adverse effects (Xue and Liu, 2021). For instance, MSW incineration produces harmful emissions of acidic gases, dioxins, and toxic heavy metals (Xu et al., 2017b). In the long term, local populations consuming food grown near incinerators and distant people consuming food transported from regions near an incinerator are both susceptible to exposure; thus, older incinerators have been linked to neoplasia, congenital anomalies, and infant mortality (Tait et al., 2020).

Due to the significance of this topic in the social, economic, and environmental spheres, reviews of WtE have been published recently (Choi et al., 2023; Nandhini et al., 2022). However, most of those efforts are focused on specific regions (Dadario et al., 2023; Karmakar et al., 2023; I. Khan et al., 2022; Roy et al., 2022), only a certain fraction of MSW (Li et al., 2022; Magama et al., 2022) or under specific approaches (Khan et al., 2022; Ochieng et al., 2022). In addition, only two bibliometric analyses have evaluated the research findings, influences, and trends of WtE for MSW, one of which is outdated (Wang et al., 2016). The other is limited to reviewing fewer than 400 documents, which is insufficient for this field and slanted toward the circular economy (Boloy et al., 2021), whereas this topic should be analyzed from a broader perspective. The present study develops a bibliometric analysis of WtE technologies for MSW management to address this research gap. This paper aims to analyze WtE technology trends for MSW management research comprehensively. The Scopus database was examined for articles published between 1971 and 2023. Bibliometric techniques such as co-citation analysis, bibliographic coupling, and keyword analysis were used to explore the data. Although it is challenging to establish a fair and valid comparison between MSW treatment technologies, the authors considered conducting an environmental performance comparison between incineration and gasification using the LCA approach to find the strengths and weaknesses of the most relevant WtE technologies. Finally, an energy potential evaluation was conducted to identify the societal benefits of WtE technologies across various sectors, such as education, healthcare, and electromobility within China.

2 Materials and methods.

In this study, the methodology was divided into four phases. The first three are related to the bibliometric analysis of WtE technologies for managing MSW. To develop it, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology was used to achieve a fast, efficient, and transparent evaluation of the collected scientific articles (Page et al., 2021). The PRISMA method complements the systematic analysis and addresses specific research questions to examine the content and approach of the researchers. Finally, the fourth phase focused on a case study of the two most relevant technologies by evaluating their environmental impact and energy potential (Figure 1).

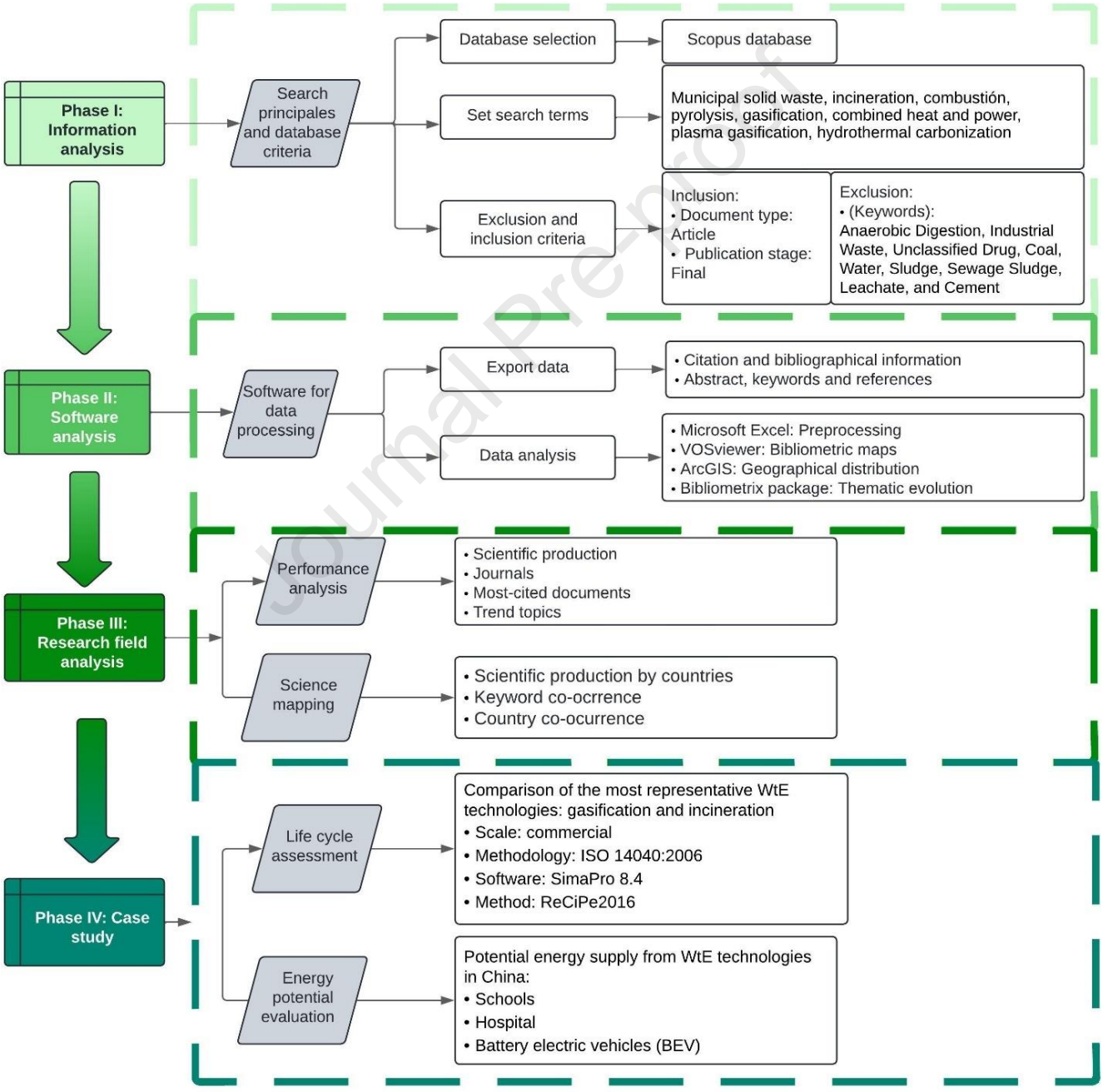


Figure 1. Diagram based on the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) methodology, depicting the four phases of bibliometric research methodology, including the case study developed in the last phase of the study.

2.1. Selection of databases and search criteria

The success of research based on bibliometric analysis depends on collecting reliable and comprehensive scientific information from academic research sources (Saltelli et al., 2008). In the academic community, the most accessible and used scientific databases in recent decades are WOS and Scopus. Scopus, launched by Elsevier Science in 2004, is one of the most relevant scientific databases today due to its comprehensive coverage in various disciplines and its ability to provide information that can be further processed by bibliometric software (Pranckutė, 2021). Although WOS offers similar services, its coverage in educational fields is lower than that of Scopus. In addition, Scopus provides information on the author's affiliation, journals, keywords, and scientific production quality indices, such as the Scimago Journal Rank (SJR) (Baas et al., 2020). Therefore, in this study, we used Scopus to generate a database incorporating the most significant number of documents to understand the historical evolution of scientific research focused on analyzing MSW Management WtE Technologies.

To conduct the search and document collection, the Scopus scientific database was queried using advanced search syntax with the following parameters: TITLE-ABS-KEY ("Municipal Solid Waste") AND TITLE-ABS-KEY ("incineration" OR "combustion" OR "pyrolysis" OR gasification OR "Combined heat and power" OR "Plasma gasification" OR "Hydrothermal Carbonization"). This process was carried out in March 2023 and yielded 9881 documents.

2.2 Exclusion criteria

First, we focused on scientific documents and selected those that belonged to the category of articles, excluding books and book chapters. The article category is commonly used in the scientific field because it offers greater depth and rigor in the information presented. In addition, we only considered papers that had already been peer-reviewed and published by March 2023, meaning they were in their final state of publication. Finally, keywords included in the previous search's results were excluded: Anaerobic Digestion, Industrial Waste, Unclassified Drug, Coal, Water, Sludge, Sewage Sludge, Leachate, and Cement. Finally, considering all these criteria, we discarded 4749 documents,

2.3 Selection of software and data

In this bibliographical review, different types of software have been used to analyze the scientific information obtained. The first is the free software RStudio 4.1.2, used for big data processing and analysis. Bibliometrix 4.1.0 was also used (Aria & Cuccurullo, 2017), a software package developed for the R environment that allows obtaining bibliometric indices and processing various bibliographic sets of scientific databases as well as CiteSpace 6.2 (Liu et al., 2023; Wang et al., 2023; Wang et al. 2024; Verdezoto-Prado, 2024); Microsoft Excel Office 16 was used for data analysis and interpretation, which helps handle large data sets obtained from scientific databases. Finally, ArcMap version 10.5 was used to map country contributions and establish global collaboration networks visually. Once the data was obtained from the Scopus database, they were exported in CSV and BibTex formats, the latter including bibliographic information, citations, abstracts, keywords, and references, while the former was used in a Microsoft Excel Office 16 sheet.

2.4 Interpretation of Data

2.4.1 Performance Analysis

Firstly, the BibTex format was used with the Bibliometrix 4.1.0 package in Rstudio 4.1.2 (Aria & Cuccurullo, 2017). Next, the annual scientific production was obtained, including the number of documents and citations per year. The information was exported in XLS format and processed in Microsoft Excel Office 16. Likewise, the scientific journals presenting the highest number of publications on MSW Management WtE Technologies were evaluated, considering the journal's name, country of origin, publisher, SJR 2021, and quartile. In addition, the most relevant scientific articles of the last decades on the topic analyzed were identified, and a ranking was created with the authors' names, the title of the article, the name of the journal, and the number of citations obtained.

2.4.2 Bibliometric Mapping

In this study, we collected information on scientific production worldwide, using the affiliation of each author to determine the country of origin. To analyze the data, we used ArcMap 10.5 to create maps that visually represented geographic information. In this study, VOSviewer (Arruda et al., 2022; Van Eck and Waltman, 2013) was employed to create both a keyword co-occurrence map and a country co-authorship map; each has a distinctive but complementary focus on WtE technology research. The co-occurrence map focused exclusively on keywords provided by authors in their manuscripts, ensuring an accurate representation of topic areas and trends as conceptualized by experts in the field. Crucial and emerging concepts were highlighted by analyzing the joint occurrence of these keywords and applying a minimum threshold of 3 connections, providing a clear picture of current and future directions in WtE research. In parallel, the co-authorship map analyzed international scientific collaborations, placing particular emphasis on the country of origin of each author. With a threshold of 5 connections, it allowed us to identify the most significant collaborations and the geographical diversity and international scope of these interactions. This dual analysis, combining keyword co-occurrence and country co-authorship, revealed comprehensive collaboration patterns and thematic trends in global WtE research, highlighting the importance of an interdisciplinary and transnational approach to advance the field.

2.5 Case study

2.5.1 Environmental assessment by life cycle analysis for MSW treatment by gasification and incineration

The ISO 14040:2006 (2006) method was followed; therefore, the steps for carrying on the LCA study are summarized in: goal definition and scoping, inventory analysis, impact assessment, and interpretation (Damgaard and Christensen, 2010; Chicaiza et al., 2020). SimaPro 8.4 was used due to its extensive application in studies of MSW (Atta et al., 2020; Catalán et al., 2017; Vassalle et al., 2023); it counts with an extensive library to help analyze, and the method ReCiPe2016 (Asadollahi et al., 2022; Buadit et al., 2020). This method applies a cause-effect model associated with the time horizon, the perspective, and the damaged pathway. There are two mainstream approaches to characterization factors, which are complementary and give helpful information to the decision-makers: middle points or endpoints (Huijbregts et al., 2016). This study used both methods to provide a comprehensive result in comparing the incineration and gasification of MSW.

2.5.2 Energy potential and its applications in social sectors

The annual generation of MSW in China is 228 million tons (Awasthi et al., 2022), with a majority production of organic waste, which averages 60% (Cheng et al., 2020). This represents a valuable

opportunity as a renewable energy source through applying WtE technologies that allow the population's energy needs to be supplied with a sustainability approach. Using the equations (1) and (2) proposed by Abushammala and Qazi (2021), the energy recovery potential of incineration and gasification, respectively, can be determined:

For MSW incineration:

$$ERP = (M\ x\ LCV_{MSW}\ x\ \eta)/1000 \quad (1)$$

where ERP is the energy recovery potential (MWh/year); M is the amount of MSW treated (kg/year); LHV_{MSW} is the lower heating value (LHV) of the MSW, which is 10 MJ/ kg (2.78 kWh/kg) for mixed MSW, while η is the average efficiency of process set at 24.5% (Pavlas et al., 2011; Lombardi et al., 2015). The overall electrical efficiency of an incineration plant is influenced by various factors, including waste combustion, lower heating value, boiler and turbo-alternator efficiency, and on-site electric energy consumption (Souza et al., 2014). Studies have estimated that WtE incineration plants can demand 520 kWh/ton of MSW (Vlaskin, 2018), with another research suggesting 152.7 kWh/ton (Hong et al., 2020). Waste incineration plants are recognized for their effectiveness in energy recovery from mixed waste and can potentially substitute energy produced by other sources (Astrup et al., 2011). These plants can generate approximately 300-700 kWh of electricity per ton of waste (Tsai, 2014). Modern plants can produce up to 640 kWh while consuming 120 kWh per metric ton of MSW (Lombardi et al., 2015), validating the self-sustainability of incineration plants for MSW.

For MSW Gasification:

$$ERP = (G\ x\ R_f\ x\ LCV_{MSW}\ x\ \eta)/1000 \quad (2)$$

Where ERP is the energy recovery potential (MWh/year); G is the amount of MSW generated (kg/year); R_f is the percentage of MSW to be treated after the sorting process, which is 72.51%; LHV_{MSW} is the LHV of the MSW after mechanical treatment, which is 14.47 MJ/kg (4.02 kWh/kg). The average efficiency η of the process is 23% (Lombardi et al., 2015; Abushammala & Qazi, 2021). The energy consumption of MSW gasification is influenced by factors such as feedstock composition, gasification technology, and the quality of the syngas produced. Generally, MSW gasification plants consume less energy per ton of MSW processed than incineration plants. For MSW gasification using a gas boiler-steam turbine system, commercial-scale efficiencies range from 15.1% to 34.8%, averaging around 26% (Dong et al., 2018). These plants typically self-consume about 119.4 kWh/t of electricity (Saft, 2007) while generating approximately 200–500 kWh/t (Lombardi et al., 2015). This underscores the self-sustained energy requirements achievable through MSW gasification.

Finally, an analysis was performed to demonstrate the potential energy supply from WtE technologies across various relevant sectors in China. Data was collected to ascertain the average energy consumption across different building types, including schools and hospitals, and the average size of these structures. Due to the expansion of electromobility, the estimation of battery electric vehicles (BEV) that can be potentially charged during their life cycle was estimated from the list of the most sold cars during 2023. Subsequently, this data was utilized to compute the potential energy supply from WtE technologies for these three sectors: education, health, and mobility.

3 Results and Discussion

3.1 Annual Scientific Production by Period

There were 5017 scientific publications focused on the thermal treatment of MSW from 1971 to 2023 (52 years). The trend of publications has been demonstrated to increase in time and the number of citations, mainly in the last decade (Figure. 2). The scientific output increased 62% from 1998 to 2023 and in an exponential manner. This indicates, on the one hand, more interest from public funding agencies in addressing the problem of MSW and, on the other hand, an alignment with the sustainable development goals (SDG).

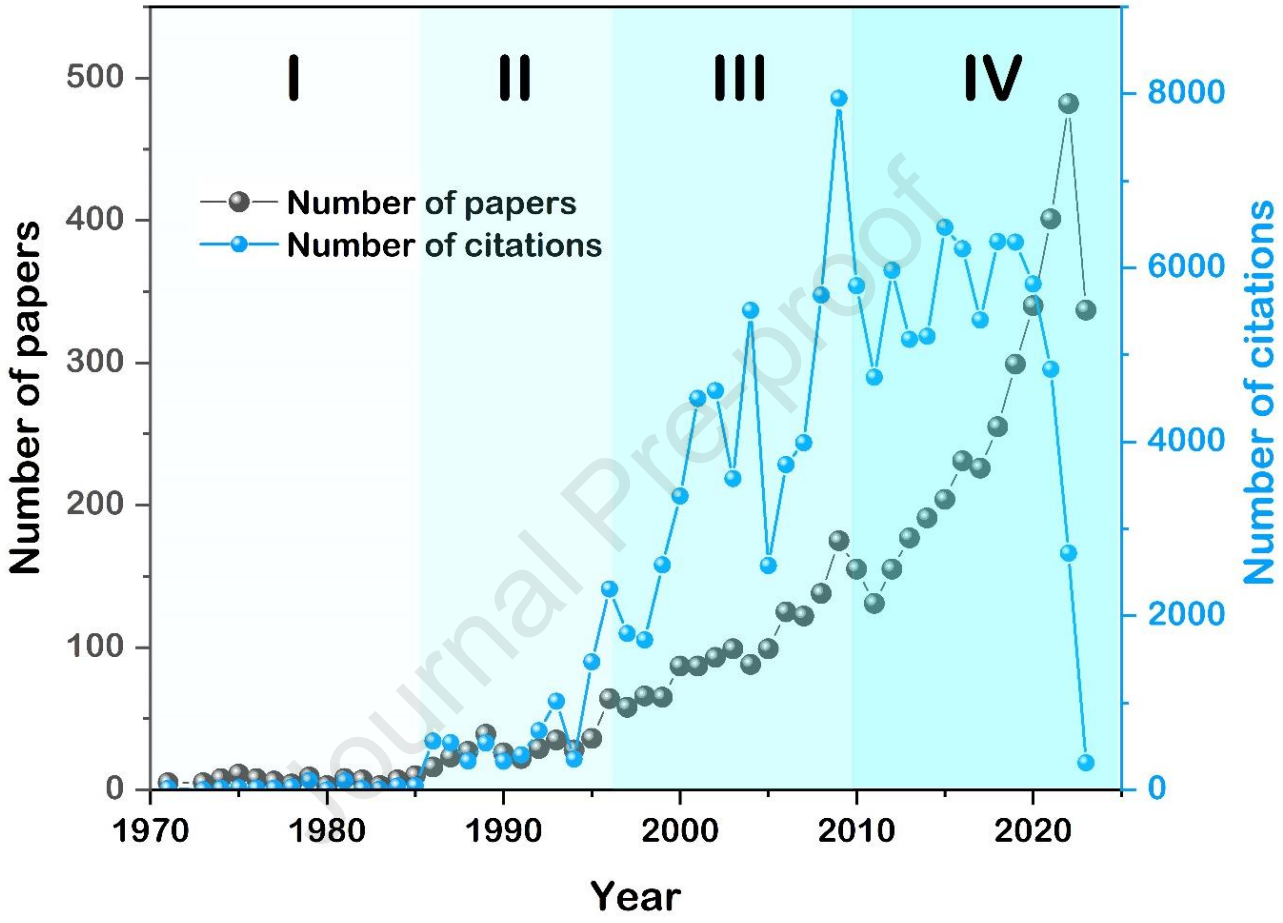


Fig. 2 Annual production and citations based on Scopus database in the period 1971-2023 for WtE technologies

This research has divided the analysis into four time periods, as shown in Table 1.

Table 1. Papers published in MSW treatment through WtE technologies.

Number	Period	Publications production
I	1971-1984	58
II	1985-1997	403

II	1998-2010	1248
IV.	2011-2023	3308

Period I (1971-1984)

We found 58 documents analyzed for this period, corresponding to 1.16% of the total production. The heat treatment with the best MSW ranking reached the incineration process (Bendersky et al., 1973a; Fernandes and Shenk, 1974), followed by a limited number of publications regarding pyrolysis and gasification (Bendersky et al., 1973b; McIntyre and Papic, 1974).

These models are novel technologies that overcome the limitations of present empirical models. The fundamental understanding of moving-bed gasifier physical and chemical processes is the main innovation of this stage. Van Swaaij (1981) provided detailed insight into these processes and stressed the need to overcome the limitations of simplified thermodynamic models. Likewise, valuable information on the limits of the simplified thermodynamic models was presented. It also made it possible to establish relationships between operating variables (particle size, solids velocity, gas composition, temperature) and gasifier performance (carbon conversion, conversion profiles), which laid the foundations for improving the design of this type of reactor, reducing the production of tars and operating under optimum conditions. All this contributed to accelerating the evolution and adoption of this technology by providing a better understanding of the limiting processes involved.

Period II (1985-1997)

There are 403 scientific articles in this period, corresponding to 8% of the total, with an average annual production of 33.6 publications and a maximum of 63 papers in 1996. A significant contribution was made by 403 scientific articles (8% of the total), with an average annual production of 33.6 and a peak of 63 in 1996. Vogg, Metzger, Stieglitz (1988), and Griffin (1986) demonstrate a relevant contribution. These studies begin to understand and control dioxin and furan formation during MSW incineration.

This period's most important finding is that dioxin and furan formation during MSW incineration is not solely due to organic precursors in the initial waste. Vogg, Metzger, Stieglitz (1988), and Griffin (1986) pointed out the mechanisms and conditions forming these compounds. Incineration and emission control technologies of that time improved significantly after this discovery. Griffin (1986) demonstrated Cl2 generation inside incinerators through the Deacon reaction and its central role in aromatic chlorination to produce PCDD, laying the groundwork for future research. This pioneering work focused on controlling pH, temperature, and HCl concentration to reduce dioxin formation. These findings shaped dioxin mitigation strategies and advanced waste incineration technologies.

Period III (1998-2010)

For this period, we found 1,248 documents related to the subject analyzed, corresponding to 24.88% of the total, with an average annual production of 104 publications and a maximum of 153 papers in 2009. It indicates an increase of 300% in scientific publications compared to the previous period. The contributions of this period are based on an integral vision of pyrolysis and gasification technologies for the sustainable treatment of the organic fraction of MSW, considering both the scientific-

technological aspects and the relevant regulations and socio-economic factors. This is relevant for MSW management since new alternatives to organic waste could replace traditional practices such as landfill, composting, or anaerobic digestion (Diéguez et al., 2022; Arellano-Yasaca et al., 2024).

The most relevant scientific contribution of the period consisted in the determination of different operating conditions that optimized the yield of biomass pyrolysis products (Yaman 2004): low temperatures (around 500°C), high heating rates, and short gas residence times favor the production of liquids (bio-oil); low temperatures (around 400°C) and low heating rates maximize the yield of char (char); high temperatures (above 700°C), low heating rates and long gas residence times improve the yield of gases (syngas rich in H_2 and CO).

On the other hand, the first step was taken in treating hazardous waste using thermal plasma technology. The treatment of various wastes, such as incineration ashes, steel sludge (Gomez et al. 2009), sanitary wastes, and medical (Park, Lee, and Kim 2005) were analyzed, pushing this technology as a viable option, even as reinforcement in concrete with the byproducts of plasma gasification (Yang et al. 2010).

Period IV (2011-2023)

Finally, the last period was the most relevant concerning the increase in scientific production focused on the thermal treatments of MSW. In this period, 3,308 articles were published, representing 65.94% of the total manuscripts considered in this analysis, with an average annual production of 275.7 publications and a maximum of 494 papers in 2022. The Enhanced Landfill Mining (ELFM) concepts began to be developed, which intended to maximize the energy recovery of MSW through a wide range of thermal processes.

Plasma gasification/vitrification is an alternative to combined energy and materials recovery (Bosmans et al., 2013; Demirbas et al., 2011). Within this context, plasma gasification is postulated as one of the most environmentally friendly alternatives due to the high temperatures that guarantee the decomposition of toxic compounds (Hameed et al., 2021; Ma et al., 2020b; Okati et al., 2023) and with more significant potential for energy recovery within WtE techniques (Chakraborty et al., 2013). In contrast, plasma gasification/vitrification still presents technical difficulties because it is a technique mainly limited to laboratory and pilot scales (Chanthakett et al., 2021; Erdogan and Yilmazoglu, 2021; Munir et al., 2019).

The development of new technologies such as Hydrothermal liquefaction (HTL) and hydrothermal carbonization (HTC) are energy-efficient thermochemical conversion processes that produce hydrochar or bio-oil (Zhang et al., 2020). HTL is pyrolysis applied to wet organic streams, such as sludge, algae, and food refuse. This method degrades liquids at 300–450°C (pressures of 2500–3000 psi). HTL produces bio-oil, gas, particulates, and an aqueous phase. The fundamental difference between thermochemical breakdown and pyrolysis is that thermochemical breakdown products are water-soluble. In addition, the aqueous phase can be recycled until its organic content renders it usable (Khan et al., 2020). On the other hand, HTC with subcritical water can process organic-rich wet MSW while providing economic benefits by recovering value-added products (Sharma et al., 2021). In all reports, the composition of HTC hydrochar depended on the primary material and operational conditions (Vallejo et al., 2020). Integrating HTC with other treatment methods to provide value with broader uses could improve circularity. The HTC method is appropriate for developing nations, such as Vietnam, where unsorted MSW is converted into solid fuel with a 17.97 wt.% ash content and 4491 kcal/kg HHV, which is economically feasible (Do et al., 2021). Although

these achievements for HTC and HTL, more research is needed to make biomass-based solvent carbonization cost-competitive with petroleum-based products (Lachos-Perez et al., 2022) and also in the byproduct's formation, for example, gaseous and liquid fractions of HTC (Vallejo et al., 2020).

In the final years of the period analyzed, research into the use of byproducts from WtE processes stands out in the context of an approach to environmentally benign building materials: developing reinforcement materials (Yin et al., 2023a), cement mortars (Loginova et al., 2023), high-performance three-dimensional (3D) printing material and printed building components (Mao et al., 2023). Therefore, three significant advancements emerged during the period under analysis, characterized by a substantial increase in scientific output on thermal treatments for MSW. To commence, WtE and ELFM became increasingly prominent, optimizing the energy extraction from MSW. Furthermore, plasma gasification and vitrification have surfaced as a feasible substitute, demonstrating their ecological sustainability by utilizing high-temperature processes and the effective decomposition of detrimental substances. Finally, noteworthy progress was observed in the fields of HTL and HTC. HTC demonstrated its economic viability for developing nations by effectively treating organic-rich wet MSW, whereas HTL swiftly transformed wet organic materials into valuable products such as gas, solid particles, and bio-oil.

3.2 Journals with the Largest Number of Documents

Table 2 shows the performance and quality indices of the ten journals with the most extensive articles on the thermal treatment of urban solid waste. These journals contain 1,275 of the 5,708 publications analyzed, representing 22.3% of scientific production. The table shows the performance indicators of journals like SJR and their quartile for 2021.

Table 2. Ranking of journals by number of publications in WtE technologies for MSW.

Journal	Country	Editorial	Number of documents	SJR	Quartile
Waste management	United Kingdom	Elsevier Ltd.	448	1.74	Q1
Chemosphere	United Kingdom	Elsevier Ltd.	251	1.51	Q1
Waste Management and Research	United Kingdom	SAGE Publications Ltd.	193	0.75	Q2
Journal of Cleaner Production	United Kingdom	Elsevier Ltd.	171	1.92	Q1
Journal of Hazardous Materials	Netherlands	Elsevier Ltd.	148	1.99	Q1
Environmental Science and Technology	United States	American Chemical Society	113	2.7	Q1
Fuel	Netherlands	Elsevier Ltd	106	1.51	Q1

Resources Conservation and Recycling	Netherlands	Elsevier Ltd.	95	2.59	Q1
Science of the Total Environment	Netherlands	Elsevier Ltd.	95	1.81	Q1
Construction and Building Materials	United Kingdom	Elsevier Ltd.	75	1.78	Q1

Waste Management, with 8.9% of the total, is the foremost journal for publications relating to the topic under analysis. One of the most relevant articles in this journal was published by Malkow and has been cited 396 times. This work presents the advantages of the gasification and pyrolysis thermochemical processes regarding the incineration of MSW in terms of reducing corrosion and polluting emissions by retaining alkaline and heavy metals, sulfur, and chlorine within the process residues, preventing significantly reduced PCDD/PCDF formation and reduce thermal NO_x formation due to lower operating temperatures (Malkow, 2004b). With 5% of all published scientific articles, Chemosphere is second. In this journal, research exposed by (Zornoza et al., 2016) analyzed the influence of the properties of the raw material, the pyrolysis temperature, the nutrient content, and the hydrophobicity of the biochar derived from the treatment of MSW, and its use as soil amendments were studied. Waste Management and Research is the third journal with the highest scientific output, accounting for 3.8% of all scientific documents published. One of the most significant contributions is the work by which the fundamentals of PCDD/PCDF formation and decomposition in MSW incineration are presented (Vogg et al., 1988b).

3.3 The top ten most-cited documents

The most cited publications within the research on the thermal treatment of MSW were identified. In this context, the scientific production focused on the subject worldwide (5,017 documents). Table 3 presents the ten most cited articles with 6,981 citations.

Table 3. Top ten most-cited papers.

Ranking	Author	Article	Journal	Quotations
1	(Demirbaş, 2001b)	Biomass resource facilities and biomass conversion processing for fuels and chemicals	Energy Conversion and Management	1403
2	(Yaman, 2004b)	Pyrolysis of biomass to produce fuels and chemical feedstocks	Energy Conversion and Management	1013

3	(Abbaspour et al., 2004)	Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure	Vadose Zone Journal	720
4	(Sørum et al., 2001a)	Pyrolysis characteristics and kinetics of municipal solid wastes	Fuel	459
5	(Demirbas et al., 2009b)	Potential contribution of biomass to the sustainable energy development	Energy Conversion and Management	449
6	(Malkow, 2004b)	Novel and innovative pyrolysis and gasification technologies for energy-efficient and environmentally sound MSW disposal	waste management	395
7	(Sabbas et al., 2003)	Management of municipal solid waste incineration residues	waste management	383
8	(Jarungthammachote and Dutta, 2007)	Thermodynamic equilibrium model and second law analysis of a downdraft waste gasifier	Energy	363
9	(Williams and Williams, 1999)	Fluidized bed pyrolysis of low-density polyethylene to produce petrochemical feedstock	Journal of Analytical and Applied Pyrolysis	305

Journal Pre-proof

10	(Nabavi-Pelesaraei et al., 2017)	Modeling of energy consumption and environmental life cycle assessment for incineration and landfill systems of municipal solid waste management - A case study in Tehran Metropolis of Iran	Journal of Cleaner Production	291

The most cited scientific article, and also the oldest, corresponds to the one proposed by (Demirbaş, 2001b). This presents an analysis of the thermal processes used for generating fuels and chemical products from biomass, where MSW takes part, highlighting pyrolysis as the best alternative to gasification, supercritical fluid extraction, and direct liquefaction. Other works that focus on the fundamentals, characteristics, and contributions to sustainable energy development of pyrolysis are introduced (Demirbas et al., 2009b; Malkow, 2004b; Sørum et al., 2001b; Yaman, 2004b). These papers highlight the importance of this heat treatment in properly managing MSW by WtE, waste-to-fuel, circular economy, and sustainable development approaches.

Table 3 shows that gasification is an alternative that has been constantly investigated (Arena, 2012; Demirbas et al., 2009b; Malkow, 2004b). In this sense, what is highlighted by Arena, (2012), where it is indicated that gasification is a technically viable option for the conversion of MSW, including the residual waste from the separate collection of this waste, allowing compliance with the existing emission limits and generating a notable effect in reducing the need from municipal landfills.

Finally, managing waste and atmospheric emissions generated in MSW incineration was studied (Hui et al., 2002; Nabavi-Pelesaraei et al., 2017; Sabbas et al., 2003). In these works, measurements and management alternatives for incineration residues are exposed to prevent any impact on our health or environment caused by unacceptable emissions of particles, gases, or solutes. Therefore, developing a spatial optimization model is essential to identify the best locations for a WtE facility in densely populated cities for transportation or economic evaluation and to prevent health problems (Sadab et al., 2023).

3.4 Trending topics

The temporal progression of research articles concerning the utilization of keywords is shown in Figure 3 (a). The topic studied in the most extensive period is "emissions," while the second is "pilot plant," indicating the significance of WtE's technical and environmental challenges. During the 1990s, the prevailing keywords associated with the byproducts produced in MSW incineration procedures were "PCDD/PCDF," "carbon monoxide," "dioxins," and "chlorobenzenes." These words emphasize the significance of quantifying and controlling byproducts. Additionally, the keywords relevant to the separation processes of the resulting gas stream included electrostatic precipitator. This exemplifies the apprehension regarding pollution generation, establishing the groundwork for advancing sustainable technologies. In contemporary literature, there has been a growing interest in research relating to "circular economy," "waste to energy," and even "gasification" since the term frequency is equal to or higher than 500. These concepts represent developmental frameworks that

aim to extract energy value from MSW, address global energy supply challenges, and promote equitable access to this fundamental service.

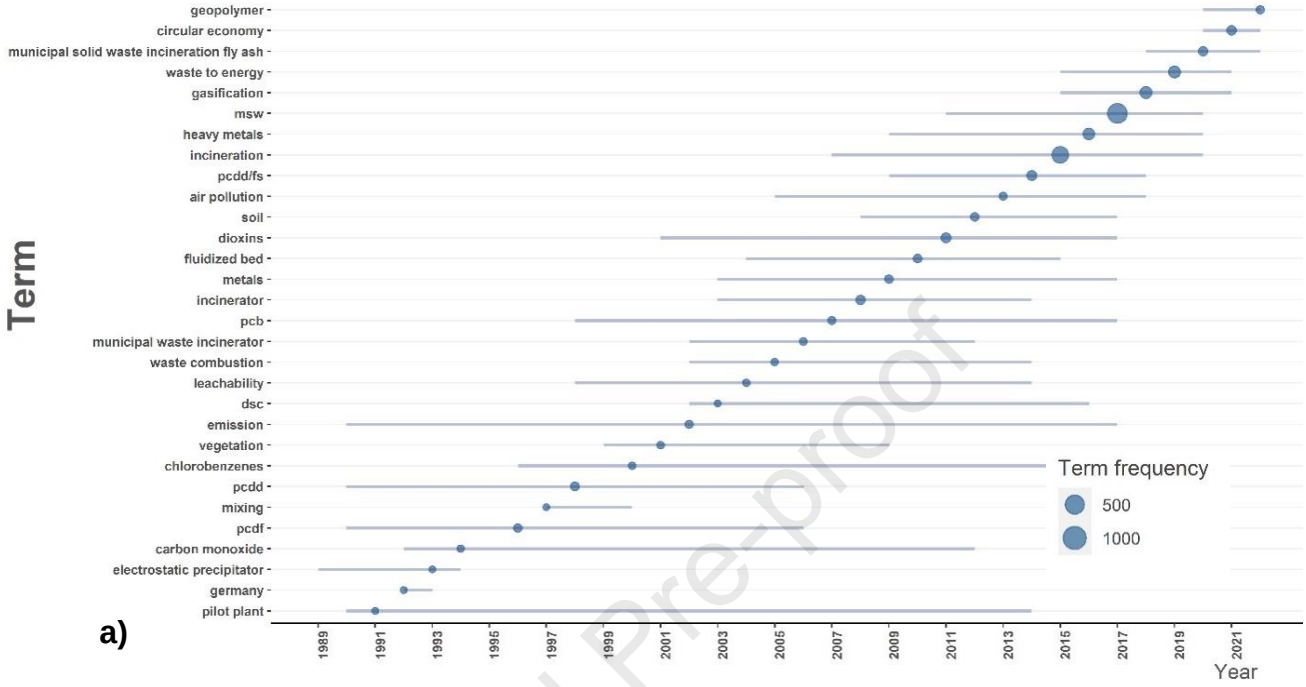




Figure 3. Trends of WtE technologies applied for MSW a) keyword term frequency generated by bibliometrics for the complete study time, b) keyword analysis during the last years focused on environmental impact assessment by CiteSpace.

Moreover, researchers have emphasized environmental impact assessment, sustainability, and LCA over the last decade, as depicted in Figure 3 (b). Recently, there has been a significant interest in chlorine compounds, solid wastes, synthesis gas, chemical analysis, and sustainable development research. Each keyword indicates the different areas; for example, synthesis gas can be linked to chemical (e.g., methanol production) and energetic uses; chemical analysis could be linked to setting new standards for environmental regulation; sustainable development can be linked to significant interest valorizing and creating value from waste resources. Each line represents a year, and a red

line represents the burst detection years. Keywords with red lines extending to the latest years indicate the frontiers. The blue bars represent infrequently cited keywords; the lighter the color, the fewer keywords are cited. The need demonstrates an understanding of environmental impacts for robust monitoring mechanisms at the beginning of the last decade. As the timeline progressed, there was a noticeable shift towards improving the sustainability quotient of WtE processes, considering factors beyond only energy recovery and encompassing economic, social, and environmental pillars. The interplay between technological advancement and sustainable development gained momentum, and research efforts focused on reducing pollutants, improving energy efficiency, and mitigating adverse ecological consequences.

3.5 Country classification by publications

For our analysis of the affiliation of the authors of scientific articles, we consider the total number of contributions from each country related to the topic of study. To visualize these contributions geographically in 108 countries, we produced Figure 4, which shows a map of the world's scientific contributions in the last 52 years on topics related to MSW WtE. The color intensity used on the map varies according to the number of scientific articles from each country, while the countries in white report zero publications. The top contributing countries include three countries from America (the United States, Canada, and Brazil), three Asian countries (China, Japan, and India), and five European countries (Italy, Spain, Germany, Sweden, and the United Kingdom). China had the highest number of publications (red), with 1,366 documents, followed by the United States and Italy (dark orange), ranked second and third with 529 and 378 papers, respectively.

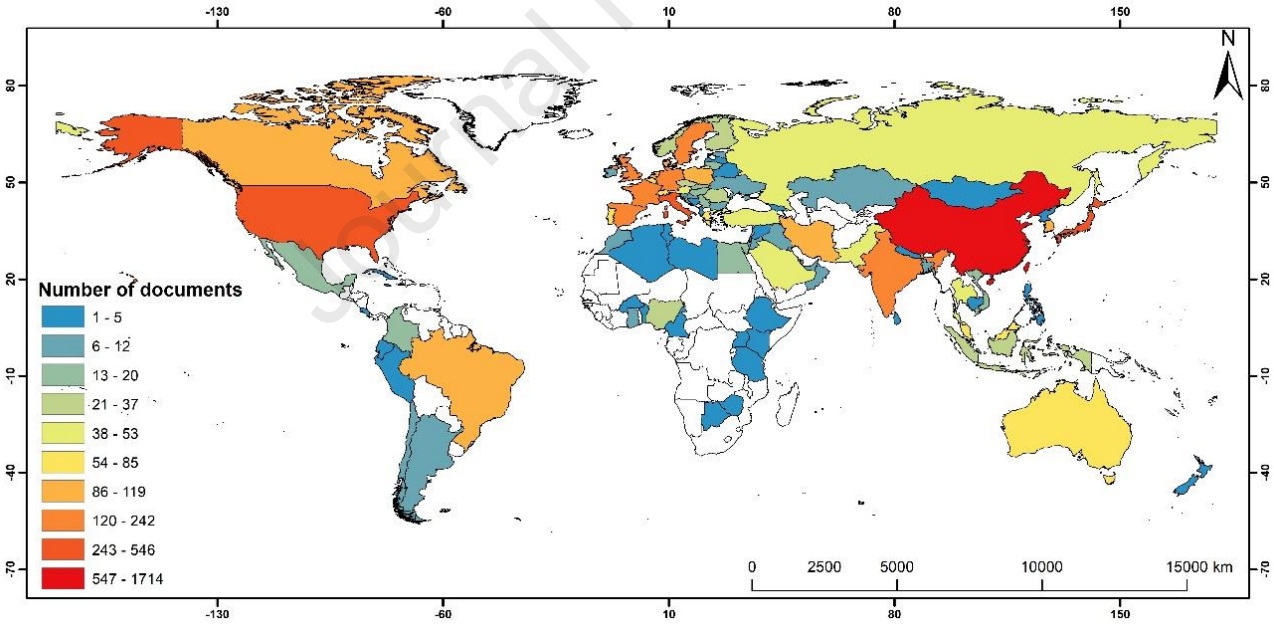


Figure 4. Country scientific production for MSW treated by WtE technologies from 1971 to 2023. Colors in the red shade indicate the highest production, while those in the blue shade show the lowest production.

Regarding China, research focused on using MSW as an energy resource to produce hydrogen-rich gas or synthesis gas by gasification (He et al., 2009). In this study, they investigated catalytic steam gasification of MSW using calcined dolomite as a catalyst. Studies also focused on evaluating the safe use of MSW fly ash in asphalt stone mastic mix and its environment (Xue et al., 2009). The

researchers focused on using MSW incinerator fly ash to partially replace fine aggregate in a stone-matrix asphalt mixture. On the other hand, recent publications now concentrate on verifying the feasibility of preparing new construction filler materials with phosphogypsum and MSW fly ash (Yin et al., 2023b). In this study, the authors describe the preparation of a new building filler material (NBFM) using phosphogypsum and MSW incineration fly ash. Finally, an interest was observed in recycling fly ash from MSW incineration into lightweight aggregates with a foaming agent (Han et al., 2023). This work investigated the recycling of Fly Ash from MSW incineration into lightweight aggregates by sintering.

Concentrations of emission hotspots were observed in three economic zones and eastern China (Guo et al., 2023). A visualization of the spatial-temporal distribution of incinerator fly ash (IFA) from China was proposed by Zhai et al. (2023). The authors suggested that by reusing high silica IFA, regions with low power emission factors emit fewer greenhouse gases (GHGs). Besides, some policies are listed to reduce GHG: a multifaceted approach involving localized strategies, demographic-economic integration, treatment structure optimization, source separation, recycling implementation, and learning from successful patterns is essential (Gu et al. 2023). Furthermore, case studies examine the challenges of optimizing resource utilization for MSW in China's extremely cold and high-altitude regions (Liu, Zhang, and Liu 2023). Novel innovations have emerged, for instance, the model proposed by Khan (2023), a design that prioritizes the generation of power, cooling, hydrogen, and potable water in addition to electricity, avoiding the corrosion challenges encountered by traditional incineration plants. Another innovation is preventing pollution and optimizing technology in fly ash treatment using nitrogen (Zhao, 2023). A recent study presents a model that eliminates the time delay issue in dioxin monitoring by generating real-time emissions predictions, demonstrating that deep learning models are superior at processing large amounts of data for dioxin prediction in WtE facilities (Wen et al., 2023).

In the United States, it was possible to verify publications related to using MSW combustion ash in the last century (Wiles, 1996b). This article addresses the controversy surrounding the proper management of MSW incinerator ash and its classification as hazardous or non-hazardous waste, highlighting the inconsistency in management requirements among states and the uncertainty in its beneficial use. The presence of heavy metals and their leaching and concerns about groundwater contamination due to soluble salts in the ash are noted as critical factors in this debate. On the other hand, several studies focused on the mechanisms and reaction products resulting from the chemical stabilization of bottom ash residues with soluble phosphate (Crannell et al., 2000). In this study, the chemical stabilization of heavy metals in bottom ash from MSW combustion using soluble phosphate was evaluated for cadmium (Cd), copper (Cu), (Pb) and zinc (Zn). Finally, interest was evidenced in publications focused on MSW management by using pyrolysis to produce energy and biochar (Gopu et al., 2018). This study investigates the activation of this biochar using CO_2. This approach of MSW pyrolysis followed by biochar activation may provide a solution for MSW valorization by producing biofuels and activating valuable biochar in water treatment. There is an increasing inclination in the United States towards the integrated evaluation of WtE technologies. For instance, studies utilizing the LCA approach are presented for advanced recycling technologies for conventional plastics (Creadore and Castaldi, 2023), mixed plastic waste (Afzal et al. 2023), biomass and plastic wastes by gasification associated with hydrogen production (Williams and Bourtsalas, 2023). In the U.S., the effort for waste gasification has advanced from theoretical models (Tavares, Ramos, and Rouboa, 2019) with conventional software such as AspenPlus for low-temperature plasma gasification (Indrawan et al. 2018) to current tools based on artificial neural networks (Jamro et al. 2023) Machine Learning (Sedej et al. 2022). Finally, some aspects are more relevant in the studies during

the last years in the U.S., such as social welfare (Ramos et al., 2020), post-recycling waste management (Themelis, 2023), and novel fuels from MSW (Seiple et al., 2023).

Finally, for Italy, scientific papers focusing on the characteristics of different volatility classes of organic compounds emitted by an MSW incineration plant were identified (Fujitani et al., 2023). In this research, the authors investigated the emissions of different classes of organic compounds, including semi-volatile and intermediate volatility compounds (IVOC/SVOC). The volatility distribution of these compounds was determined, highlighting the importance of IVOC as a dominant volatility class in Incineration MSW emissions. These findings underline the need to understand the volatility distribution of emissions to properly assess the impact of different dilution sampling conditions on emission factors and, thus, on total organic compound emissions in MSW incineration facilities. On the other hand, studies focused on analyzing the drivers and limitations of WtE incineration for sustainable MSW management in developing countries were evidenced (Nguyen et al., 2021). The research mentions that WtE implementation has experienced significant growth in developing countries due to several key drivers. These include increasing waste generation and shortage of landfill space, the introduction of legislative incentives and landfill restrictions, the active involvement of local government, and the influence exerted by previous WtE projects. These factors have helped to overcome historical barriers and have driven interest in WtE technology. However, several constraints affect the sustainability of WtE projects, including legal, financial, technical, environmental, and social challenges. These constraints can arise at different stages of projects, from investment to operation.

The sustainable success of WtE incineration in developing countries will depend on addressing these constraints effectively and leveraging the identified drivers to ensure growing waste treatment capacity. Additionally, studies focusing on the behavior of metals in smelting facilities for gasification and smelting of MSW and ash could be ascertained (Jung et al., 2005). This study examined the behavior of metals in ash melting and MSW gasification-melting facilities in detail. Melting furnace fly ash and molten slag were sampled from various facilities and feedstock for ash melting processes. Therefore, the design of WtE installations must be modeled in advance, considering the particular conditions of high temperatures and pressures with specialized software (Chicaiza, et al., 2021). Finally, the possible effects of co-gasification of MSW with MSW bottom ash and non-combustible waste and the potential for material and energy recovery from waste are reported (Tanigaki et al., 2012). This study focused on the cogasification of MSW with and without bottom ash in large-scale plants. Compared to conventional waste management methods, cogasification significantly reduced the amount of waste going to landfills, suggesting that this approach benefits the environment and resource recycling.

3.6 Co-relation network

3.6.1 Keywords co-occurrence map

Examining the network structure where keywords co-occur is one of the most potent methods for revealing trends and scientific themes that have progressed over time, achieved through concise visual representations and summarized in maps (Chen et al., 2022; Fang et al., 2017). For this co-occurrence network analysis, VOSviewer software was used, where 74 keywords were categorized into 5 clusters (Figure 5). "Municipal solid waste" is the keyword with the largest node with 801 occurrences. The other most relevant terms are: "incineration" with 352 occurrences, "fly ash" with 250 occurrences, "gasification" with 246 occurrences, "heavy metals" with 212 occurrences,

"pyrolysis" with 198 occurrences, "bottom ash" with 167 occurrences, "waste management" with 154 occurrences, "waste-to-energy" with 142 occurrences and life cycle assessment with 134 occurrences.

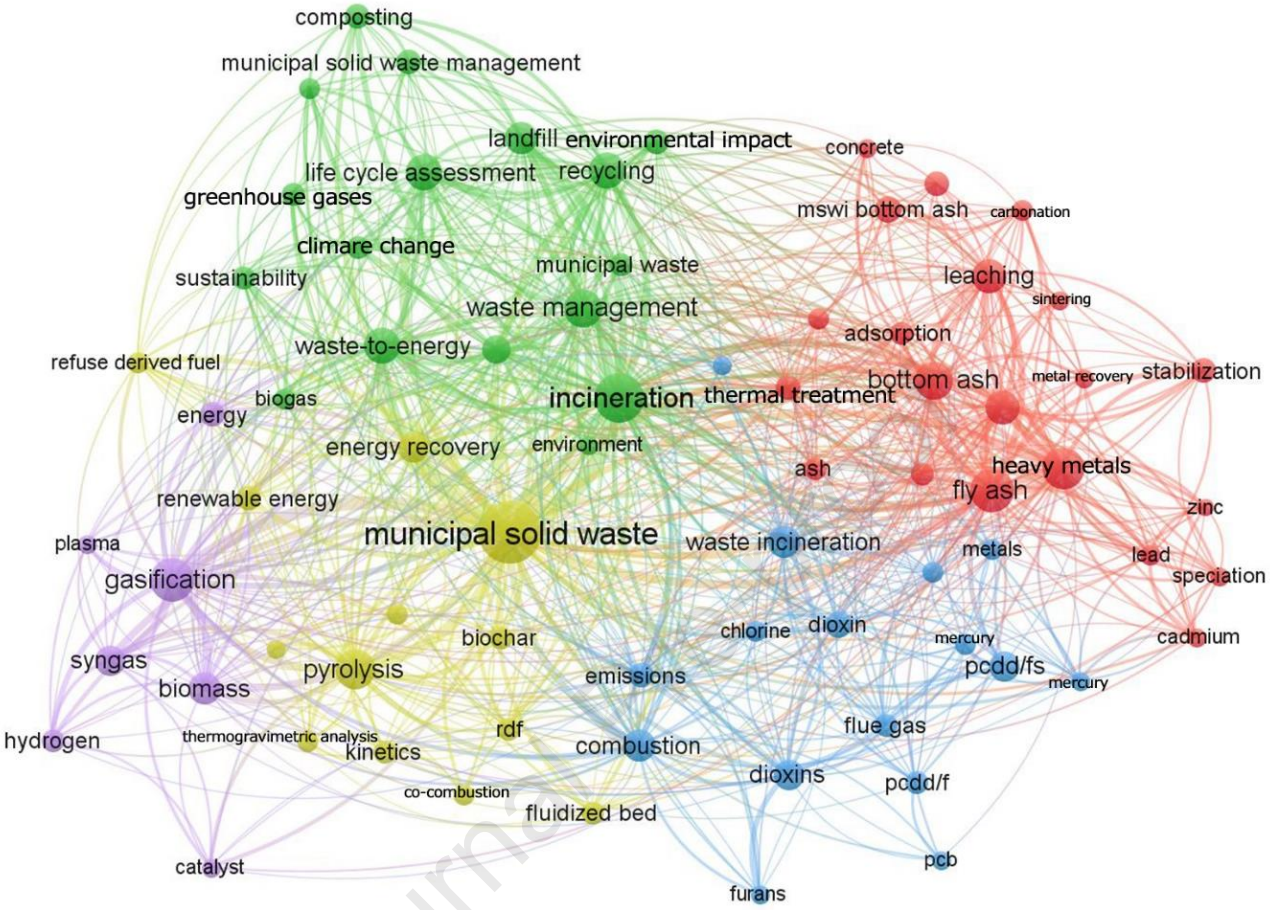


Figure 5. Keyword co-occurrence network map for WtE technologies in the period 1971-2023. The size is proportional to the keyword frequency, the color corresponds to the different clusters, and the links between nodes represent the co-word relationship.

3.6.1.1 Cluster 1. Hazardous wastes from thermal treatments

Cluster 1 (blue) addresses critical issues in managing and mitigating hazardous wastes from thermal processes. Thermal treatments, such as incineration, are common in MSW but can produce fly and bottom ash and a concentration of heavy metals such as cadmium, lead, and zinc. If not properly managed, these by-products pose significant environmental and human health risks.

One of the revealing research projects in this field is the study by Zhao et al. (2023) that addresses the thermal degradation kinetics of heavy metals in fly ash under a nitrogen atmosphere, offering vital insight into mitigating the environmental impact of incineration hazardous waste. The findings point out that pyrolysis emits harmful gases and transforms metals such as As, Cr, and Pb while forming compounds such as $Ca_2SiO_4CaCl_2$ presents additional challenges by inhibiting chlorine volatilization. This research emphasizes that developing more effective and sustainable strategies in MSW management is of utmost importance. On the other hand, a study by Chen et al. (2023)

addresses the sustainable valorization of MSWI fly ash and electrolytic manganese waste, proposing a synergistic melt treatment to transform these wastes into high-value glassy products. The study concludes with a predictive model that relates cooling rate to glass content, providing a valuable basis for industrial applications. This work offers a path toward efficient hazardous waste management and contributes to advancing more sustainable industrial solutions.

Additionally, Cao et al. (2023) focus on the feasibility and safety of geopolymers derived from MSW incineration fly ash, a typical by-product of incineration. By evaluating their durability against corrosive agents such as Na_2SO_4 and H_2SO_4, the study reveals a decrease in strength with higher concentrations of acid and MSW incineration fly ash. This deterioration is attributed to decalcification and crack formation, affecting the solidification efficiency of hazardous heavy metals such as Zn and Pb. However, elements such as Cu and Cr maintain high solidification efficiency. This work is essential to develop more resistant and safer materials that minimize the environmental and health risks associated with heat treatment waste, thus driving the application and standardization of sustainable technologies in hazardous waste management.

Finally, Huang et al. (2024) explored the effective recovery of lead and chlorine from hazardous wastes originating from thermal treatments. The main objective is to explore a synergistic process to treat fly ash and cathode ray tubes, where the synergistic effect was demonstrated by significantly increasing the mass loss and removal rates of Pb and Cl. Furthermore, the study reveals that co-processing reduces the melting temperature and enables the recovery and reuse of Pb and Cl, transforming hazardous waste into valuable resources. This research provides a promising solution for hazardous waste management and contributes significantly to understanding chlorination volatilization mechanisms and process optimization for efficient and sustainable recovery.

3.6.1.2 Cluster 2. Circular Economy and Environmental Impact Assessment

Cluster 2 (green) focuses on adopting sustainable practices and carefully analyzing the environmental consequences of various human activities. The circular economy is an approach that seeks to minimize waste and maximize the use of resources through reuse, recycling, and regeneration, thus promoting a sustainable life cycle for products and materials.

Among the research highlights are the findings of Khosravi et al. (2023), who present an innovative solar energy-based sorption-enhanced gasification system to co-generate energy and hydrogen. This system, which integrates MSW gasification and an *in situ* CO_2 capture and liquefaction process, shows a remarkable synergistic effect that enhances CO_2 removal and optimizes energy and green H_2 production. With an annual electrical efficiency of 11.9% and a total energy efficiency of 54.8%, the system promises a net electrical power generation of 19.48 MW and produces 0.58 kg/s of pure H_2, highlighting its potential to contribute to the Circular Economy and Environmental Impact Assessment. The study underlines the importance of optimizing CO_2 capture efficiency, associated costs, and environmental viability, proposing future research to deepen the utilization and improvement of these integrated systems.

On the other hand, Tsai et al. (2014) focused on analyzing WtE's current status and evolution, focusing on its contribution to a circular and low-carbon society. In addition, policies and regulatory incentives aligned with the SDGs and carbon neutrality have been implemented. Finally, another example is the study by Bourguig et al. (2022), who examined the feasibility of cogasification as a strategy for the sustainable management of MSW in Morocco, focusing on hydrogen production as an alternative to fossil fuels. The results highlight that increasing the gasification temperature and the

appropriate steam ratio lead to hydrogen mole fractions above 30%, especially at 750°C and SFR > 1.2. In addition, the optimal combination of MSW and biomass was identified to maximize hydrogen production. It is suggested that cogasification may be a promising avenue to reduce toxic emissions and harmful gases associated with conventional treatment methods, and it is proposed to further improve the cogasification plant model by including a water-gas shift reactor, which could contribute to the production of sustainable alternatives to fossil fuels in various industrial sectors, such as aviation, automotive, industrial and power.

3.6.1.3 Cluster 3. Risks and Pollutant Control in Incinerators

Cluster 3 (red) focuses on several critical issues related to the assessment and management of environmental and health risks associated with the operation of incinerators. Incinerators are a standard method of waste disposal, but their process can generate air pollutants and hazardous waste, raising concerns about air quality, ash management, and other by-products. This cluster is dedicated to addressing the challenges associated with the operation of incinerators, including emission control strategies and the safe management of the waste generated, to minimize negative impacts on the environment and public health.

Initially, studies such as Guo et al. (2023) focused on the issue of dioxins in the atmosphere, which originate primarily during MSW incineration. China has implemented ambitious plans to reduce dioxin emissions from the MSW incineration industry. The study used actual measurements to estimate dioxin emissions and their impacts on health and the environment. It found that most Chinese incinerators met emissions standards in 2018, significantly reducing health risks and environmental impacts. On the other hand, Xie et al. (2023) investigated the application of a ball mill pretreatment with additives and flotation of fly ash to remove carbon and dioxins derived from MSW incineration. The ball mill pretreatment resulted in significant degradation of dioxins and release of carbon in the fly ash, markedly reducing its content. Flotation tests demonstrated that ignition loss in the tailings could be effectively reduced by froth flotation using combined reagents in an alkaline system. Wastewater recycling did not affect flotation efficiency. In addition, a reduction of dioxins to less than 50 ng I-TEQ/kg was achieved, meeting standards. This pretreatment and flotation process and wastewater recycling are promising methods for separating carbon and dioxins from fly ash. It has relatively low operating costs, making it a good alternative for fly ash treatment.

Additionally, Ji et al. (2022) addressed the health effects on the population surrounding an MSW incinerator in China. Among the main findings, significantly higher age-adjusted mortality rates were observed among downwind residents within 3 km. However, this higher mortality existed before the ISMU began operation, and no significant differences in standardized mortality rate were found before and after ISMU operation, both upwind and downwind. Higher levels of PCDD/F were detected in sera from downwind residents and in eggs from upwind hens. This highlights the importance of adequate distance between an ISMU and residential areas, especially on the downwind side. In summary, the study provides relevant information to assess the health risk to the population near an ISMU and has important implications for public health.

3.6.1.4 Cluster 4. Emerging WtE technologies

Cluster 4 (purple) analyzes Emerging WtE technologies under the circular economy framework. This model emphasizes maximizing material and energy value throughout their life cycles by treating waste as a resource. Recent WTE findings show these technologies close the loop, supporting circular economy principles. In particular, recovering energy and materials from post-recycling

wastes diverts these residual fractions from landfills, making waste management more resource-efficient and environmentally friendly.

A holistic helps decision-makers adopt and optimize WtE technologies in the circular economy. Recent advances in gasification, microbial conversion, and other WtE methods can reduce environmental impacts, supporting circular economy goals. Thus, integrating circular economy principles with Environmental Impact Assessment (EIA) results ensures that WtE practices promote sustainability goals and a regenerative, resource-efficient waste management paradigm (Mallick et al., 2022). It has been reported that some alternatives suggested accoupling Hybrid/integrated thermo-chemical and biological conversion, i.e., HTL and AD procedures can enhance biomass waste recovery of valuable liquid fuels (Ambaye et al., 2023); AD to direct solar-assisted biogas system, concentrator solar assisted biogas system and Solar Photovoltaic (PV) assisted biogas system (Kalaiselvan et al., 2022). Other studies that allow the extraction of bioactive compounds involve Microwave-Assisted Extraction (MAE), Supercritical Fluid Extraction (SFE), Ultrasonic-Assisted Extraction (UAE), Pressurized Liquid Extraction (PLE), Enzyme-Assisted Extraction (EAE) (Zhu et al., 2023) among others options linked to advanced oxidation processes (AOP), including photocatalysis, Fenton process for biomass conversion, etc (Ambaye et al., 2023). Among the options available, a high energy recovery could be achieved in the dual AD and incineration scenarios when the digestate is incinerated (Abdallah and Elfeky, 2021); Mechanical biological treatment (MBT) and AD have performed better than gasification and incineration. However, no studies combine gasification with biological processes such as anaerobic digestion (Abdeljaber et al., 2022).

Incorporating a circular economy involves comprehensive MSW management plans that promote recycling, reuse, and resource efficiency to achieve SDGs. To reduce risks, prioritize MSW collection, transportation, and disposal. Microbial Fuel Cells (MFCs) and Microbial Electrochemical Cells (MECs) are environmentally friendly WtE options (Vyas et al., 2022). When viewed as a resource, MSW can drive environmentally and economically attractive WtE solutions, especially with innovative technologies like MFCs and MECs. The use of byproducts of WtE conversion is still limited in biological applications. The use of biochar has demonstrated its applications in the enhancement of the methanogenic stage of Anaerobic Digestion (Qi et al., 2021), obtention of valuable chemicals and energy from the organic fraction (Zhang, et al. 2024), fertilizers for more sustainable agriculture (Zhang et al., 2022), removal of pollutants from water bodies, solidification of pollutants and reduction of VOC release when incorporation biochar in cementitious constructions (Chen et al., 2023). Other study considered the combination of anaerobic digestion and gasification to produce sustainable WtE, considering the advantages of AD as an adequate technique for FW, and gasification can generate more electricity from MSW (Shi, Y., Huang, Y., & Xu, J. 2024).

Bioenergy with Carbon Capture and Storage is a promising solution since it has been analyzed under the LCA. It can convert waste into a zero or negative-emission energy source and remove GHGs by integrating carbon capture utilization and storage (CCUS). Reports suggest that WtE for CCUS plants could use up to 40% of waste fuel energy for heat and electricity, halving power sales revenues (Materazzi et al., 2024). A holistic socio-economic and environmental understanding and techno-economic analysis are needed in future studies to overcome limitations and sustain these transformative technologies (Wang et al., 2019).

3.6.1.5 Cluster 5. WtE-derived products

Cluster 5 (yellow) focuses on transforming MSW into valuable products through WtE technologies and represents a key achievement in developing a low-carbon, circular economy. This transition

addresses the challenges of sustainable MSW management and offers a promising route for producing renewable energy and recyclable materials. As we move towards implementing more sustainable and efficient solutions, research and innovation in WtE-derived products play a crucial role.

Williams and Bourtsalas (2023) evaluated advanced thermochemical gasification methods using thermodynamic process models and LCA in this context. Among the main findings, it is mentioned that steam-based gasification can reduce CO_2 emissions by up to 38% compared to conventional methods. In addition, using active materials, such as metal hydroxides, can further reduce emissions and achieve CO_2 capture. Using renewable energy to generate steam can also significantly reduce the environmental impact. These results suggest that MSW gasification with biomass and plastics has significant potential and can contribute to a circular, low-carbon economy.

On the other hand, Arruda Ferraz de Campos et al. (2023) focused on utilizing a mixture of synthesis gas (syngas) and biodiesel in an internal combustion engine, where syngas is produced from biomass and MSW. The study covered a series of control and analysis parameters of the engine and the gasification process. The results indicated that the syngas produced from biomass and MSW have an LHV of approximately 6 MJ/m^3 and a hydrogen content of 15% by volume. The engine test with the synthesis gas and biodiesel blend showed a 20% reduction in specific consumption compared to conventional diesel. In addition, a significant increase in exhaust gas temperature was observed, which could be exploited to improve efficiency by employing a heat exchanger.

Similarly, Faishal (2022) analyzed the three essential methods used in MSW gasification to produce hydrogen-rich syngas: Catalytic Gasification, Co-Gasification, and Modified Gasification System. The analysis emphasizes that gasification is one of the techniques that can be used to convert MSW into hydrogen-enriched syngas. Using catalysts, such as NiO/MD, can increase the hydrogen concentration in the syngas. In addition, the importance of adapting gasification methods to the specific characteristics of MSW at each location is mentioned. Moreover, the authors suggest future research focused on better understanding the properties of MSW and optimizing gasification methods to achieve higher efficiency in producing hydrogen-rich syngas. They also highlight the need to evaluate the financial and environmental impact of MSW gasification as a hydrogen source, with the potential to be a cost-effective and environmentally friendly alternative in the energy field.

Gasification of MSW presents a promising alternative for waste management; however, it is accompanied by challenges such as increased tar formation and equipment damage. Effective moisture control of the feedstock is imperative, as a moisture content exceeding 35% diminishes efficiency due to lower gasification temperatures (Wijayasekera et al., 2022). Conversely, plasma gasification yields raw syngas, necessitating further processing, purification, cooling, and conversion into valuable products such as hydrogen or synthetic fuels. Approximately 93-96% of sulfur manifests as hydrogen sulfide (H_2S), a marketable byproduct (Nemitallah et al., 2024). Nonetheless, this multi-step process entails heightened complexity and expense (Munir et al., 2019).

Despite these challenges, hydrogen derived from MSW holds promise, particularly in applications where hydrogen is a desired product. This potential is underscored by projections indicating a 30% increase in global population by 2050, necessitating a 70% rise in food production (Falcon et al., 2022; Samal et al., 2022). The world faces an imminent food crisis exacerbated by fertilizer shortages, posing threats to the global economy and livelihoods (Gliessman, 2022; Rother et al., 2023). The depletion of natural resources and escalating demand for fertilizer macronutrients contribute to this crisis, impeding accessibility for farmers (Sniatala et al., 2023).

Hydrogen is critical in the Haber-Bosch (H-B) process and is essential for ammonia (NH_3) fertilizer production. The H-B process is the predominant technique for ammonia production globally (Ghavam et al., 2021), generating approximately 80% of the world's ammonia supply (Avşar, 2024; Faria, 2021). However, conventional H-B ammonia production is energy-intensive, contributing approximately 1.6% of global anthropogenic emissions (Wang et al., 2021; Yüzbaşıoğlu et al., 2021). Hydrogen's reaction with nitrogen yields ammonia, a fundamental component in inorganic fertilizers (Abghoui et al., 2015). Integrating hydrogen derived from MSW in the H-B process can bolster food production systems and enhance the sustainability of fertilizer manufacturing (Leong et al., 2021).

Utilizing hydrogen from renewable sources as a feedstock in the H-B process mitigates carbon emissions associated with conventional hydrogen production methods (Chang et al., 2021). The energy demand for ammonia production via the H-B process is substantial, ranging from 9 to 15 MWh per ton (Giddey et al., 2017). Nonetheless, studies suggest that utilizing sorted MSW for hydrogen production in the H-B process could achieve fertilizer self-sufficiency (Gómez-Camacho et al., 2017). Recent advancements aim to enhance the sustainability of the H-B process by integrating hydrogen from renewable sources or MSW, thereby reducing reliance on fossil fuels and transforming nutrient pollutants into valuable resources for fertilizer production. This integration promotes a circular economy in waste management and fertilizer manufacturing (Ojelade et al., 2023). Furthermore, ongoing efforts to optimize the H-B process through novel catalysts and process enhancements seek to enhance ammonia synthesis efficiency (Tian et al., 2024; Ye and Tsang, 2023), thereby reducing energy requirements and environmental impacts, and fostering more sustainable agricultural practices (Spatolisano and Pellegrini, 2023).

Hydrogen production from MSW presents an economically viable alternative, as gasification enables previously unattainable applications when the waste material is in solid form (Nemitallah, 2024). By utilizing waste materials as feedstock, waste-derived hydrogen production can lower production costs by reducing raw material expenditures (Chen et al., 2022). Consequently, alternative hydrogen sources, including MSW, are relevant in diminishing the energy consumption associated with ammonia production, thereby contributing to sustainability efforts. These alternatives facilitate the integration of WtE technologies and address societal demands (Nami et al., 2024).

WtE technologies are presented as crucial pathways to transform the global waste problem into an energy opportunity. Table 4 summarizes the relationship between different WtE techniques and the SDGs, highlighting how these technologies can contribute to achieving important environmental, economic, and social goals pillars of sustainability.

Table 4. Relationship of WtE technologies to SGDs

WtE Techniques	Associated Clusters	Contribution to SDGs
Incineration	1, 3, 4	

Pyrolysis	4, 5	
Gasification	2, 4, 5	
Plasma gasification	5	
Hydrothermal Carbonization	4	

Incineration facilitates the utilization of renewable energy sources (SDG 7), thereby mitigating the accumulation of waste in landfills (SDG 11). Conversely, pyrolysis produces energy and facilitates the extraction of valuable chemical products, thereby contributing to developing resilient infrastructure and innovation (SDG 9). In the interim, gasification has proven to be an efficient method for generating syngas, thereby making a significant contribution to industrial sustainability (SDG 12) and fostering advancements in sustainable energy (SDG 7), urban development (SDG 11), and climate action (SDG 13). The shift towards using renewable hydrogen sources is consistent with promoting sustainable agricultural and manufacturing methods. Therefore, gasification and plasma gasification involve the zero-hunger goal (SDG 2).

Additionally, plasma gasification and HTC are state-of-the-art technologies in WtE that efficiently and environmentally treat waste while making significant contributions to sustainable urban development (SDG 11), climate action (SDG 13), and innovation (SDG 9). In particular, using biochar production, HTC may contribute to the improvement of soil health (SDG 15), the advancement of energy efficiency (SDG 7), and the facilitation of sustainable consumption and production (SDG 12).

3.6.2 Country co-occurrence map

Figure 6 illustrates this network, composed of 70 nodes and distributed in 8 clusters, reflecting 2485 links. In particular, China has extensive and diverse collaborations with countries such as the United States, Canada, and the United Kingdom. These links highlight the importance of international relationships in advancing WtE research. The co-authorship network structure between countries and authors underscores the collaborative nature of WtE research. The eight clusters identified represent diverse geographic regions and disciplines, ranging from optimization of energy conversion processes to advanced environmental impact and sustainability studies. The interaction among these clusters illustrates a pattern of global collaboration, where interdisciplinary research and cross-border partnerships are crucial to addressing MSW management challenges.

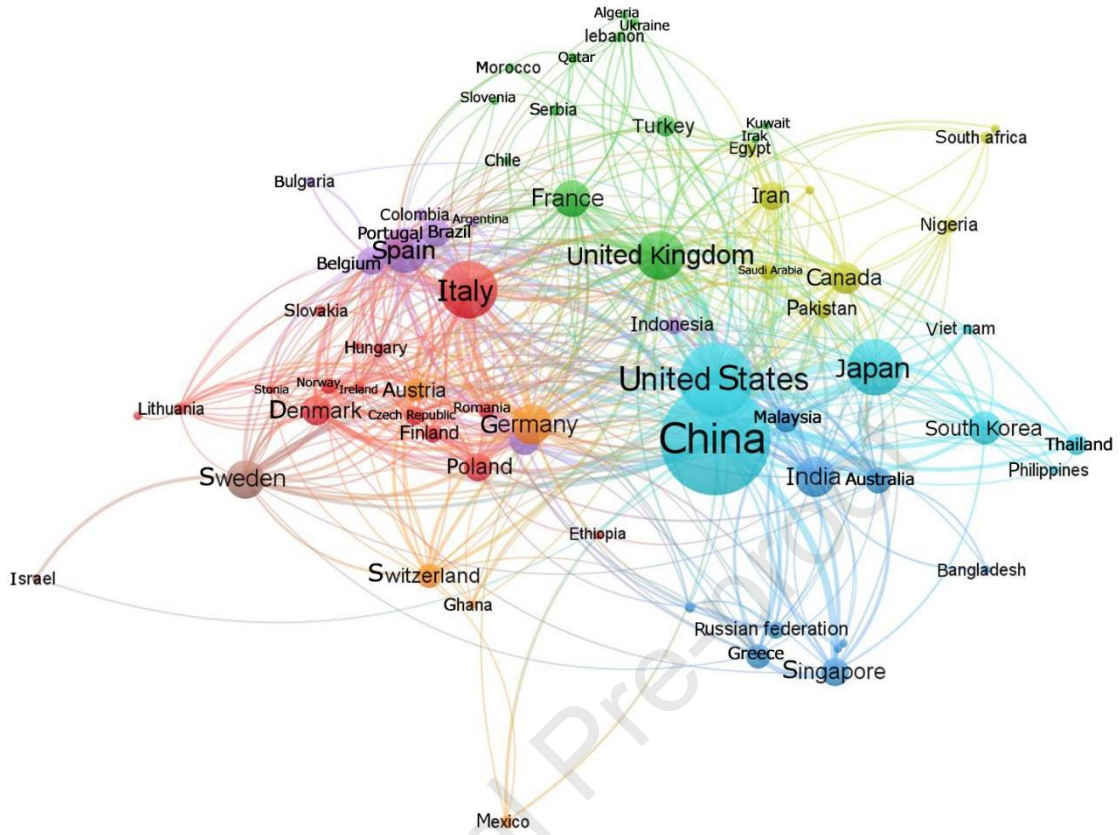


Figure 6. Co-authorship map of countries for WtE technologies in the period 1971-2023. The size is proportional to the country frequency, the color corresponds to the different clusters, and the links between nodes represent the co-word relationship.

Cluster 1 is integrated by European countries, with some located in Central and Eastern Europe: Croatia, Czech Republic, Denmark, Estonia, Ethiopia, Finland, Hungary, Ireland, Italy, Latvia, Lithuania, Norway, Poland, Portugal, Romania and Slovakia. Cluster 2 corresponds to Algeria, Chile, France, Iraq, Kuwait, Lebanon, Morocco, Qatar, Serbia, Slovenia, Turkey, Ukraine, and the United Kingdom. Cluster 3 has ten countries integrated: Australia, Bangladesh, Greece, India, Jordan, Kazakhstan, Malaysia, Oman, Russian Federation, and Singapore. Cluster 4: Canada, Egypt, Iran, Mauritius, Nigeria, Pakistan, Saudi Arabia, South Africa, United Arab Emirates. Cluster 5: Argentina, Belgium, Brazil, Bulgaria, Colombia, Indonesia, Netherlands, Spain. Cluster 6 predominates Asian countries (86%): China, Japan, Philippines, South Korea, Thailand, United States, and Vietnam. Cluster 7: Austria, Germany, Ghana, Mexico, Switzerland. Finally, cluster 8 is composed of Israel and Sweden.

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3.7 Case study

We established 1 ton as the functional unit for treating MSW for grate furnace and gasification technologies. As reported in previous studies (Song et al., 2017a; Su, 2014a), we based our analysis of the Incineration Grate Boiler scenario on a Tianjin, China, operating plan for the Incineration Grate Boiler (Figure 7, right). Regarding the gasification scenario, no full-scale gasification facilities for MSW treatment have been built in China. Therefore, our study relied predominantly on primary data from a well-established gasification plant in Norway (Ellyin and Themelis, 2011a; Yao, 2018a). The system boundary included the treatment process, including the resulting products such as syngas and electricity produced by the gasification and only incineration generated by incineration.

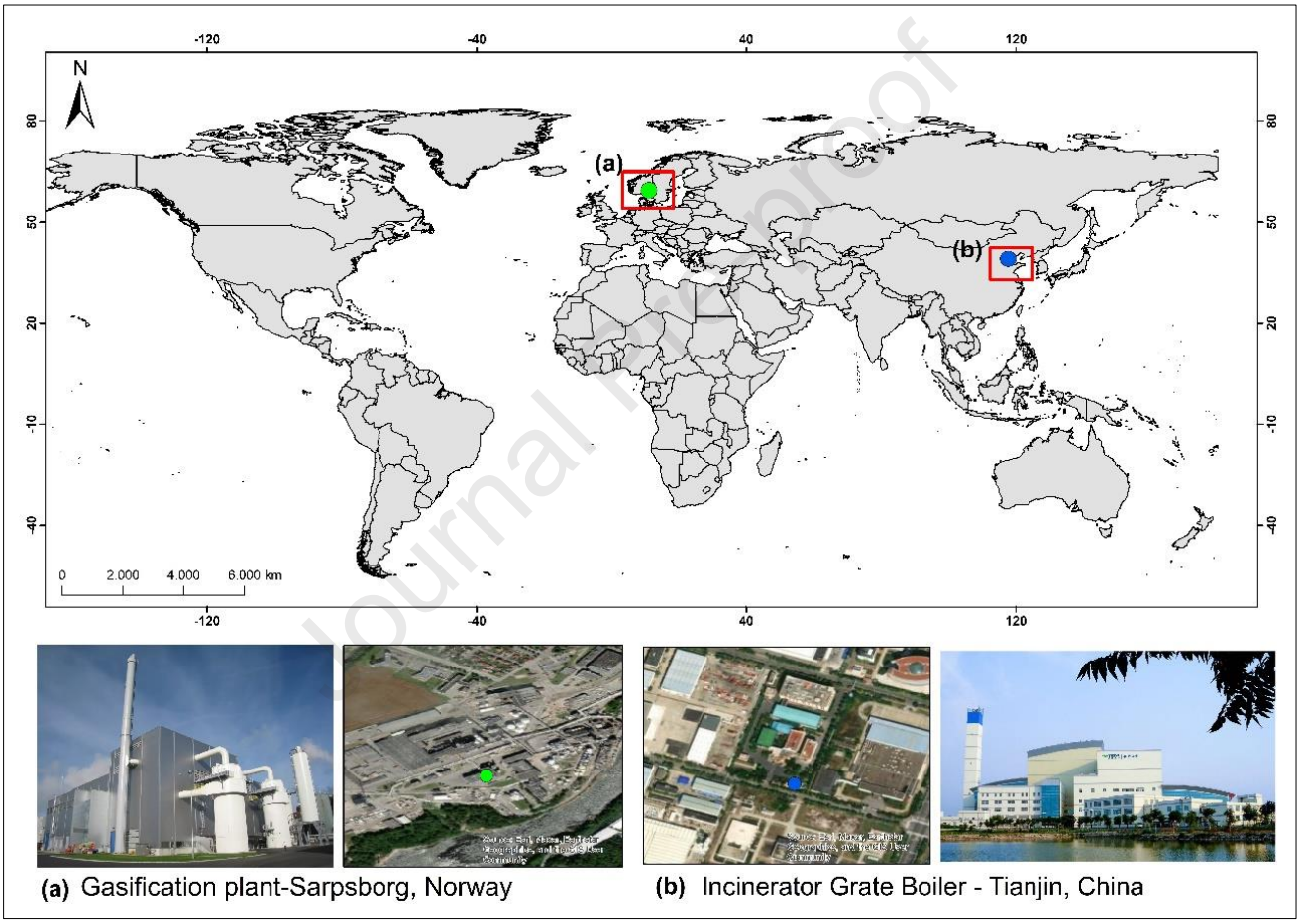


Figure 7. Location of the facilities: Gasification plant-Sarpsborg, Norway and Incinerator Grate Boiler - Tianjin, China

3.7.1 Incineration Grate Boiler, China

The government has strongly supported MSW treatment methods, particularly emphasizing landfills and incineration (Pariatamby and Tanaka, 2014). As of 2017, China had effectively collected and transported 215 million tons of MSW, representing a treatment rate of 97.7% of all generated waste. Notably, 40.24 % of this waste was incinerated as the preferable treatment method (NBSC 2017). The considerable increase in the use of incineration can be attributed to China's proactive promotion of this technique. In the country's context, incineration has proved to be a more

effective waste management technique because of the high generation rate of MSW. Remarkably, the daily capacity of incineration facilities has increased from 15,000 Mg/d in 2003 to an astounding 231,600 Mg/d, demonstrating the nation's commitment to effectively managing its waste challenges (Lu et al., 2017).

For this case study, we selected the Tianjin waste incineration facility, which began construction in 2001 and went into operation in 2004. This facility may dispose of between 400 and 1,200 tons of MSW per day, generating 123 million kilowatt-hours of energy, of which 108 million kilowatt-hours are delivered to the power grid (Liu, 2017; Su, 2014b). We compiled proximate and ultimate analysis data to shed light on the characteristics of Tianjin's MSW. Notably, the lower heating value (LHV) was determined to be approximately 6,480 kJ/kg, with a moisture content of 46.7% and a carbon content of 43.26 wt.% (Ma et al., 2010).

3.7.2 Gasification of MSW, Norway

In contrast to the waste incineration case study in Tianjin, the gasification facility in Sarpsborg, Norway, demonstrates an alternative approach to MSW management worldwide. The fact that Norway is a member of the European Economic Area (EEA) despite not being a member of the European Union has led to the country adopting and adhering to European Union regulations, including waste hierarchy and restrictions on landfilling biological refuse. In addition, Norway has implemented the 2030 Energy Strategy, legislation, and circular economy strategies (Kjær, 2013). In Norway, the WtE sector comprises 17 facilities with a total capacity of 1.7 million tons, resulting in 13,300 TJ of heat and 1,200 TJ of electricity (Lausselet et al., 2016b). The WtE sector contributes approximately half of Norway's renewable energy. Since 2009, Norway has prohibited organic waste landfills, reducing the number of landfills (Becidan et al., 2020).

Our analysis of the gasification facility in Sarpsborg shows that it was established in 2010 and occupies approximately 9,000 m^2. The facility has two production lines, each with a processing capacity of 5 t/h, for a total annual processing capacity of 78,000 tons. The gasification procedure yields steam (at 23 bars and 217°C) with an annual heat output of 250 GWh. The gasification facility operates for 8,000 hours annually and has a 19% efficiency rate. Operating expenses represent 10.4% of the total investment. MSW is crushed and mixed as part of the pretreatment procedure at the gasification facility. The gasifier accommodates feedstock with calorific values between 8 and 18 MJ/kg, bulk densities between 250 and 350 kg/m^3, and particle sizes less than 200 mm. In addition, a magnetic separation phase is implemented, with 1-3% of the metal content being separated and collected (Yao, 2018b). Refer to Figure 7 (b) for a visual representation of the pretreatment and scope of the study.

In 2004, the city of Sarpsborg managed 62,517 tons of MSW. During the gasification operation, 9,322 tons of bottom ash and 3,615 tons of fly ash were produced. Notably, the facility made a substantial quantity of energy, generating 165,000 MWh while delivering 154,000 MWh of heat. The initial investment for this facility was estimated to be $525 per ton of annual capacity and $195 per MWh of thermal energy. In addition, the gasification facility demonstrated a heat production rate of 256,000 MWh annually (Ellyin and Themelis, 2011b). Therefore, while promising, MSW gasification presents drawbacks such as high capital costs, operational complexities, and the necessity for stringent waste sorting. Moreover, the technology's efficiency and reliability can vary, and improper management may lead to harmful emissions, posing environmental risks (Ukwin 2016).

3.7.3 Life cycle assessment of WtE commercial scale facilities

The Inventory Analysis section compares the Tianjin (China) and Sarpsborg (Norway) WtE facilities based on their primary and secondary data. Both facilities have an approximate annual operating time of 8000 hours. However, significant differences are observed in the average yearly calorific value of the waste treated, with Tianjin processing waste at 4.19 MJ/kg and Sarpsborg processing waste with a broader range of 8-18 MJ/kg, indicating differences in the energy content of the input waste streams. In addition, Tianjin processes 400-1,200 tons of waste per day, whereas Sarpsborg processes 214-427 tons per day. The power generation capacities vary significantly, with Tianjin employing two generators, each with a capacity of 12 MW (24 MW), and Sarpsborg using a single generator with a capacity of 32 MW. These differences and more details (Table 5) emphasize the distinct operational characteristics and capacities of the Tianjin incineration technology and the Sarpsborg gasification technology.

Table 5. Technical information on the WtE facilities in Tianjin- China (Song et al., 2017b; Su, 2014b) and Sarpsborg -Norway (Ellyin and Themelis, 2011b; Whiting, 2013; Yao, 2018b).

Parameter	**Tianjin, China. Grate Boiler Incinerator**	**Sarpsborg, Norway. Gasification**	**Units**
Established	2001	2010	Year
Investment amount	761,829,886.14	56,850,843.53	USD (equivalent)
Annual operating time	≥ 8,000	~ 8,000	h
Average annual calorific value	4.19	8-18	MJ / kg
Daily throughput (t)	400-1,200	214-427	ton/d
Generator Power	2*12	32	MW
Area	-	9,000	m^2
Auxiliary fuel addition	< 20	-	%
Unit service power	25,000,000	-	KWh
Power generation	147,000,000	-	KWh
On-grid energy	122,000,000	-	KWh
Annual power generation (steam for heating consumers)		250,000,000	KWh
Synthesis gas, calorific value	-	2-4	MJ / Nm^3
Excess oxygen ratio	-	1.05	-
Proportion of recirculated flue gas	-	0.74	-

Additionally, Table 6 compares the MSW composition in Tianjin, China, and Norway. Notably, there is a significant difference in the proportion of organic waste between the two regions. In particular, the organic waste fraction in Norway is approximately 32% less than in Tianjin. This difference can be attributed to the fundamental differences between waste characteristics in developed and developing regions. This characteristic of an organic fraction is prevalent in developing nations whose population habits generate MSW with high moisture content (Pariatamby et al., 2019). Wet waste is slow to ignite and must be pre-dried before it can reach the required temperature in the combustion chambers, so the presence of a significant amount of moisture in the waste poses obstacles to efficient incineration. Regional waste characteristics, such as moisture

content and combustibility, must be considered to optimize WtE conversion processes. These distinctions should be considered in future waste management efforts to create more effective and sustainable regional waste treatment strategies (Buekens, 2013).

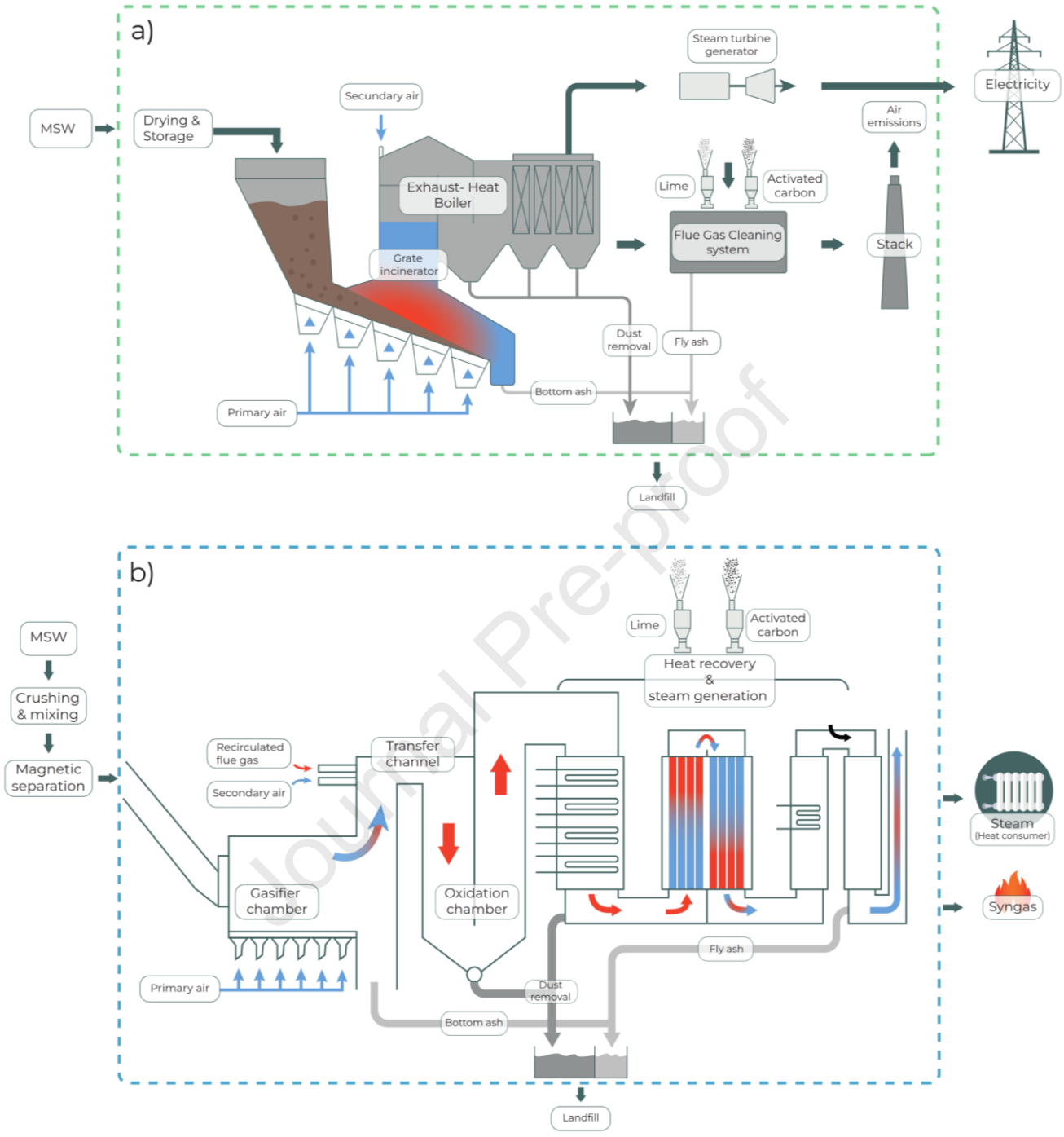
Table 6. Waste composition for Tianjin, China (Zhang et al., 2010) and Norway in 2010 (Kjær, 2013).

Component	Tianjin, China 2010 (wt.%)	Sarpsborg, Norway 2010 (wt.%)
Kitchen waste	56.9	24.8
Slag & ceramics	16.2	0
Metals	0.42	6.7
Glass	1.3	5.0
Paper	8.7	28.9
Plastics	12.12	2.4
Textiles	2.47	1.4
Wood	1.9	26.7
Waste from Electrical and Electronic Equipment (WEEE)	0	4.1
TOTAL	100	100

As shown in Figure 8, the stages for both WtE technologies are explained. The stages of incineration included the drying and storage of MSW; the actual combustion process in a Grate boiler, which is complemented by the injection of secondary air to facilitate efficient combustion; the utilization of the exhaust heat in a dedicated boiler for energy recovery; and the flue gas cleaning stage, which involves the application of lime and activated carbon to remove pollutants and ensure air quality. In contrast, the phases of gasification are as follows: waste is first crushed and mixed to achieve compositional uniformity in a chamber designed for syngas. After gasification, heat recovery and steam production occur, with the high-temperature effluent vapors used to produce steam for various applications.

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990 **Figure 8.** System boundaries and stages considered for MSW treatment by a) Incineration and b)
991 Gasification. Colors in the red shade indicate higher temperatures, while those in the blue shade show
992 lower temperatures. Adapted from: (Ellyin, C., & Themelis, N. 2011; Whiting, 2013; United Nations
993 Environment Programme 2024).

994 In this case, the reports mentioned previously were used as a primary source to supplement the
995 inventory secondary source as literature data to calculate outputs in terms of emissions to air. The
996 collected data is displayed in Table 7. A previous study demonstrated that the highest energy
997 recovery was achieved in the gasification strategy compared to incineration. Moreover, the MBT and

AD alternatives were the most environmentally viable (Abdeljaber et al., 2022). According to Zhang (2023), the ideal location for a WTE facility is determined by Three-Phase Method for Determining Criteria: a) A robust geographical index system is developed, taking into account various geographical aspects to provide a comprehensive basis for subsequent evaluations; b) the process of weight determination: for the evaluation of alternative scenarios, these weights are crucial and are optimized using a combined method to ensure precision; c) set model based on decision theory for site selection: this guarantees a thorough assessment procedure, taking into account multiple criteria and streamlining decision-making to select the most suitable site. Therefore, the spatial perspective facilitates the selection of the most advantageous location for the WTE plant, thereby improving the decision-making process.

Table 7. Inputs and outputs for Tianjin, China, and Sarpsborg, Norway, in 2010 based in a Functional unit of 1 ton

Parameter	Units	Tianjin, China. Grate Boiler Incineration	Sarpsborg, Norway. Gasification
Dioxins (TEQ)	*kg/ton*	8.17E-13	9.43E-14
Total Dust	*kg/ton*	0.00E+00	6.01E-02
Carbon dioxide	*kg/ton*	1.09E+03	3.37E+02
Carbon monoxide	*kg/ton*	1.59E-01	2.73E-02
Nitrogen oxides (NO_x)	*kg/ton*	1.68E+01	2.27E+00
Sulfur dioxide (SO_2)	*kg/ton*	3.51E-01	4.64E-01
Arsenic	*kg/ton*	3.40E-04	0.00E+00
Cadmium	*kg/ton*	6.58E-06	0.00E+00
Mercury	*kg/ton*	2.04E-04	5.46E-06
Hydrogen chloride (HCl)	*kg/ton*	6.52E-01	3.36E-02
Hydrogen fluoride	*kg/ton*	0.00E+00	2.24E-04
Hydrogen sulfide (H_2S)	*kg/ton*	1.43E-04	0.00E+00
TOC, Total Organic Carbon	*kg/ton*	0.00E+00	2.73E-02
Methyl mercaptan (CH_4S)	*kg/ton*	1.74E-05	0.00E+00
Ammonia	*kg/ton*	2.64E-03	0.00E+00
Cadmium + Titanium	*kg/ton*	0.00E+00	2.73E-05
Antimony	*kg/ton*	5.32E-03	8.20E-05
Arsenic	*kg/ton*	0.00E+00	2.73E-05
Lead	*kg/ton*	0.00E+00	1.09E-03
Chromium	*kg/ton*	0.00E+00	5.46E-05
Cobalt	*kg/ton*	0.00E+00	2.73E-05
Copper	*kg/ton*	0.00E+00	2.73E-04
Manganese	*kg/ton*	0.00E+00	8.20E-05
Nickel	*kg/ton*	0.00E+00	5.46E-05
Vanadium	*kg/ton*	0.00E+00	5.46E-05
Raw materials/Consumables			
Lime	*kg/ton*	7.94	10.8
Active carbon	*kg/ton*	0.34	0.45
Tap water	*m^3/ton*	0.22	0.225
Sodium hydroxide	*kg/ton*	65.7	2.2
Ammonia (NH_3-25%)	*g/ton*	-	2.3
Hydrogen Chloride HCl	*kg/ton*	-	0.18

CaO	*kg/ton*	7.5	
Precipitating agents	*kg/ton*	-	0.17
Diesel oil (aux. burners)	*L/ton*	-	1.8
Electricity	*kwh/ton*	-	120
Ashes			
Fly ash	*kg/ton*	1.53E+02	28.6

The effect of Incineration and Gasification on MSW using the endpoint approach is presented in Figure 9. Gasification performs better than incineration in most parameters.

In the context of our investigation, as depicted in Figure 9, incineration technology has a more significant environmental impact across all evaluated parameters than gasification does. Human health demonstrates the most significant disparity, likely because of the elevated emissions of deleterious constituents associated with incineration. Our findings, supported by the data in Table 7, demonstrate that CO_2 is the primary contributor to climate change. Interestingly, gasification technology exhibits negative values in the domain of ecosystem quality, indicating its potential for mitigating environmental burdens, which is validated in (Elwan and Habibuddin, 2021).

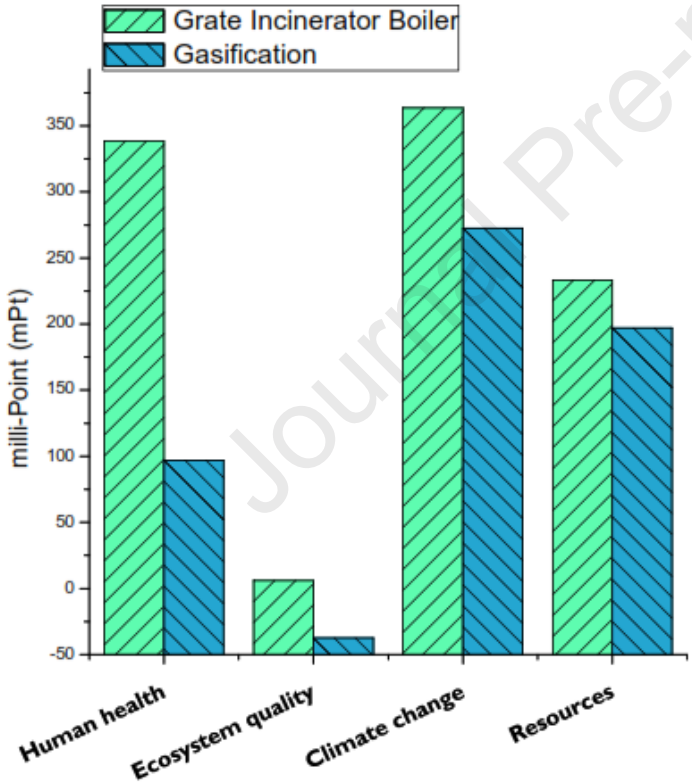


Figure 9. Comparison of the effect of incineration and gasification for MSW treatment under the endpoint approach.

To evaluate the sustainability performance of a system, the system boundary must be precisely defined. One of the proper environmental indicators to quantify it in the field of MSW focuses on the following medians: Global-warming potential (GW), associated with climate change; Ozone layer depletion; Photochemical smog, based on Nitrogen Oxides and Volatile Organic Compounds (VOCs) associated with the industrialization and transportation through fossil fuel uses; Human and

Ecotoxicity, related to public health; Resources conservation potential (Chang and Pires, 2015). On the other hand, Dong., et al. (2018) considered these impact categories: GW, Acidification (AC), Terrestrial eutrophication (TE), Photochemical ozone formation to human health (POFh), Human toxicity via air (HTa), Human toxicity via solid (HTs), Ecotoxicity via solid (ETs) (Dong et al., 2018b). Consequently, a comprehensive approach should be taken when selecting the parameters for the midpoint; the following parameters are discussed in detail in this study: Global warming, depletion of the ozone layer, ozone formation, acidification, and eutrophication. Negative values represent decreased environmental burdens, whereas positive values represent increased environmental loads. Consequently, greater values have a more significant effect on the corresponding parameter.

According to Figure 10. except for Ozone depletion, where incineration has a more favorable environmental impact, gasification technology demonstrates superior performance across most parameters. It is important to note that MSW incineration facilities are expensive due to their high initial investment, operational costs, need for trained personnel, and stringent maintenance (Bran et al., 2010). On the other hand, Waste incineration is a remarkable way to neutralize waste; among the advantages, the incineration allows to reduce the waste volume significantly, it can be located not far from the generation points, reducing the cost of waste transportation (T. Rand J. Haukohl, 2000).

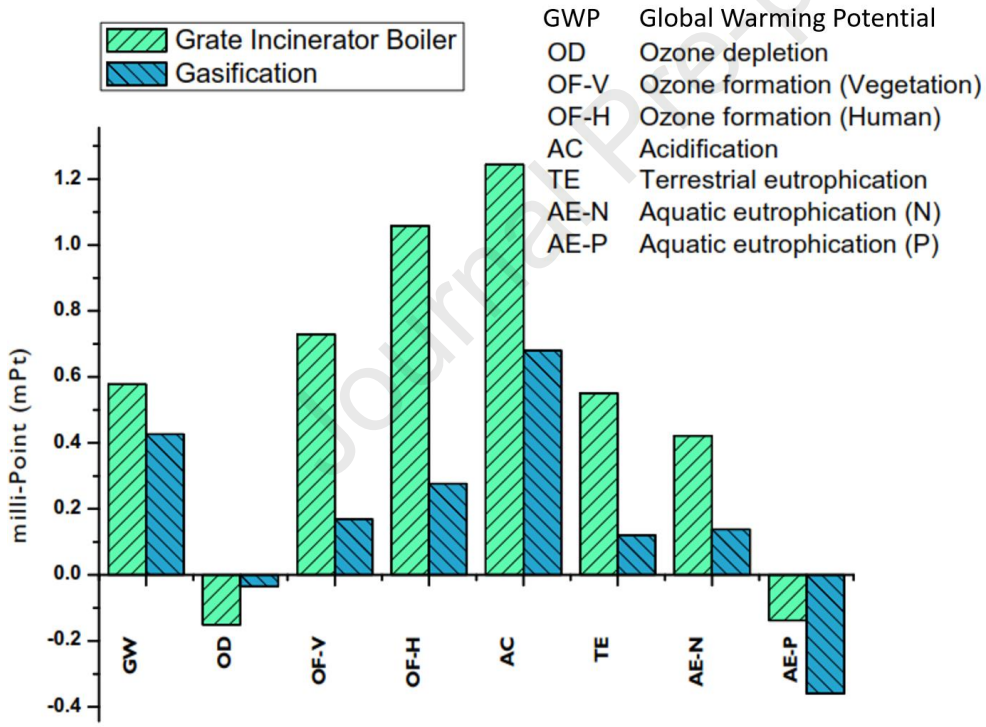


Figure 10. Midpoint Life Cycle Impact Assessment of Incineration and Gasification for MSW treatment.

Global Warming Potential: Within the context of LCA, the impact of electricity recovery and emissions such as carbon dioxide (CO_2) and nitrogen oxides (NO_x) are of great significance (Dong et al., 2018c). Since methane (CH_4) has a negligible impact on GHG accounting in incineration and gasification processes, special attention was paid to CO_2 emissions. Our analysis reveals that incineration contributes approximately 30 % more to the environmental burden of global warming

potential than gasification. Higher CO_2, CO, and NO_x emissions can be attributed to the incineration process for this difference. These emissions are converted to CO_2 equivalents using specific factors that evaluate their contribution to the Climate Change outcome. This disparity may be influenced by the differences in feedstock composition between the two processes and the technologies utilized. Moreover, regional differences in electricity generation practices, such as those observed in China, contribute to the variations in emissions over time (Chen et al., 2012).

Ozone Depletion: The ozone depletion assessment indicates that incineration and gasification favorably influence the environment, as shown by their negative values in Figure 7. However, compared to gasification, incineration has a marginally more significant potential for avoiding environmental loads. This observation could be attributed to the production of electricity and steam in incineration and gasification, respectively, and the avoidance of methane emissions, which substantially affect this parameter. Compared to gasification, incineration has a more significant impact on the environment regarding ozone formation, which is detrimental to plant life and human health. This subsequently affects the ecosystem quality parameter and several other midpoints, suggesting that gasification performs better.

Acidification: The environmental burden associated with acidification is more significant for combustion than gasification. Both processes contribute significantly to acidification relative to other midpoint categories, predominantly due to the higher concentration of acidic compounds observed (Table 7). The atmospheric deposition of nitrogen and other nutrients affects terrestrial eutrophication, affecting ecosystems' quality. However, free nitrogen does not contribute to the eutrophication of the earth's surface. Regarding gasification, terrestrial eutrophication is comparable to aquatic eutrophication, with nitrogen being the determining factor in both instances. In the case of incineration, the values for terrestrial eutrophication are marginally higher than those for aquatic eutrophication due to particular characterization factors. Additionally, aquatic eutrophication demonstrates a notable reduction in environmental load for gasification and incineration, with the savings marginally less significant in the incineration case.

Therefore, gasification is a promising technology for sustainable MSW management, but it also emphasizes the importance of addressing technical and environmental obstacles for its successful implementation on a larger scale. Public participation and ongoing research and development efforts are essential to realize the full potential of WtE technologies in addressing current waste management issues. However, implementing MSW gasification on a commercial scale presents some obstacles. When operating on heterogeneous waste, conventional systems may manifest inherent instability, necessitating efforts to achieve high levels of efficiency. In addition, waste gasification produces a complex mix of organic compounds, and tar separation is an inefficient process that drives up plant expenses. In addition, substantial quantities of fly ash and pollution management residues necessitate post-treatment measures to reduce land disposal (Materazzi, 2016b). Besides that, gasification requires pre-processing and classification, requires maintenance extensively, and not every location is the site of the preponderance of large-scale operations (Ambaye et al., 2023)

3.7.4 Energy potential of MSW recovery

3.7.4.1 Influence of MSW recovery within the Chinese energy matrix.

Some studies have highlighted China's transition towards utilizing MSW as an energy resource, emphasizing the significance of sorting and recycling, particularly in food waste separation (Shapiro-Bengtsen et al., 2020). Others have explored optimized MSW conversion into energy in critical

regions such as the Greater Bay Area of China and cities like Beijing and Shanghai (Zhou and Zhang, 2022; Gu, Liu, and Wang, 2021; Dai, 2016). For instance, a gasification model proposed for Shanghai offered energy estimations, showcasing higher efficiency (33.5%) compared to incineration (27%) for electricity production (Dai, 2016). These studies provide valuable insights into the energy potential of MSW related to the most relevant WtE facilities.

Table 8 illustrates the availability and consumption of energy sources across different areas in China based on data from the China Statistical Yearbook (2023). The table presents percentages of electricity consumption by area, followed by the potential substitution by WtE incineration and gasification. Notably, regions with the highest potential for substitution are imports, with gasification and incineration offering replacement scales exceeding 2.6 and 3.0 thousand times, respectively, enhancing the country's energy sovereignty. However, feasibility analyses are essential, particularly in regions facing energy deficits, to assess the viability of WtE substitution.

Additionally, thermal power constitutes the most significant proportion of energy production at 70.73%, with approximately 45% (Yuan et al., 2018) of China's coal consumption dedicated to power generation. The industrial sector emerges as the largest consumer of electricity (66.46%), followed by household usage (14.41%). Therefore, WtE technologies contribute to replacing 2.67-3.09% of energy consumption and offer ancillary benefits such as job creation, progress toward carbon neutrality goals, and improved MSW management, especially during the winter, when more coal is burned for heating.

Table 8**.** Potential energy substitution in China's electricity and energy balance through MSW incineration and gasification.

Electricity available for consumption in China (2021)				
	Electricity production (kWh)	**Percentage by source (%)**	**Potential substitution by MSW incineration (%)**	**Potential substitution by MSW gasification (%)**
Hydropower	1.34E+12	16.31	11.60	13.40
Thermal Power	5.81E+12	70.73	2.67	3.09
Nuclear Power	4.08E+11	4.96	38.11	44.03
Wind Power	6.56E+11	8.01	23.67	27.35
Imports (+)	5.90E+09	0.07	2,632.05	3,041.38
Exports (-)	2.02E+10	0.25	768.77	888.32
Consumption of Electricity by Sector				
	Electricity demand (kWh)	**Percentage by source (%)**	**Potential substitution by MSW incineration (%)**	**Potential substitution by MSW gasification (%)**
Agriculture, forestry, livestock and fisheries	1.60E+11	1.87	97.24	112.36
Industry	5.66E+12	66.46	2.74	3.17
Construction	1.13E+11	1.33	137.06	158.38
Transport, Storage and Post	1.99E+11	2.34	77.92	90.04
Wholesale and Retail Trades, Hotels and Catering Services	3.87E+11	4.54	40.13	46.37
Other Sectors	7.71E+11	9.05	20.15	23.28
Household Consumption	1.23E+12	14.41	12.65	14.61

Average daily energy consumption according to the China Statistical Yearbook (2023)		
	Production in 2021 (1000 tons)	Percentage by source (%)
Coal	1176.9	73.19
Coke	127.8	7.95
Crude Oil	198.1	12.32
Fuel Oil	15.0	0.93
Gasoline	39.0	2.43
Kerosene	9.6	0.60
Diesel oil	41.6	2.59

3.7.4.2 Potential use of the energy from MSW in social sectors and mobility in the context of China.

The results demonstrate significant energy recovery potentials: $1.55x10^8$ MWh/year ($4.25x10^5$ MWh/d) for incineration and $1.79x10^8$ MWh/year ($4.92x10^5$ MWh/d) for gasification. Notably, gasification emerges as the most efficient technology, boasting a 15.5% increase in energy generation compared to incineration. This underscores the superior efficiency of gasification in harnessing energy from MSW, positioning it as a critical player in waste management and energy recovery strategies. Adopting WtE plays a crucial role in reducing reliance on landfills, mitigating environmental pollutants, and promoting the sustainable utilization of resources.

Moreover, this potential could address society's energy requirements in essential sectors such as education, health, and electromobility. Table 9 provides further insights into the scope of this proposal, highlighting its potential societal benefits.

Table 9. Potential energy supply from WtE technologies in the context of China.

Social sector	**Average energy consumption by sector kW/(m².a)**	**Average area of establishment (m²)**	**Estimated units supplied annually by WtE technology**		**References**
Education	95.64	7,910	Incineration	205,272 schools	(Xing et al., 2015)
			Gasification	237,196 schools	
Health	178.52	9,1600	Incineration	9,497 hospitals	(Shi et al., 2021)
			Gasification	10,973 hospitals	
Electromobility sector					
Type of car	**Energy consumption (Wh/km)**	**Expected distance to be traveled (km)**	**Estimated BEV supplied by WtE technology**		**References**
Battery electric vehicles (BEV)	188	199,558.66*	Incineration	4,139,209 BEV	(Elliott et al., 2024; Lu, 2023)
			Gasification	4,782,931 BEV	

*This value was calculated considering a median life of 18.4 years

These findings indicate the potential positive impact of WtE technologies on China's social sectors, including education and health. Waste incineration can annually supply energy to 205,272 schools, while waste gasification could power 237,196 schools. Similarly, waste incineration could provide energy for 9,497 hospitals, with gasification potentially supplying 10,973 hospitals annually. Moreover, WtE technologies could also support the growth of electromobility, with MSW

incineration capable of powering over 4.1 million BEVs and waste gasification, potentially supplying 4.8 million BEVs nationwide.

The results suggest that WtE technologies offer a promising avenue for enhancing China's energy supply and reducing reliance on fossil fuels. However, these calculations are subject to certain limitations. Firstly, it was assumed that all MSW generated was successfully collected and reached WtE facilities. However, economic constraints, logistical hurdles, and cultural practices can influence the effectiveness of MSW collection systems. Secondly, the composition of MSW varies geographically and temporally, influenced by factors such as seasonal changes and holidays. Therefore, while the calculated values provide valuable insights into the potential benefits of WtE technologies, their interpretation should be cautious and validated with local data and considerations.

4 Perspectives and Outlook

Proper management of waste is critical to maximizing environmental and health gains. Waste management is an area with emerging and progressive research. Incineration reduces environmental impact and landfill waste (Mubeen and Buekens, 2019). Recently, gasification and incineration have become environmentally preferable alternatives to traditional methods. However, according to Cooper et al. (2019), challenges persist for gasification, including the lack of proven experience at scale, hindering financial security, and necessitating further research to develop cost-effective technologies and enhance syngas production. Insufficient funding support for commercial gasification and uncertainties in quantity, confidence, and application barriers could be addressed by integrating biomass gasification with CCUS.

Forecasts predict an expansive trajectory for the global WTE technologies market by 2023, driven by advances that simultaneously reduce GHG emissions. The potential rise of AD in the future WTE technology landscape is noteworthy due to its ability to develop globally. Despite their suboptimal nature, landfills are poised to maintain their relevance in the waste management spectrum. Nations at the forefront of environmental acumen, such as Belgium, Sweden, Austria, the Netherlands, and Denmark, present developed solid waste management paradigms. However, the horizon for developing countries is marked by population growth, increasing waste, and urban sprawl, posing unique challenges. Regional differences call for the adoption of appropriate technologies for efficient energy recovery. Hence, energy security is paramount and depends on local planning and decision-making.

For instance, some common points exist in developing countries such as Nigeria (Nubi et al., 2022) and Indonesia (Mustafa et al., 2022). In energy policy and sustainability, the predominant focus on energy security must not overshadow environmental and social considerations. A successful sustainability plan for electricity and waste requires a view that covers various sustainability dimensions. Encouraging research into cleaner WtE technologies and strengthening regulations to mitigate environmental impacts is essential. Future research avenues include refining methodologies, integrating multi-criteria decision models, and improving strategies for communicating life cycle sustainability assessment results (Elegbede et al.,2023). Mitigation strategies also include advanced filtering, optimization of recycling infrastructure, and improving gas scrubbing systems at WtE facilities. In addition, the study recommends extending incineration to selected cities, optimizing waste collection, and adapting feedstock characteristics for WtE plants (Nubi et al., 2022). Urgent recommendations include aligning research with sustainable development goals, GIS-based modeling, COVID-19 waste impacts, and circular economy implications (Ndou and Rampedi, 2022).

Rural communities and sectors lack access to essential services, and WtE technologies could have a positive influence. There are limited studies on their real application in these contexts, such as the one in the Ecuadorian Amazon (Heredia Salgado et al., 2021), using pyrolysis to convert waste into biochar to implement the bioeconomy principles. Another limitation to work on is the social component, where the interests and activities of the indigenous peoples must be known before applying a project of this nature and should be supported by academia and government (Chicaiza Ortiz et al., 2022). More multi-criteria studies could support the decision to choose WtE technologies or their potential combinations of them (Alfonso-Cardero et al., 2023). Employment opportunities for local people are crucial to social sustainability, providing them with personal protective equipment to avoid medical risks (Sondh et al., 2024). Among the solutions, centralized and source separation are desired to address MSW complexity.

Future co-substrate feeding of FW into existing plants might reduce capital investment for new facilities. Exploring ethanol-methane and biohydrogen synthesis linked to additives could enhance energy recovery and economics (Chicaiza-Ortiz et al., 2023). Biorefineries need more research to operate commercially (Sharma et al., 2022). In this context, financial analysis indicates WtE alternatives are profitable for Muscat (Oman), with incineration leading in profitability, followed by Anaerobic digestion and gasification (Abushammala and Qazi, 2021). Sensitivity analysis highlights key parameters impacting WTE plant profitability, including carbon credit allowance, electricity tariff, and Capital Expenditure (CAPEX). Decision-makers should closely monitor these factors to optimize project outcomes. Future research should explore integrating different WTE technologies and consider recycling's financial benefits. It is key to realize that technology development and implementation are tightly related to social, economic, and environmental incentives. It is of utmost importance to understand the socio-economic aspect of the place where the technology will be applied to increase the chances of success and better implement a technological approach.

Muhammad Sajid Khan et al. (2022) point out a need to share strategic information and engage the public in meaningful discussions. There are opportunities to assess energy production and improve oil recovery by including external costs in our modeling and LCA. Opportunities in developing countries are available through policies, investments, and regulations. Developing countries strive to mitigate landfill risks, encourage waste reduction, improve recycling, and transition to renewable energy through WtE solutions. To grow waste treatment tech sustainably, businesses must adjust their business models to fit local contexts and attract investment.

Further study should establish an integrated waste management system, focusing on trash classification and product-centric methods for product separation. MSW valorization technologies in a circular economy can benefit the competitive economy by maximizing the use of MSW resources and reducing environmental impact. It also eliminates waste and primary resource input reliance at the source (Ambaye et al., 2023). This approach can inform national MSW management policies and encourage sustainable practices in developing countries.

5 Conclusions

MSW Management has become a valuable alternative for some developed nations but remains challenging for most developing countries. Generating energy more efficiently and with fewer emissions is possible than current methods. Based on the 5132 published articles related to waste-to-energy technologies for MSW from the Scopus database, an overview of research on denitrifying carbon sources was performed by bibliometric analysis. Several significant findings have been identified in this field. Within the statistical period, China ranked first in the number of publications,

followed by the USA and Italy. Keyword analysis revealed research hotspots in this field. Traditional emissions, such "PCDD/PCDF," "carbon monoxide," "dioxins," and "chlorobenzenes.", and novel alternative carbon sources, such as sludge, "circular economy" and "gasification" have been introduced. Most cited papers and most relevant journals have also been identified. Despite its prevalence, incineration generates more significant GHGs and pollutant emissions than gasification and pyrolysis. The latter options offer superior emission control and the opportunity to recover valuable byproducts such as biochar and bio-oil. However, their widespread adoption requires technological advancements and surmounting economic obstacles. In addition, hydrothermal liquefaction and hydrothermal carbonization are promising and energy-efficient methods for organic waste with a high-water content.

Moreover, a case study compared gasification and incineration for MSW under the LCA approach. Based on the results, the middle stages indicate the load in eight parameters, with gasification exhibiting the most remarkable environmental performance in most parameters. In addition, the gasification technology outperformed incineration in all endpoint parameters, and a significant difference was observed in the human health and climate change stages. Incineration technology can explain this result, which produces more hazardous elements and carbon dioxide. Except for ozone depletion, where incineration exhibits marginally superior performance in avoiding environmental loads, gasification generally produces improved environmental outcomes for most parameters. These findings provide valuable insights into the ecological implications of each technology, assisting in making informed decisions and developing sustainable MSW management strategies.

In the context of this study, it can be concluded that gasification technology is recommended from an environmental standpoint. Enhancing policies related to waste sorting and conducting feasibility studies for gasification technology are among the recommendations for stakeholders. If gasification technology could be implemented in the primary generators of MSW, significant environmental burden reductions would result. In the interim, economic evaluation should be performed in future investigations. Future research can explore hybrid processes that combine thermo-chemical (e.g., gasification, HTC) and biological conversion methods (e.g., AD). Studies can examine the benefits and drawbacks of combining HTL and AD to recover liquid fuels from biomass waste. Such integrated approaches' performance, efficiency, and environmental impacts may help optimize waste recovery systems. Research can investigate advanced oxidation processes (AOP), such as photocatalysis and the Fenton process, for biomass conversion. Studying these processes can improve WtE conversion by revealing their effectiveness in breaking down complex organic compounds. For large-scale applications, they must be assessed for environmental impact and scalability.

The study also underscored the potential positive influence of WtE technologies on critical social sectors in China, such as education, health, and electromobility. Additionally, by estimating the possible replacement of a significant fraction of China's energy consumption, the study suggests an enhancement in energy sovereignty and a reduction in reliance on traditional energy sources like thermal power. In addition, this study contributes to the existing literature by understanding the energy sustainability of WtE technologies.

Future research endeavors can enhance their comprehension of emissions patterns and positively contribute to the sustainable advancement of WtE initiatives by using machine learning and deep learning capabilities to uncover valuable insights and predict potential energy recovery. Assessment criteria, including social well-being, human rights, employment opportunities, public involvement, financial elements, and technology innovation, should be included in future studies to help policymakers and industry stakeholders adopt sustainable WtE practices.

6 Author Contributions

CCO: Writing – original draft, review & editing, conceptualization, methodology; PPA: Writing – review & editing; RHF: Writing, methodology; WM: Resources, funding acquisition, supervision; WL: Formal analysis, writing – review & editing; HT: supervision, validation; WY: Data curation, supervision; validation.

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Declaration of interests

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

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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