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Corso di Laurea Magistrale in Environmental Engineering

**TESI DI LAUREA**

# AIR POLLUTION EMISSIONS FROM PYROLYSIS PLANTS A SYSTEMATIC MAPPING

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**ANNO ACCADEMICO 2022-2023**

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# Air pollution emissions from Pyrolysis plants: A systematic mapping

**Abstract**

Pyrolysis plants are gaining popularity for their ability to process various waste materials, such as sewage sludge, plastics, biomass, and tires, for waste management and energy generation. However, the environmental and health impacts of the gas emissions generated by these plants have yet to be extensively studied, and the available evidence needs to be more comprehensive and cohesive.

The current systematic mapping critically evaluates the existing literature on air pollution emissions from pyrolysis plants, synthesizing the available evidence to identify the essential findings and research gaps in the field. The review examines the potential pollutants emitted by pyrolysis plants according to the feedstocks, process parameters, and APC system applied.

The review highlights that pyrolysis plants can emit a wide range of air pollutants depending on the feedstock and operating conditions of the pyrolysis plants; in particular, they include:

**a.** Particulate Matter (PM)

Depending on the plant's design and efficiency of control measures, PM emissions can range from a few milligrams (1.11e-3 mg/Nm$^3$ [83]) to hundred milligrams per cubic meter (mg/m$^3$) of exhaust gas (72.50 mg/Nm$^3$ [71]).

**b.** Nitrogen Oxides ($NO_x$)

$NO_x$ emissions from studied pyrolysis plants ranged from 1.1138 mg/Nm$^3$ to 131 mg/Nm$^3$. [75, 53].

**c.** Volatile Organic Compounds (VOC)

VOC emissions can range from a few ppm to several hundred ppm.

**d.** Polycyclic Aromatic Hydrocarbons (PAHs)

PAH emissions can range from trace amounts to a few milligrams per cubic meter (mg/m$^3$) of exhaust gas.

The magnitude and composition of the emissions depend on the feedstock and operating conditions of the pyrolysis plants.

The review also identifies several areas for improvement in the current knowledge on this topic. For example, there needs to be more emission measurement and reporting standardization, making it challenging to compare results across studies. Additionally, few studies have investigated the long-term health effects of exposure to pyrolysis plant emissions, and further research is needed to understand better the impacts of these emissions on vulnerable populations, such as children and the elderly. It is worth noting that while health assessments are essential for understanding the potential human and environmental impact of these emissions, the current scope of this thesis primarily focuses on emission data and their implications. To address these gaps, the review recommends that future research should focus on the development of standardized methods for emission measurement and reporting, the investigation of the long-term health effects of exposure to pyrolysis plant emissions, and the identification and implementation of effective mitigation measures to reduce the environmental and health impacts of these emissions.

In conclusion, this systematic mapping review offers a comprehensive assessment of the current knowledge concerning air pollution emissions from pyrolysis plants. The collective evidence underscores that pyrolysis plants produce notable air pollution emissions, necessitating continued investigation and effective mitigation measures to mitigate the associated environmental ramifications. It is noteworthy, however, that when compared to conventional combustion plants, pyrolysis processes generally yield emissions at comparatively lower levels, thereby presenting pyrolysis as a potentially more environmentally friendly option, although the full extent of its advantages warrants ongoing scholarly inquiry.

**Keywords**: pyrolysis plants, air pollution, emissions, particular matter, nitrogen dioxide, volatile organic compounds, polycyclic aromatic hydrocarbons, health effects, environmental impact, mitigation measures, waste management, energy generation, waste-to-energy, systematic mapping

# 1. Introduction

Pyrolysis is a process that has been gaining traction in recent years as a sustainable and cost-effective method for waste management. Pyrolysis plants are designed for the thermochemical processing and utilization of various waste organic residues, such as plastics, tires, and biomass, into valuable resources such as fuel, gases, and carbon black. [1, 2, 3, 6] Moreover, pyrolysis, mainly when applied to biomass, is crucial in mitigating climate change and reducing greenhouse gas emissions. This is particularly notable in biochar production, a stable form of carbon that can sequester carbon dioxide from the atmosphere for extended periods. The conversion of biomass into biochar through pyrolysis represents an essential strategy for carbon capture and storage (CCS) [2].
The significance of pyrolysis in addressing climate change must be considered. It offers a unique avenue for carbon sequestration by locking carbon in biochar, which can be utilized in various agricultural applications to enhance soil health and fertility while preventing the release of $CO_2$ back into the atmosphere. This dual benefit of waste reduction and carbon sequestration underscores the multifaceted potential of pyrolysis technology in contributing to sustainable environmental practices and reducing the overall carbon footprint.
Furthermore, it is essential to recognize that pyrolysis is an independent conversion technology and a part of gasification and combustion [2-5], which consists of the thermal degradation of solid feedstock into gases and liquids in an oxygen-free environment. [3,4] These plants have the potential to decrease the amount of waste sent to landfills while contributing to the circular economy by creating a closed-loop system for waste management. [7] Therefore, beyond its role in greenhouse gas reduction, pyrolysis also aligns with resource efficiency and waste minimization principles. It is a crucial component of sustainable waste management practices and a key player in transitioning toward a more environmentally responsible and carbon-neutral future.
Pyrolysis can be categorized into three main types, conventional, fast, and flash, based on various operational conditions such as process temperature, heating rate, residence time, particle size, etc. Product distribution depends on pyrolysis technology and operating parameters, as shown in Table 1.

**Table 1.** Typical operating parameters and pyrolysis products [1, 3, 6].

| Pyrolysis Type | Temperature (K) | Heating Rate (K/s) | Vapor Residence Time (s) | Particle Size (mm) | Product Yield (%) | | |
|---|---|---|---|---|---|---|---|
| | | | | | Oil | Gas | Char |
| **Slow** | 550–950 | 0.1–1 | 600-6000 | 5–50 | 30 | 35 | 35 |
| **Fast** | 850–1250 | 10–200 | 0.5-5 | <1 | 50 | 30 | 20 |
| **Flash** | 1050–1300 | >1000 | <0.5 | <0.2 | 75 | 13 | 12 |

The feedstock and pyrolysis temperature primarily influences the pyrolytic gas composition. When biomass waste such as wood, garden waste, and food residue is subjected to slow pyrolysis at low temperatures below 400°C, it produces a small amount of gas rich in $CO_2$, CO, and light hydrocarbons [22, 35, 36]. The gas yields are usually less than 30 wt% of the product, but increasing the temperature can boost the gas yields due to secondary reactions and partial char decomposition. The gas heating value from slow pyrolysis ranges from 10 to 15 MJ/Nm$^3$ and depends on temperature and heating rate [7,8]. According to Prabir et al., high temperature and low residence time, along with a high heating rate, provide the best conditions to maximize gas production in the pyrolysis process, Fig. 1. Fast pyrolysis of biomass produces gas with a heating value of around 14 MJ/Nm$^3$.

Conversely, high temperatures above 700°C, mainly when gasification and pyrolysis are combined, produce syngas with more hydrogen and carbon monoxide as the main product. Pyrolysis of plastic yields pyrolytic gas comprising hydrogen and various light hydrocarbons, including methane, ethane, ethene, propane, and butane [24, 25, 26, 45]. The gas from Polypropylene (PP) and Polyethylene (PE) pyrolysis has a heating value that varies between 42 and 50 MJ/kg [9]. However, the gas from co-pyrolysis of polymers and biomass leads to higher CO and $CO_2$ production, especially at lower temperatures. The syngas derived from municipal solid waste (MSW) consist of $CO_2$, CO, hydrogen, methane, and various light hydrocarbons, exhibiting an average heating value of approximately 15 $MJ/Nm^3$, which escalates as the temperature rises. [10-12]. The syngas is suitable as an energy source for the pyrolysis process. Still, emission control units and gas cleaning devices are necessary to regulate exhaust gas, which may contain unwanted compounds. Syngas from tires may contain H2S, which oxidizes to $SO_2$, while PVC pyrolysis produces a substantial amount of HCl [10,13]. Moreover, food waste processing may yield harmful nitrogen compounds [13].

Air pollution from pyrolysis plants is a significant issue that requires attention from researchers, policymakers, and the public. The swift expansion of the pyrolysis sector, spurred by the demand for eco-friendly waste disposal and the aspiration to generate renewable energy, has generated apprehension regarding the possible environmental and health repercussions of its emissions. [14].

Emissions stemming from pyrolysis facilities exhibit complexity and variability, contingent upon various factors, encompassing the feedstock's characteristics and nature, the pyrolysis temperature and duration, the plant's design and operational aspects, and the employed emission control technologies. For example, the further combustion of syngas - a process often carried out for energy recovery - can result in significant $NO_x$ and $SO_2$ emissions [15,16]. Moreover, emissions from these plants can include particulate matter, volatile organic compounds (VOCs), and carbon monoxide (CO) [17]. These pollutants can have various adverse effects, including respiratory problems, cardiovascular disease, and climate change. Therefore, it is crucial to understand the emissions from pyrolysis plants and their impact on the environment and human well-being.

This systematic mapping will provide a comprehensive overview of the air pollution emissions from pyrolysis plants, focusing on the types and quantities of pollutants emitted and their potential environmental impacts. We will also investigate the variables influencing emissions, such as the choice of feedstock, the configuration and functioning of the pyrolysis facility, and the utilization of emission control technologies.

Studies have shown that VOCs are a particularly concerning group of pollutants that can harm human health and the environment. Dastjerdi et al. found that the pyrolysis of MSW can result in the release of various VOCs, including benzene, toluene, and formaldehyde, among others [18].

Efforts have been made to mitigate the environmental and health impacts of pyrolysis plant emissions. These include using advanced air pollution control technologies, such as electrostatic precipitators and scrubbers, to reduce the release of pollutants [21]. Rajarao et al. investigated the effectiveness of a wet electrostatic precipitator for reducing VOC emissions from pyrolysis plant flue gases [22]. Additionally, optimizing pyrolysis conditions and using more sustainable feedstocks can help to reduce emissions [23]. Compared to the other waste management techniques, decisions on which process to use would be heavily influenced by policy requirements.

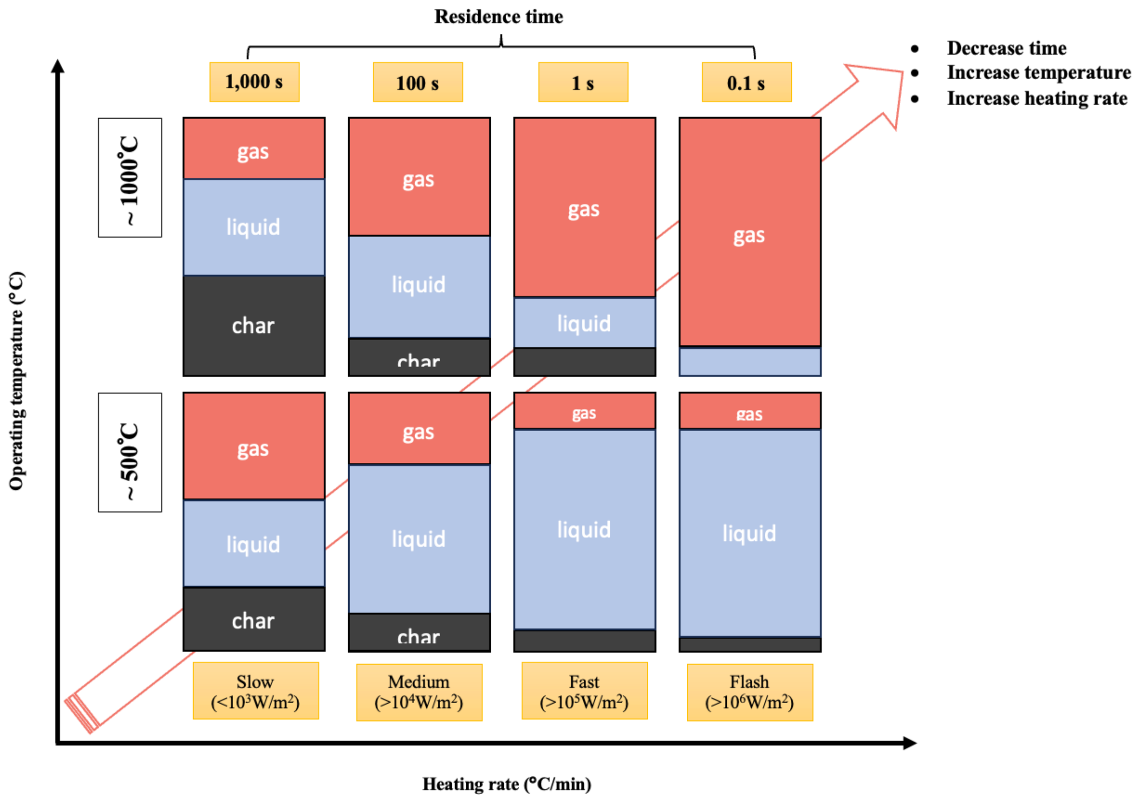


**Fig. 1.** Figure summarizing different pyrolysis conditions and the effect on product distribution [1].

This systematic mapping aims to provide a comprehensive and up-to-date understanding of the air pollution emissions from pyrolysis plants, their potential health and environmental impacts, and the factors that influence emissions. The findings of this review will be of great interest to researchers, policymakers, and stakeholders in the waste management and energy sectors concerned with minimizing the environmental impacts of pyrolysis plants.
The potential health impacts of air pollution emissions from pyrolysis plants have also been investigated. A study by Singh et al. [19] found that exposure to particulate matter from a pyrolysis plant increased mice's inflammation and oxidative stress levels. Similarly, Martínez et al. [20] showed that exposure to emissions from a pyrolysis plant increased levels of pro-inflammatory cytokines in human lung cells.

## 2. Methodology

This methodology section employs a systematic mapping approach to investigate air pollution emissions from pyrolysis plants. The primary goal of this study is to locate and scrutinize pertinent literature, emission factors, and their consequences for developing efficient air pollution control systems and evaluating environmental repercussions. [18, 85].

### *2.1 Specific Research Questions*

The research objectives and corresponding questions were formulated to define the scope and objectives of the systematic mapping process. These questions guide the systematic identification, categorization, and analysis of pertinent literature. The primary goal is to comprehensively understand air pollution emissions from pyrolysis plants and their associated emission factors, enabling insights into developing effective air pollution control systems and environmental impact assessments [85].
Research objectives and corresponding questions were developed and presented in Table 2 to achieve this goal.

**Table 2.** Systematic mapping objectives and questions.

| Objectives | | Questions |
|---|---|---|
| **1** | To identify the types and levels of air pollutants emitted by pyrolysis plants and the sources of such emissions. | What are the types and levels of air pollutants emitted by pyrolysis plants? |
| **2** | To investigate the main factors that influence the emission of air pollutants from pyrolysis plants and their potential interactions. | What are the main factors that affect the emission of air pollutants from pyrolysis plants? |
| **3** | To review and evaluate the available technologies and strategies for reducing or controlling air pollution emissions from pyrolysis plants, and their performance and limitations. | What are the available technologies and strategies for reducing or controlling air pollution emissions from pyrolysis plants? |
| **4** | To identify the gaps and limitations in the current knowledge and research on air pollution emissions from pyrolysis plants, and to propose potential avenues for future research to address those gaps. | What are the gaps and limitations in the current knowledge and research on air pollution emissions from pyrolysis plants, and what are the potential avenues for future research? |

### *2.2 Criteria and bibliographical search strategy*

A structured protocol was developed to conduct this systematic mapping, encompassing the selection of search terms, criteria, and data extraction methods. A review of relevant literature in pyrolysis technologies and air pollution control informed the choice of keywords. A trial-and-error approach was used initially to identify keywords, ensuring their effectiveness in capturing many relevant papers related to the topic of interest.

### *2.3 Screening*

To initiate the screening process, non-English articles were eliminated in this investigation. Then, duplicate records were searched and deleted after including other studies from supplementary sources. As a result of examining electronic databases and other supplementary sources, multiple matches were identified. Following the removal of duplicates, the remaining records were assessed for their relevance. At this point, articles published before 2005, retracted, book chapters, inaccessible full-text, dissertations, conference proceedings, editorial papers, abstract-only papers, and other non-relevant records were eliminated. Figure 2 represents the screening process to achieve the final selected studies.

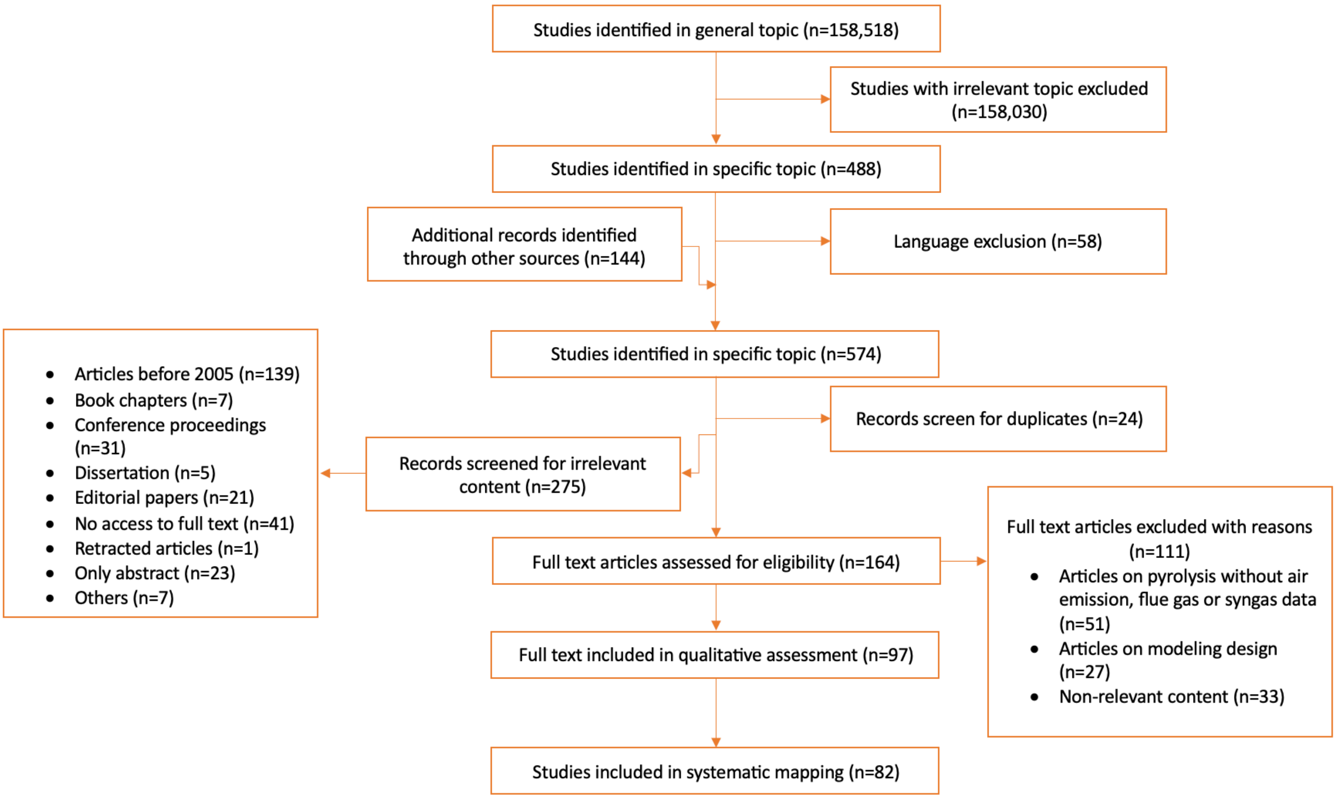


**Fig. 2.** Search and inclusion flowchart of investigated articles.

### *2.4 Criteria for article exclusion and inclusion*

To identify the most crucial articles for the systematic mapping outlined in this paper, a comprehensive search was conducted with a focus on pieces that contained valid research, clear contributions, and enriched data. The inclusion and exclusion criteria were carefully designed to locate the optimal studies and to extract and synthesize the necessary data. Initially, a large number of articles were gathered for analysis from the selected databases.

Studies employing diverse research designs, including experimental studies, field measurements, and case studies, were considered for inclusion. However, articles lacking a transparent methodology or research approach were excluded.

A flowchart illustrated in Figure 2 was developed to show the process of selecting and introducing the identified papers to the database. In the first step, 158,032 papers that did not include (“Waste” OR “sludge” OR “biomass” OR “MSW” OR “MPW” OR “tire” OR “tyre”

OR “wood” OR “plastic”) AND (“air pollution” OR “air emission”) AND NOT (“diesel” AND “engine”) strings in their topics were considered as irrelevant. Fifty-eight articles were excluded due to their language. Continuingly, 144 additional papers from supplementary sources (Google Scholar and Web of Science) were added. After excluding the duplicates and screening papers with reasons mentioned above, 164 English articles and reviews with (“pyrolysis”) AND (“Waste” OR “sludge” OR “biomass” OR “MSW” OR “MPW” OR “tire” OR “tyre” OR “wood” OR “plastic”) AND (“air pollution” OR “air emission”) AND NOT (“diesel” AND “engine”) strings in their ‘topic’ were examined. However, in further examination, 82 publications were considered irrelevant papers. They were excluded since the studies mainly focused on policies and legislation, economic and social aspects, technical issues, agricultural and industrial production, modeling and optimization, and biochar carbon for climate change mitigation, and they had no extractable data for this review.

## 3 Review and analysis of documents

The authors, year of publication, the journal where it was published, and the number of citations were recorded for each paper. Then, information related to the scale, pyrolysis technology, feedstock, operating conditions, syngas characteristics, type of pollutants analyzed, mitigation strategies, and comparison between pyrolysis and combustion for each paper was extracted. A summary table was developed to record information obtained from the selected papers. The scale of the plants was categorized into lab, pilot, and full scale. Plants with a capacity of up to 100 kg/h were considered a pilot scale, and plants with a running capacity of more than 100 kg/h were considered full-scale plants. Moreover, three different types of pyrolysis technology (slow or conventional, fast, flash) and microwave assistance in these processes were evaluated. [24]

Amidst technological advances, interest in air pollution derived from pyrolysis plants and their mitigation consistently increased from 2005 to 2023. However, one thing that may be of interest is that various applications were investigated during the studied time frame. According to Figure 3, 2020 had the most articles with 13, followed by 2021 with 10. It can also be seen that 2002, 2004, and 2008 had the fewest articles with a single article.

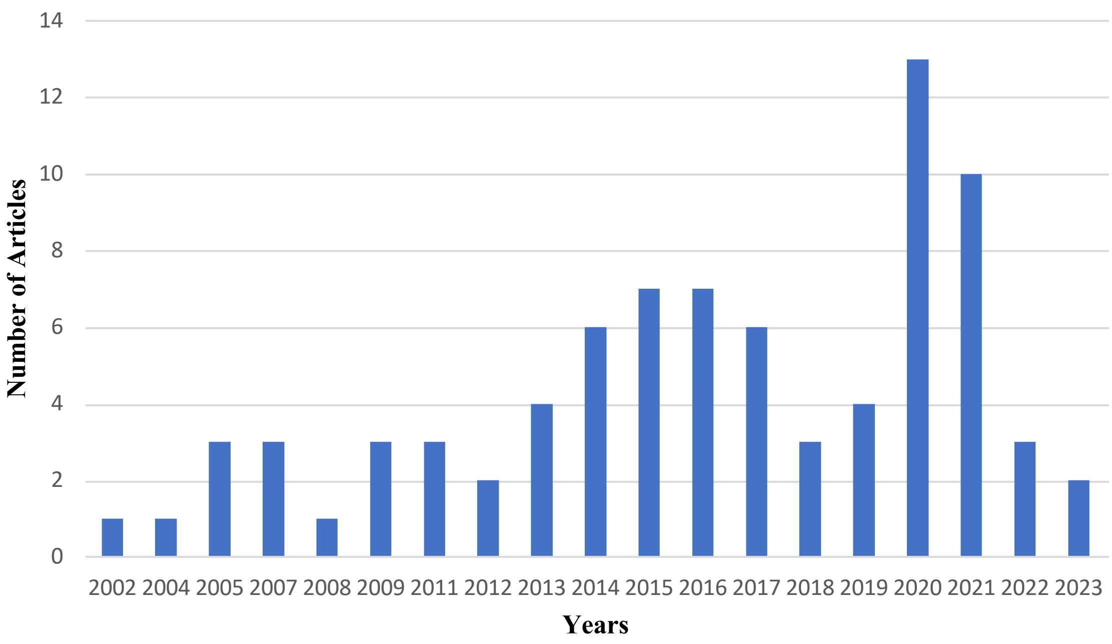


**Fig. 3.** Published articles on air pollution of pyrolysis plants per year (82 articles).

Thirty-seven different sources were evaluated in this systematic mapping. This proves that pyrolysis and its environmental assessment, especially that of air pollution emissions, are common in different engineering fields. Surprisingly, only four sources published more than five articles, for a total of 30 articles. Of the four sources, the journal with 11 articles was "The Journal of Analytical and Applied Pyrolysis." The journal specializes in publishing research articles on pyrolysis processes and their applications. The other most common journals were "Waste Management," "Fuel," and "Environmental Science and Technology," having eight, six, and five articles, respectively. According to Figure 4, the journals "Renewable and Sustainable Energy Reviews," "Journal of Cleaner Production," "Science of the Total Environment", and "Chemosphere" had three articles.

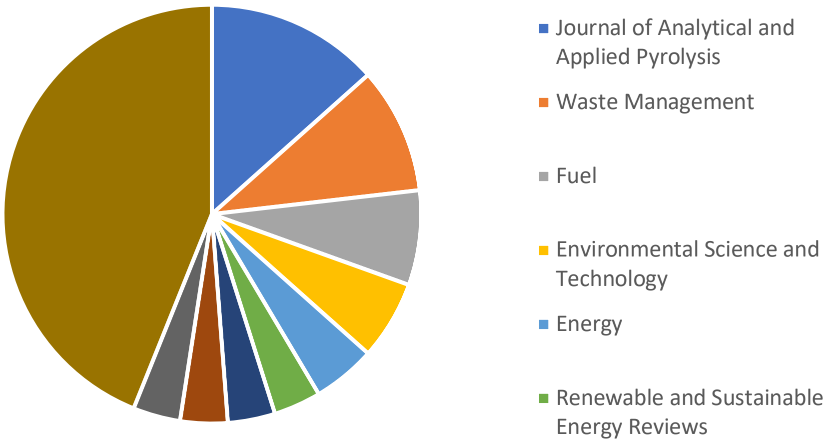


**Fig. 4.** Percentage of articles published per journal.

Six journals, having two articles each, and twenty-one journals, having an article each, covered 40.2% of the total 82 articles examined in this systematic mapping. These journals were as follows: Energy Conversion and Management, Chemical Engineering Journal, Journal of the Energy Institute, Process Safety and Environmental Protection, Fuel Processing Technology, Thermal Science and Engineering Progress, Applied Thermal Engineering, Journal of Hazardous Materials, Scientific Reports, Journal of Physics, Atmospheric Environment, Environmental Pollution, Energy and Fuels, International Journal of Energy Research, Frontiers in Chemistry, Applied Energy, Applied Sciences (Switzerland), International Journal of Hydrogen Energy, Renewable Energy, ACS Sustainable Chemistry and Engineering, Environmental Chemistry Letters, Sustainability (Switzerland), Journal of $CO_2$ Utilization, Biomass Conversion and Biorefinery.

It is worth mentioning that, when evaluating these sources, most had an ordinary reach concerning air pollution emissions of pyrolysis plants. In which syngas characteristics as a pyrolysis product were investigated.

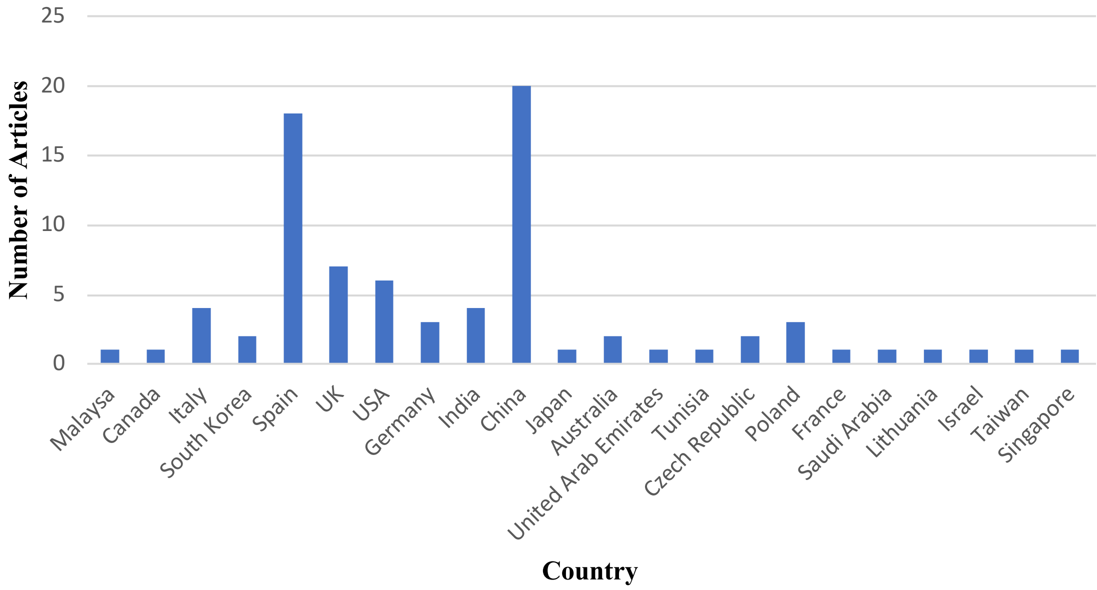


**Fig. 5.** Selected research studies across countries (82 articles).

Content analysis was utilized to identify the geographical locus of the articles. Although neither term was included in the keywords, content analysis was conducted to categorize the location articles. Different countries were involved in studying air emissions of pyrolysis, with 22 countries globally identified.

China and Spain, with twenty and eighteen articles, respectively, were the two countries with the highest number of published articles considered in this study (Fig. 5). The United Kingdom with seven, the United States of America with six, Italy and India with four, Germany and Poland with three, South Korea, Australia, and Czech Republic with two articles each, were the other countries in the list. Some countries, like Singapore, Taiwan, Israel, etc., published only one article each.

The keywords in the title and abstract of the 82 papers recorded from the Scopus source into this systematic mapping were evaluated using VOS viewer as free text-mining software [84]. The thesaurus file was used by VOS viewer software to ignore generic words in text data entered the analysis. Initially, the software identified 1232 terms in the title and abstract of the selected papers, and then the terms with less than seven times occurrence were filtered. The most occurrence terms were detected by following the mentioned procedure, and 40 terms met the conditions observed in Figure 6; the connection lines were drawn between the terms with a minimum of 30 times co-occurrence.

As can be seen from the figure, the term pyrolysis is the core keyword of the research. Other central or essential keywords include gas emissions, waste management, waste disposal, incineration, waste incineration, and combustion, which is because, in most of the articles included in this study, the air pollution emission data were compared to data coming from conventional incineration plants. Therefore, there is a strong connection of these keywords to the topic of current work. Operating temperature as a vital factor of the pyrolysis processes and its effect on the emission data is to be seen as another central keyword. This reveals the importance of this operating factor compared to others, such as working pressure or residence time among the included studies. As seen in the dataset, studies often investigated the effect of different temperatures on emission data or syngas characteristics, regardless of the other operating factors. On the other hand, the climate change keyword shows up as one of the isolated terms within the studies, representing a less-explored topic within the field. As mentioned before, the lack of comprehensive emission data from pyrolysis plants and the research gap in the air pollution emissions from these plants can be the main reason for this isolation. Having emission data to investigate these emissions' climate change effects is vital.

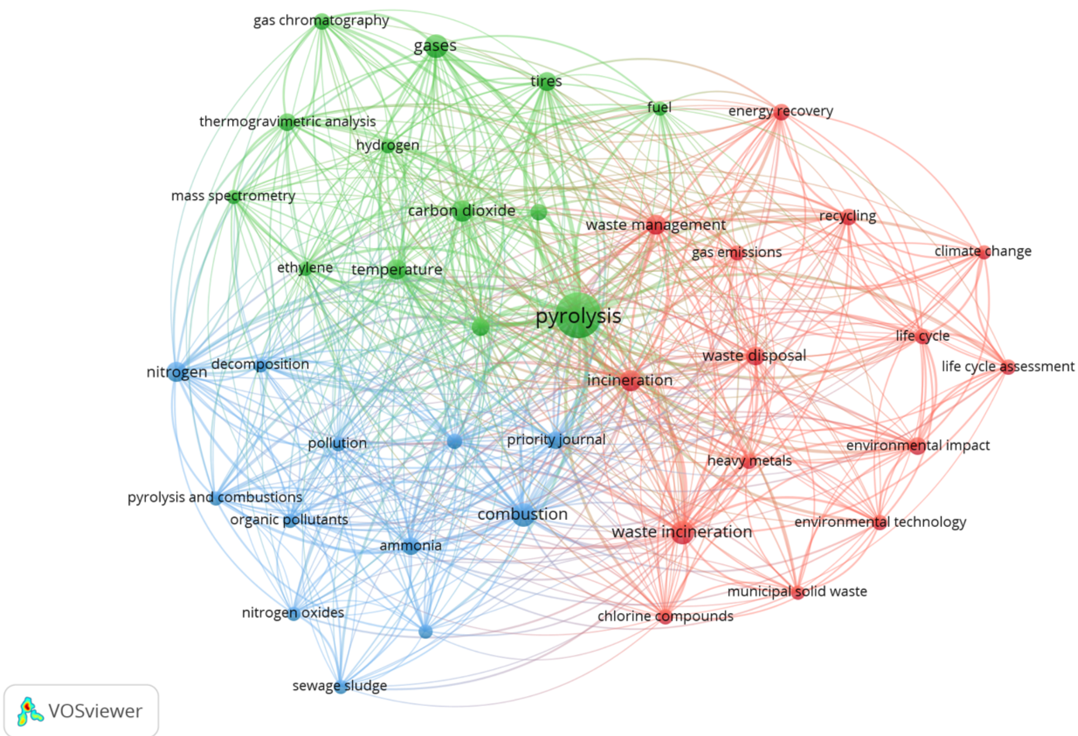


**Fig. 6.** The scientific landscape of the papers on air pollution emissions from pyrolysis plants by the publication [84].

# 4 Review of the literature results

### *4.1 Syngas characteristics*

The composition of syngas or so-called synthesized gas from pyrolysis plants varied across the selected references, reflecting the influence of different factors such as feedstock composition, pyrolysis conditions, and plant design. The dataset in the supplementary materials represents the syngas characteristics of various plants extracted from reviewed literature. Sixty-six articles over a total of 82 references included syngas characteristics data. According to this data, the significant components of syngas, including carbon monoxide (CO), hydrogen ($H_2$), methane ($CH_4$), and carbon dioxide ($CO_2$), were analyzed in the reviewed studies. The collection of values for these gas components was extracted from the dataset and used to plot a box and whisker figure, Fig. 7. This figure summarizes the distribution of the values for each gas component. CO has the highest median concentration among the four gas components, followed by $H_2$, $CH_4$, and $CO_2$. Moreover, CO has the largest IQR (interquartile range) and the most outliers, indicating high variability in its concentration.

This pattern is because CO is highly sensitive to the pyrolysis conditions, such as temperature, pressure, residence time, and feedstock composition. Different pyrolysis processes may produce different amounts of CO depending on these factors. For example, Honus et al. [26] reported the syngas characteristics for different plastic pyrolysis in three different operating temperatures. According to their study, CO and $CO_2$ concentrations generally decline when the operating temperature rises from 500 °C to 900°C. Another study by Czajczyńska et al. shows the concentration of CO and $CO_2$ in syngas produced in a pilot-scale plant. In this waste tyres pyrolysis plant, the concentration of 3.2% and 8.73% are reported for CO and $CO_2$, respectively [9], showing the effect of feedstock on the concentration of these gases compared to plastic pyrolysis.

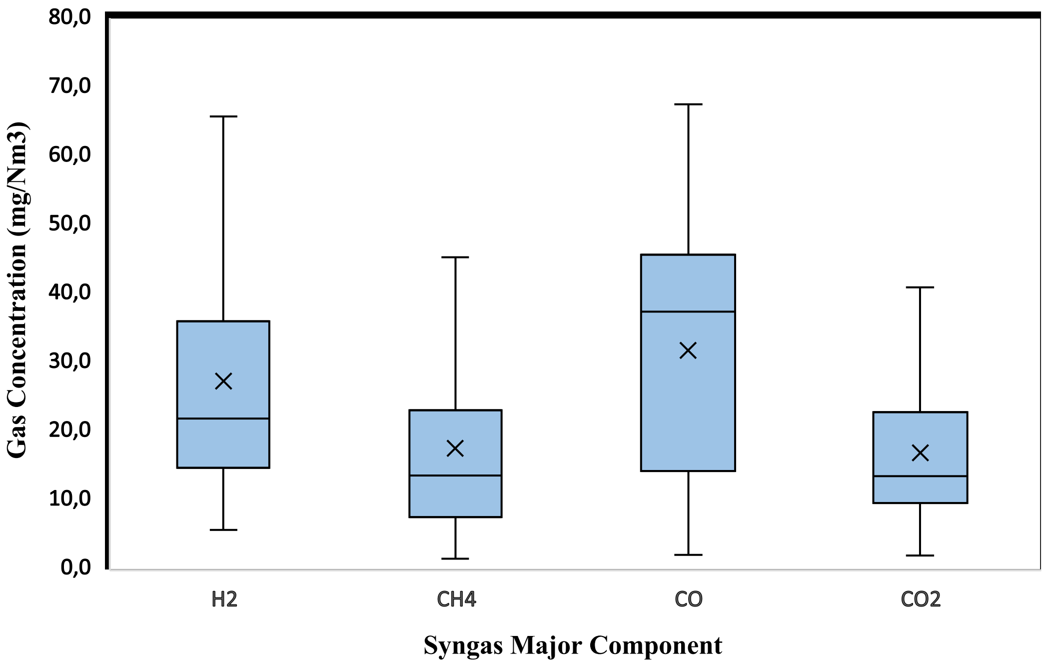


**Fig. 7.** Concentration distribution for the main components of pyrolytic gases from extracted data (66 articles).

**Table 3.** Air pollution emission data extracted from articles and industrial confidential reports.

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | Mixed Virgin Plastic | | | | | | CO2: 302.475 mg/Nm3<br>NO2: 1.1138 mg/Nm3<br>SO2: NA<br>H2O: 192.335 mg/Nm3<br>ASH: NA | |
| Full-scale | Conventional | PET-12 (PET content 11.8%) | <1% | Continuous | 500 | Yes | NA | CO2: 275.299 mg/Nm3<br>NO2: 2.600 mg/Nm3<br>SO2: 0.065 mg/Nm3<br>H2O: 116.226 mg/Nm3<br>ASH: 11.285 mg/Nm3 | 75 |
| | | PET-28 (PET content 27.5%) | | | | | | CO2: 431.445 mg/Nm3<br>NO2: 2.442 mg/Nm3<br>SO2: 0.0 mg/Nm3<br>H2O: 104.812 mg/Nm3<br>ASH: 12.95 mg/Nm3 | |

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| NA | NA | NA | NA | NA | 700 | Yes | PM10<br>winter 43.41 µg/Nm3<br>summer 34.36 µg/Nm3<br>PM2.5<br>autumn 17.57 µg/Nm3<br>winter 32.77 µg/Nm3 | PM: 7.242 mg/Nm3<br>Sox: 4.313 mg/Nm3<br>Nox: 53.671 mg/Nm3<br>CO: 10.859 mg/Nm3<br>HCl: 2.253 mg/Nm3<br>PCDD/F: 1.073e-3 ng/Nm3 | 76 |
| Full-scale | Fast | NA | NA | Continuous | 750-1000 | Yes | NA | PM: 5.75 mg/Nm3<br>Nox: 129 mg/Nm3<br>Sox: 0.44 mg/Nm3<br>PCDD/F: 5.81e-4 ng/Nm3 | 77 |
| | Conventional | Organic waste | NA | | NA | | | PM: <4.7 mg/Nm3<br>HCl: 11.6 mg/Nm3<br>PCDD/F: 2.5e-2 ng/Nm3 | |
| | | Municipal waste | NA | | 450 | | | PM: <1 mg/Nm3<br>HCl: 55.8 mg/Nm3<br>Nox: 82.8 mg/Nm3<br>Sox: 25.9 | |

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | mg/Nm3 PCDD/F: 4.5e-3 ng/Nm3 | |
| Full-scale | Fast | MSW | NA | Continuous | 500 | No | NA | CO2: 174.215 mg/Nm3 CO: 63.88 mg/Nm3 H2: 5.807 mg/Nm3 CH4: 29.036 mg/Nm3 Ethane: 2.033 mg/Nm3 | 10 |
| Lab | Fast | MSW | 20% | Continuous | 500 | No | SO2: 0.99 µg/Nm3 Nox: 1.25 µg/Nm3 PM: 0.099 µg/Nm3 CO: 0.51 µg/Nm3 | CO: 18 mg/Nm3 Nox: 44.5 mg/Nm3 So2: 36.1 mg/Nm3 PM: 3.6 mg/Nm3 | 81 |
| Lab | NA | Solid tire waste | NA | Batch | NA | Yes | Sox: 0.47 µg/Nm3 Nox: 0.12µg/Nm3 PM: 0.02 µg/Nm3 THC: 7e-4 µg/Nm3 PCDD/F: 7e-4 ng/Nm3 | Metal: 26.8e-4 mg/Nm3 PCDD/F: nd ** no Cl content in tires Sox: 265 mg/Nm3 Nox: 67.7 mg/Nm3 PM: 8.4 | 17 |

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | VOC: 1.2 µg/Nm3 | mg/Nm3<br>THC: 3.7 mg/Nm3 | |
| Lab | Flash | Tire powder | 2.1% | Batch | 800 | No | NA | H2S: 16.90 g/Nm3 | 45 |
| Pilot | Fast | Rubber from old tyres | NA | NA | 600 | Yes | NA | PM: 6.7 mg/Nm3<br>CO: 5.6 mg/Nm3<br>Nox: 131 mg/Nm3<br>SO2: 47.80 mg/Nm3<br>TOC: 23.6 mg C/Nm3<br>HF: <0.5 mg/Nm3<br>HCl: 12 mg/Nm3<br>PCDD/F: 6.3e-3 ng ITEQ/Nm3 | 53 |
| Pilot | Fast | Dry sewage sludge | 4.6% | Continuous | 900 | Yes | NA | Nox: 100.34 mg/Nm3<br>SO2: 22.12 mg/Nm3<br>PM: 74.50 mg/Nm3<br>CO: 2.80 mg/Nm3<br>HCl: 0.38 mg/Nm3<br>Hg: 2.42e-5 mg/Nm3<br>TEQ: 1.9e-2 ngTEQ/Nm3 | 71 |

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| Pilot | NA | NA | NA | NA | NA | Yes | NA | PM: 0.2 mg/Nm3 HCl: 3.6 mg/Nm3 HF: 0.02 mg/Nm3 SO2: 19.8 mg/Nm3 NO2: 42 mg/Nm3 CO: 2 mg/Nm3 Hg: 3e-3 mg/Nm3 PCDD/F: 1 ng/Nm3 | Industrial confidential |
| Pilot | NA | NA | NA | Continuous | NA | Yes | NA | PM: 1.11e-3 mg/Nm3 Nox: 14.44 mg/Nm3 SO2: 10.58 mg/Nm3 CO: 34.01 mg/Nm3 VOCs: 126.62 mg/Nm3 | Industrial confidential |
| Full-scale | NA | Waste tyres | NA | Continuous | NA | Yes | NA | PM: 6.94 mg/Nm3 NOx: 244 mg/Nm3 CO: 52 mg/Nm3 SO2: 33 mg/Nm3 HCl: 0.03 | Industrial Confidential |

| Scale | Pyrolysis technology | Feedstock | Moisture yield | Batch/continuous | Operating temperature | Integrated process | Ambient air level | Pollutant concentration | Reference |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | mg/Nm3<br>HF: 0.02 mg/Nm3<br>TOC: 71 mg/Nm3<br>PCDD/F: 5.94e-3 ng/Nm3 | |

Here, we will explore the syngas characteristics based on the extracted data:

### 4.1.1 Hydrogen ($H_2$)

$H_2$ is a vital component of syngas and significantly impacts its energy content and reactivity. The presence of hydrogen suggests the potential for syngas to be utilized as a fuel source. The $H_2$ content in syngas ranges from 0.179 to 67.9 vol.%, depending on the feedstock and gasification conditions. For example:
In syngas derived from MSW, the $H_2$ content ranges from 0.179 to 3.16 wt% MSW [79].
In syngas produced from gasification, the $H_2$ content varies from 5.2 to 67.9 vol.% [26, 35].

### 4.1.2 Methane ($CH_4$)

$CH_4$ is another critical component of syngas, and its presence can influence the energy content and stability of the gas. The $CH_4$ content in syngas ranges from trace amounts to as high as 44.5 vol.%. Some examples include:
MSW-based syngas, the $CH_4$ content ranges from 3.5 vol.% to 27.5 vol.% [26, 31].
In gasification-derived syngas, the $CH_4$ content varies from 13.7 vol.% to 44.87 vol% [29].

### 4.1.3 Carbon Monoxide (CO)

CO is a crucial intermediate in syngas production and plays a significant role in various downstream processes. The CO content in syngas ranges from trace amounts to 41.2 vol.%. For instance:
MSW-based syngas, the CO content ranges from 2.05 vol% to 39.2 vol.% [24, 27].
In gasification-derived syngas, the CO content varies from 1.622 vol.% to 40.4 vol.% [28, 33].

### 4.1.4 Carbon Dioxide ($CO_2$)

$CO_2$ is a non-combustible component that can dilute the energy content of syngas. The $CO_2$ content in syngas ranges from trace amounts to as high as 49.8 vol.%. Some examples include:
MSW-based syngas, the $CO_2$ content varies from 19.09 vol% to 46.0 vol.% [14, 35].
In gasification-derived syngas, the $CO_2$ content ranges from 1.5 vol.% to 67.9 vol.% [25, 26].

### 4.1.5 Other Trace Gases

Syngas may contain various other trace gases, such as ethylene ($C_2H_4$), ethane ($C_2H_6$), propane ($C_3H_8$), and others. The content of these trace gases can vary widely depending on the feedstock and gasification process [30].

It's important to note that syngas composition is crucial for determining its potential applications, as different industries may require specific syngas compositions for optimal performance. Additionally, impurities such as sulfur compounds (e.g., $H_2S$) should be minimized, mainly if syngas are intended for use in fuel cells or gas turbines, where high-purity syngas are essential for efficient operation [32, 40, 41]. In most cases, syngas is utilized in an integrated process to partially supply the heat in the pyrolysis reactor [42, 43]. Therefore, it's essential to understand the syngas characteristics before studying the air emissions from pyrolysis plants. According to a process engineer from an existing plant [24], syngas usually enter the combustion chamber without any treatment.

Therefore, syngas characteristics disclose essential qualitative data about air pollution of such plants. According to the dataset, some of the impurities in the syngas composition give us a vision of possible air emissions. For instance, in a complete combustion, CO converts to $CO_2$. However, if there is insufficient oxygen, some CO may remain after the combustion. Hydrogen sulfide ($H_2S$) suggests the potential for sulfur emission. In which sulfur is converted to sulfur oxides ($SO_x$) during the combustion [44].

The presence of methane ($CH_4$) in a low percentage and other hydrocarbons like C3 and C4 indicates the possibility of unburned hydrocarbon emissions. Incomplete combustion or insufficient oxygen levels can release unburned hydrocarbons, which contribute to air pollution and can have adverse health effects [46].

In the subsequent portion of this section, we present synthesized data through a visually informative segmented column graph, offering a clear and concise representation of syngas composition patterns across plastic waste types and pyrolysis temperatures. This graphical representation will be a valuable addition to our systematic review, facilitating a holistic understanding of the interplay between plastic waste feedstock, pyrolysis conditions, and resultant syngas properties as reported in the selected studies.

According to Figure 8, $H_2$ and $CH_4$ concentrations in the syngas generally increase by increasing the temperature from 500°C to 900°C. On the other hand, real-world data from pyrolyzing Japanese, European, and USA mixed plastic waste shows that the concentration of CO and $CO_2$ decreases by increasing the temperature, promoting the production of hydrocarbons. Even though these hydrocarbons are typically more desirable products in many pyrolysis processes, they can negatively affect air pollution emissions. For instance, Ethylene ($C_2H_4$) concentration increases dramatically with the temperature rise. In terms of other unsaturated hydrocarbons, Propylene ($C_3H_6$) and Butene ($C_4H_8$) are increasing with rising temperature. However, the maximum reported concentration for these gases occurs at 700°C pyrolysis. The presence of these unsaturated gases in an integrated system that burns the syngas for energy recovery reasons can lead to incomplete combustion, which eventually increases the concentration of CO and PM in the flue gas.

According to Stanislav et al. [26], a high concentration of CO in the syngas composition promises higher $CO_2$ pollution. Reported flue gas composition after combustion shows that the higher $CO_2$ concentration occurs with burning the syngas from PET-500, PET-700, PET-900, EU MIX-500, USA MIX-500, and JP MIX-500, respectively. As can be seen from Figure 8, these pyrolysis processes produce the most CO in their syngas. Consequently, flue gases from these processes contained less $N_2$ and water vapor. It is worth mentioning that the higher concentration of $CO_2$ for PET was boosted by the higher concentration of $CO_2$ in the syngas itself. On the other hand, pyrolyzing PVC produces a higher $H_2$ content in the syngas than other plastics. Which eventually leads to a higher water vapor content in the flue gas composition.

## 4.2 Factors Influencing Air Pollution Emissions

Several factors were found to influence the air pollution emissions from pyrolysis plants, including operating conditions and feedstock characteristics [47].

### *4.2.1 Operating Conditions*

Temperature, residence time, heating rate, and the presence of catalysts were identified as significant factors affecting emissions [70, 72, 74]. Higher temperatures increase the production of gaseous pollutants like nitrogen oxides ($NO_x$) and sulfur oxides ($SO_x$) by enhancing the oxidation of nitrogen and sulfur compounds. [27-31].

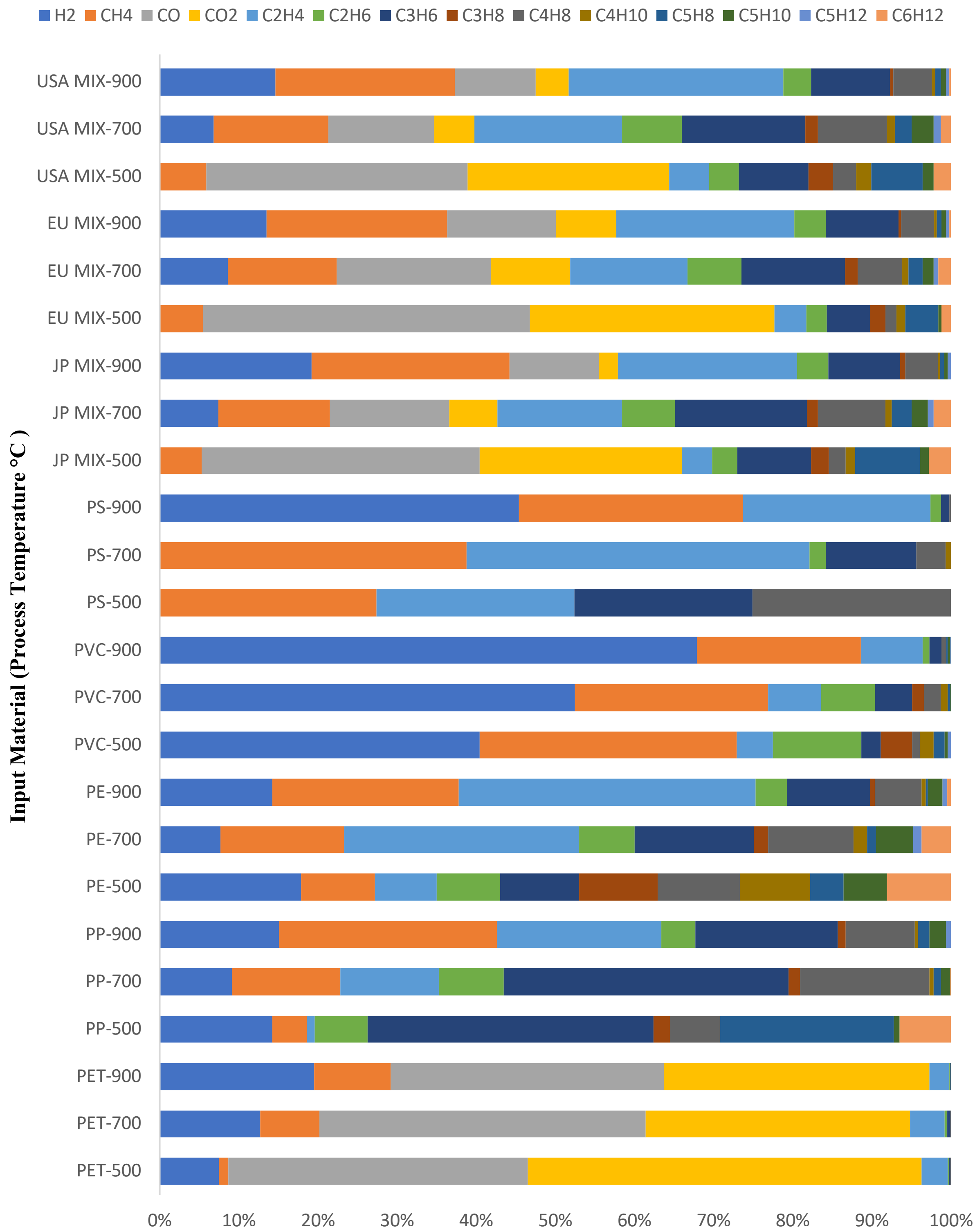


**Fig.8.** Composition of syngas produced from individual plastic waste pyrolysis [26].

Table 3 shows $NO_x$ emission increases when we increase the operating temperature from 450°C to 750-1000°C. However, Nitrogen and Sulfur content in the feedstock is a crucial factor affecting $SO_x$ and $NO_x$. Residence times can be extended to decrease VOC and PAH emissions by facilitating their transformation into other substances [32, 78, 80].

On the other hand, longer residence time can promote more excellent conversion of Nitrogen and Sulfur compounds to $NO_x$ and $SO_x$, respectively. A high heating rate results in more volatile components being released during pyrolysis, which can increase the number of pollutants emitted. In contrast, a low heating rate results in more char formation and reduces the number of pollutants emitted.

#### *4.2.2 Feedstock Characteristics*

The type and composition of the feedstock greatly influence the emission profiles of pyrolysis plants. For instance, biomass pyrolysis typically results in lower sulfuric, chloric, and heavy metal emissions than waste tire or plastic pyrolysis due to the lower content of sulfur, chlorine, and heavy metals [33]. The feedstock's moisture content and particle size can also influence emissions, typically resulting in higher emissions when moisture levels are elevated, and particle sizes are larger [34]. According to Table 3, two different emission data from a lab-scale experiment and a full-scale plant, both operating at 500°C show us how moisture content can affect air pollution from these plants. According to the dataset, by increasing the moisture content from less than 1% up to 20%, pollutant concentrations dramatically will drop. However, while pyrolyzing plastic waste, we always have a higher amount of $CO_2$ pollution due to the higher carbon and hydrogen content. [35,36]

### *4.3 Types of Pollutants*

The air pollutants emitted from pyrolysis plants include PM, VOCs, PAHs, $NO_x$, $SO_x$, CO, and GHGs like $CO_2$, $CH_4$, and $N_2O$ [37, 38]. Table 3 shows air emissions concentrations from the pyrolysis process reported in the literature. Among 82 reviewed studies, only the presented studies (in Table 3) included extractable quantitative data for air pollution concentrations.

In an environmental impact assessment of an existing pyrolysis plant in Singapore [35], authors reported air emission data for three types of plastic waste. However, reported numbers are related to an integrated pyrolysis process. In which pyrolytic gas is used in the burner for energy recovery reasons. By comparing the emission concentration for $CO_2$, $NO_2$, $SO_2$, $H_2O$, and Ash for three different feedstock, one can conclude that by increasing the PET content in the mixed plastic waste, $CO_2$ and ASH concentration is increasing while $NO_2$ and $H_2O$ content in the flue gas are decreasing. Another report from an existing plant in the USA shows that emission concentrations depend on feedstock dramatically [39].

According to Table 3, particulate matter emission from pyrolysis of mixed municipal waste is less than 1 mg/Nm$^3$. However, it emits more HCl than pyrolysis of only organic waste [77]. Polychlorinated dibenzo-p-dioxins and polychlorinated dibenzofurans (PCDD/F) for municipal waste are twice as many for organic waste. By comparing the data from another plant in north California [10], it can be seen that $CO_2$ emission for municipal solid waste pyrolysis is almost two times lower than that for plastic waste. However, it is worth mentioning that using different pyrolysis technologies also affects the emission data [48, 49]. In general, one can conclude that emission data reported on a laboratory scale are lower than ones in a pilot or full-scale plant [Table 3].

### 4.4 *Mitigation Strategies*

Several strategies have been proposed to minimize air pollution emissions from pyrolysis plants. These include optimizing operating conditions, utilizing catalysts, and implementing emission control technologies such as wet scrubbers, electrostatic precipitators, and baghouse filters (40, BAT 2010/75/EU). However, academic, and industrial reports need to include mitigation strategy information. Due to the need for more information in articles investigated in this study, an attempt has been made to gather information from existing plants and operating companies. Except for three companies willing to disclose some information or technical reports, the rest refused to provide us with helpful information.

Based on industrial reports, we can state that the baghouse filter after the heat recovery steam generator is widely used to reduce dust levels below 5 mg/Nm$^3$. According to an industrial report funded by Energimyndigheten in Sweden, several different technologies, such as hot gas filters, in-situ filters, and cyclones, purify pyrolysis gases.
The difficulties with different filters have led to commercial-scale plants today only using cyclones to clean coke, ash, and particles from the pyrolysis gases [50, 51]. Table 4 represents the emission control technologies (APC) commonly used to reduce pollutant concentrations below the emission limit.

**Table 4**
Best available control technology (BACT) for the air emissions from pyrolysis plants.

| Pollutant | APC | Reference |
|---|---|---|
| PM | Baghouse filters, Panel filter (course particulate filter), Header filter (fine particulate filter) | 24, 52, 54 |
| $NO_x$ | Selective catalytic reduction (SCR) and selective non-catalytic reduction (SNCR) | 36, 55 |
| $SO_x$ | Flue gas desulfurization (FGD) systems, such as wet scrubbers | 56, 57, 58 |
| VOCs | Catalytic oxidation, Carbon filter (Cartridge type) | 56, 76 |
| Dioxins and Furans | High temperature filtration and wet scrubbers (usually below the limit) | 53, 59, 60 |

According to Table 5, the commercial pyrolysis processes are equipped with emissions abatement devices resembling those found in incineration plants, ensuring a clean pyrolysis process. However, compared to incineration plants, they are smaller in size.

**Table 5**

Some pyrolysis involved units and technologies used in pilot, demonstration, and industrial plants.

| Process name | Reactor & operation conditions | Feedstock & products | Technologies | Mitigation strategy |
|---|---|---|---|---|
| **ConTherm technology [61]** | Rotary kilns, pyrolysis taking place at 500–550 °C for about 1 h, gas combustion in a pulverized coal (PC)-fired boil | Input: Shredded MSW, automotive shredder residues as well as up to 50% waste plastics Output: Power from steam turbine | Pyrolysis & combustion | The pyrolysis gas passed through a cyclone before boiler Flue gas scrubbing system of the coal-fired power plant |
| **Pilot pyrolysis process in Tianjin, China [62]** | A gasification-coupled pyrolysis process. The main reactor is a screw-bed reactor, and gasification takes place in the subsidiary reactor. No information on pyrolysis temperature. | Input: pre-treated MSW Output: syngas with moderate to low calorific value, char, metals, and ash | Pyrolysis & partial gasification | Gas cooler and filter |
| **Honghoo technology [63]** | Multi-sectional rotary kilns, pyrolysis at lower temperature of approximately 400–450 °C, none-catalytic pyrolysis, indirect heat transfer; the gas is burnt online to supply the heat. | Input: Raw MSW with bottles, stones, bricks, and glass separated Output: Oil, char, cleaned gas (for power generation) | Pyrolysis | Pyrolysis gas was scrubbed before burning. Char was quenched and separated from metals |

| | | | | |
|---|---|---|---|---|
| **CNRS thermo-chemical converter [64, 65]** | A tubular rectilinear reactor heated by circulation of hot flue- gases (natural gas burner) within an external double envelope. The solid continuously advances by vibro-fluidized transport<br>Flow rate up to 50 kg/h<br>Running from pyrolysis to combustion with temperature changing from 400 to 1000 °C | Input: Ground MSW<br>Output: Syngas or flue gas depending on whether comburant or inert gas is supplied; accordingly, char or ash output | Pyrolysis | Not mentioned |
| **Takuma SBV [66, 67] (Derived from the above Siemens Schwel-Brenn process)** | Rotary kiln and ash-melting system. Pyrolysis at 500–550 °C in the rotary kiln; pyrolysis gas is burnt in a high temperature chamber | Input: MSW, industry waste, sewage sludge, etc.<br>Output: Energy (power & steam), iron, aluminum | Combination of pyrolysis and gasification & melting process | Flue gas quencher followed by two scrubber stage |
| **Noell-KRC conversion process (now Future Energy) [68]** | A rotary kiln and a gasifier, pyrolysis at approximately 550 °C, gasification at 1400–2000 °C and 2–50 bars | Input: MSW, other feedstocks (dried sewage sludges) may be co-gasified<br>Output: Medium calorific value gas; a part of the cleaned gas is used to heat the kiln. Metals and slag can be used as construction materials | Pyrolysis and entrained flow gasification | Pyrolysis gas is dedusted and dewatered before entering the gasifier. There are two scrubbers to clean gas from the gasifier. The first stage removes $H_2S$ and heavy metals, and the second stage washes all the other contaminants |
| **Compact Power process (now Ethos Renewables Avonmouth (ERA) Limited) [69]** | Pyrolysis in the two tubular reactors at 800 °C; the char is reacted with steam and air in a fixed bed gasifier, and gas combustion is in a cyclone chamber at 1200–1250 °C | Input: Dewatered sewage sludges, pre-treated MSW, clinical wastes, scrap tire crumbs.<br>Output: Energy in form of steam or power; Char/ash material from the gasification unit | Pyrolysis, gasification, and high temperature combustion | Dry scrubber with sodium bicarbonate and Selective Catalytic $NO_x$ Reduction (SCR). The solid residues from the dry scrubbing unit are sent for landfill disposal |

## 5 Conclusion

This systematic mapping has provided valuable insights into the air pollution emissions from pyrolysis plants, highlighting the need for robust mitigation strategies and further research. The findings emphasize the importance of addressing environmental challenges at these facilities to safeguard human health and the ecosystem.

Mitigation strategies are crucial in reducing air pollution emissions from pyrolysis plants. This review has identified several fundamental approaches that can be employed to mitigate emissions effectively. These include implementing advanced emission control technologies, such as electrostatic precipitators, scrubbers, baghouse filters, SCR, and SNCR, to remove pollutants from exhaust gases. Additionally, optimizing process parameters and adopting stricter emission standards can enhance the overall performance of pyrolysis plants regarding air pollution reduction.

However, one major limitation identified in this review is the need for comprehensive data on air pollution emissions from pyrolysis plants. Many studies have focused on specific pollutants or provided insufficient information to draw robust conclusions. Therefore, it is essential for upcoming studies to fill this information void and offer a more complete comprehension of the emission patterns of pyrolysis facilities. Collecting live and ongoing data on different pollutants will allow scholars and decision-makers to make knowledgeable judgments and create efficient reduction tactics.

Furthermore, exploring additional air pollution reduction techniques specific to pyrolysis plants is essential. Future research should investigate alternative feedstock options that produce fewer emissions and explore the potential for process optimization and energy recovery systems. Additionally, adopting cleaner technologies and developing innovative approaches, such as catalytic converters or novel filtration methods, can further enhance the efficiency of air pollution control in pyrolysis plants.

In conclusion, addressing air pollution emissions from pyrolysis plants requires a multi-faceted approach that includes implementing effective mitigation strategies, collecting comprehensive data, and developing innovative pollution reduction techniques. By embracing these strategies and conducting further research, we can work towards minimizing the environmental impact of pyrolysis plants, safeguarding human health, and promoting sustainable waste management practices.

## 6 ANNEX

In the following, we represent the dataset table consist of syngas characteristics extracted from 66 studies among the references as a supplementary document to this systematic mapping.

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| Baggio, P., Baratieri, M., Gasparella, A., Longo, G.A. | lab | Fast pyrolysis | MSW | 20% | 500 | H2 | 65,300 |
| | | | | | | CH4 | 12,800 |
| | | | | | | CO | 3,380 |
| | | | | | | CO2 | 18,500 |
| | | | | | | OTHER | 0,020 |
| Islam, M.R., Joardder, M.U.H., Hasan, S.M., Takai, K., Haniu, H. | lab | NA | Solid tyre waste | NA | NA | H2 | 14,11-18,1 |
| | | | | | | CH4 | 18,41-21,00 |
| | | | | | | CO | 3,3-4,5 |
| | | | | | | CO2 | 8,0-10,23 |
| | | | | | | N2 | 3,0-3,07 |
| | | | | | | OTHER | 46,8-56,9 |
| Berrueco, C., Esperanza, E., Mastral, F.J., Ceamanos, J., García-Bacaicoa, P. | lab | NA | shredded scrap tyres | NA | 400 | H2 | 6,544 |
| | | | | | | CH4 | 2,610 |
| | | | | | | CO | 2,721 |
| | | | | | | CO2 | 35,953 |
| | | | | | | OTHER | 52,172 |
| | | | | | 500 | H2 | 86,460 |
| | | | | | | CH4 | 2,637 |
| | | | | | | CO | 0,158 |
| | | | | | | CO2 | 6,231 |
| | | | | | | OTHER | 4,514 |
| Stančin, H., Šafář, M., Růžičková, J., Mikulčić, H., Raclavská, H., Wang, X., Duić, N. | lab | Fast pyrolysis | Sawdust | 7.4% | 600 | H2 | 8,400 |
| | | | | | | CH4 | 10,900 |
| | | | | | | CO | 40,300 |
| | | | | | | CO2 | 38,900 |
| | | | | | | OTHER | 1,500 |
| | | | Rigid polyurethane foam (PUR) | 2.7% | | H2 | 24,600 |
| | | | | | | CH4 | 6,900 |
| | | | | | | CO | 20,600 |
| | | | | | | CO2 | 46,000 |
| | | | | | | OTHER | 1,900 |
| | | | 0.25 PUR | NA | | H2 | 11,000 |
| | | | | | | CH4 | 10,600 |
| | | | | | | CO | 39,200 |
| | | | | | | CO2 | 37,800 |
| | | | | | | OTHER | 1,400 |
| | | | 0.5 PUR | NA | | H2 | 14,100 |
| | | | | | | CH4 | 9,800 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | CO | 34,100 |
| | | | | | | CO2 | 40,500 |
| | | | | | | OTHER | 1,500 |
| | | | 0.75 PUR | NA | | H2 | 17,500 |
| | | | | | | CH4 | 8,800 |
| | | | | | | CO | 28,200 |
| | | | | | | CO2 | 43,600 |
| | | | | | | OTHER | 1,900 |
| Leung, D.Y.C., Yin, X.L., Zhao, Z.L., Xu, B.Y., Chen, Y. | lab | flash | tyre powder | 2.1 % | 800 | H2 | 20,700 |
| | | | | | | CH4 | 44,500 |
| | | | | | | CO | 2,600 |
| | | | | | | CO2 | 1,800 |
| | | | | | | OTHER | 30,400 |
| Hita, I., Arabiourrutia, M., Olazar, M., Bilbao, J., Arandes, J.M., Castaño Sánchez, P. | lab | Fast pyrolysis | scrap tires | NA | 500 | H2 | 21,500 |
| | | | | | | CH4 | 17,300 |
| | | | | | | CO | 5,100 |
| | | | | | | CO2 | 26,200 |
| | | | | | | H2S | NA |
| | | | | | | OTHER | 29,900 |
| | | | | | 800 | H2 | 20,700 |
| | | | | | | CH4 | 44,500 |
| | | | | | | CO | 2,600 |
| | | | | | | CO2 | 1,500 |
| | | | | | | H2S | NA |
| | | | | | | OTHER | 30,700 |
| Honus, S., Kumagai, S., Molnár, V., Fedorko, G., Yoshioka, T. | lab | Fast pyrolysis | PET | NA | 500 | H2 | 7,500 |
| | | | | | | CH4 | 1,200 |
| | | | | | | CO | 37,800 |
| | | | | | | CO2 | 49,800 |
| | | | | | | C2H4 | 3,300 |
| | | | | | | C2H6 | 0,100 |
| | | | | | | C3H6 | 0,200 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 0,100 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | 700 | H2 | 12,700 |
| | | | | | | CH4 | 7,500 |
| | | | | | | CO | 41,200 |
| | | | | | | CO2 | 33,400 |
| | | | | | | C2H4 | 4,400 |
| | | | | | | C2H6 | 0,300 |
| | | | | | | C3H6 | 0,400 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 0,100 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | | NA | 900 | H2 | 19,500 |
| | | | | | | CH4 | 9,700 |
| | | | | | | CO | 34,500 |
| | | | | | | CO2 | 33,600 |
| | | | | | | C2H4 | 2,500 |
| | | | | | | C2H6 | 0,100 |
| | | | | | | C3H6 | 0,100 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 0,000 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | PP | NA | 500 | H2 | 14,200 |
| | | | | | | CH4 | 4,400 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 1,000 |
| | | | | | | C2H6 | 6,700 |
| | | | | | | C3H6 | 36,100 |
| | | | | | | C3H8 | 2,100 |
| | | | | | | C4H8 | 6,300 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 22,000 |
| | | | | | | C5H10 | 0,700 |
| | | | | | | C5H12 | 0,000 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C6H12 | 6,500 |
| | | | | NA | 700 | H2 | 9,100 |
| | | | | | | CH4 | 13,700 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 12,500 |
| | | | | | | C2H6 | 8,200 |
| | | | | | | C3H6 | 36,000 |
| | | | | | | C3H8 | 1,400 |
| | | | | | | C4H8 | 16,400 |
| | | | | | | C4H10 | 0,500 |
| | | | | | | C5H8 | 0,900 |
| | | | | | | C5H10 | 1,200 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,100 |
| | | | | NA | 900 | H2 | 15,100 |
| | | | | | | CH4 | 27,500 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 20,800 |
| | | | | | | C2H6 | 4,300 |
| | | | | | | C3H6 | 18,000 |
| | | | | | | C3H8 | 1,000 |
| | | | | | | C4H8 | 8,700 |
| | | | | | | C4H10 | 0,400 |
| | | | | | | C5H8 | 1,500 |
| | | | | | | C5H10 | 2,100 |
| | | | | | | C5H12 | 0,600 |
| | | | | | | C6H12 | 0,000 |
| | | | PE | NA | 500 | H2 | 17,900 |
| | | | | | | CH4 | 9,300 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 7,800 |
| | | | | | | C2H6 | 8,000 |
| | | | | | | C3H6 | 10,000 |
| | | | | | | C3H8 | 9,900 |
| | | | | | | C4H8 | 10,400 |
| | | | | | | C4H10 | 8,900 |
| | | | | | | C5H8 | 4,200 |
| | | | | | | C5H10 | 5,500 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 8,100 |
| | | | | NA | 700 | H2 | 7,700 |
| | | | | | | CH4 | 15,600 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 29,700 |
| | | | | | | C2H6 | 7,000 |
| | | | | | | C3H6 | 15,100 |
| | | | | | | C3H8 | 1,800 |
| | | | | | | C4H8 | 10,800 |
| | | | | | | C4H10 | 1,700 |
| | | | | | | C5H8 | 1,100 |
| | | | | | | C5H10 | 4,700 |
| | | | | | | C5H12 | 1,100 |
| | | | | | | C6H12 | 3,700 |
| | | | | NA | 900 | H2 | 14,200 |
| | | | | | | CH4 | 23,600 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 37,500 |
| | | | | | | C2H6 | 4,000 |
| | | | | | | C3H6 | 10,500 |
| | | | | | | C3H8 | 0,600 |
| | | | | | | C4H8 | 5,900 |
| | | | | | | C4H10 | 0,500 |
| | | | | | | C5H8 | 0,300 |
| | | | | | | C5H10 | 1,800 |
| | | | | | | C5H12 | 0,600 |
| | | | | | | C6H12 | 0,500 |
| | | | PVC | NA | 500 | H2 | 40,400 |
| | | | | | | CH4 | 32,500 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 4,600 |
| | | | | | | C2H6 | 11,200 |
| | | | | | | C3H6 | 2,400 |
| | | | | | | C3H8 | 4,000 |
| | | | | | | C4H8 | 1,000 |
| | | | | | | C4H10 | 1,700 |
| | | | | | | C5H8 | 1,400 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C5H10 | 0,400 |
| | | | | | | C5H12 | 0,400 |
| | | | | | | C6H12 | 0,000 |
| | | | | NA | 700 | H2 | 52,500 |
| | | | | | | CH4 | 24,400 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 6,700 |
| | | | | | | C2H6 | 6,800 |
| | | | | | | C3H6 | 4,700 |
| | | | | | | C3H8 | 1,500 |
| | | | | | | C4H8 | 2,100 |
| | | | | | | C4H10 | 0,900 |
| | | | | | | C5H8 | 0,300 |
| | | | | | | C5H10 | 0,100 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | | NA | 900 | H2 | 67,900 |
| | | | | | | CH4 | 20,700 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 7,800 |
| | | | | | | C2H6 | 0,900 |
| | | | | | | C3H6 | 1,500 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 0,600 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 0,200 |
| | | | | | | C5H10 | 0,300 |
| | | | | | | C5H12 | 0,100 |
| | | | | | | C6H12 | 0,000 |
| | | | PS | NA | 500 | H2 | 0,000 |
| | | | | | | CH4 | 27,400 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 25,000 |
| | | | | | | C2H6 | 0,000 |
| | | | | | | C3H6 | 22,500 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 25,100 |
| | | | | | | C4H10 | 0,000 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | | NA | 700 | H2 | 0,000 |
| | | | | | | CH4 | 38,800 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 43,300 |
| | | | | | | C2H6 | 2,100 |
| | | | | | | C3H6 | 11,400 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 3,700 |
| | | | | | | C4H10 | 0,700 |
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | | NA | 900 | H2 | 45,400 |
| | | | | | | CH4 | 28,300 |
| | | | | | | CO | 0,000 |
| | | | | | | CO2 | 0,000 |
| | | | | | | C2H4 | 23,700 |
| | | | | | | C2H6 | 1,300 |
| | | | | | | C3H6 | 1,100 |
| | | | | | | C3H8 | 0,000 |
| | | | | | | C4H8 | 0,200 |
| | | | | | | C4H10 | 0,000 |
| | | | | | | C5H8 | 0,000 |
| | | | | | | C5H10 | 0,000 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 0,000 |
| | | | Japanese mix PLASTICS | NA | 500 | H2 | 0,000 |
| | | | | | | CH4 | 5,300 |
| | | | | | | CO | 35,100 |
| | | | | | | CO2 | 25,600 |
| | | | | | | C2H4 | 3,800 |
| | | | | | | C2H6 | 3,200 |
| | | | | | | C3H6 | 9,300 |
| | | | | | | C3H8 | 2,300 |
| | | | | | | C4H8 | 2,100 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C4H10 | 1,200 |
| | | | | | | C5H8 | 8,200 |
| | | | | | | C5H10 | 1,100 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 2,800 |
| | | | | NA | 700 | H2 | 7,400 |
| | | | | | | CH4 | 14,100 |
| | | | | | | CO | 15,100 |
| | | | | | | CO2 | 6,100 |
| | | | | | | C2H4 | 15,700 |
| | | | | | | C2H6 | 6,700 |
| | | | | | | C3H6 | 16,700 |
| | | | | | | C3H8 | 1,400 |
| | | | | | | C4H8 | 8,500 |
| | | | | | | C4H10 | 0,800 |
| | | | | | | C5H8 | 2,500 |
| | | | | | | C5H10 | 2,100 |
| | | | | | | C5H12 | 0,700 |
| | | | | | | C6H12 | 2,200 |
| | | | | NA | 900 | H2 | 19,200 |
| | | | | | | CH4 | 25,000 |
| | | | | | | CO | 11,300 |
| | | | | | | CO2 | 2,400 |
| | | | | | | C2H4 | 22,600 |
| | | | | | | C2H6 | 4,000 |
| | | | | | | C3H6 | 9,100 |
| | | | | | | C3H8 | 0,600 |
| | | | | | | C4H8 | 4,100 |
| | | | | | | C4H10 | 0,300 |
| | | | | | | C5H8 | 0,500 |
| | | | | | | C5H10 | 0,500 |
| | | | | | | C5H12 | 0,400 |
| | | | | | | C6H12 | 0,000 |
| | | | European mix PLASTICS | NA | 500 | H2 | 0,000 |
| | | | | | | CH4 | 5,500 |
| | | | | | | CO | 41,300 |
| | | | | | | CO2 | 30,900 |
| | | | | | | C2H4 | 4,000 |
| | | | | | | C2H6 | 2,600 |
| | | | | | | C3H6 | 5,500 |
| | | | | | | C3H8 | 1,900 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C4H8 | 1,400 |
| | | | | | | C4H10 | 1,100 |
| | | | | | | C5H8 | 4,200 |
| | | | | | | C5H10 | 0,400 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 1,200 |
| | | | | NA | 700 | H2 | 8,600 |
| | | | | | | CH4 | 13,800 |
| | | | | | | CO | 19,500 |
| | | | | | | CO2 | 10,000 |
| | | | | | | C2H4 | 14,800 |
| | | | | | | C2H6 | 6,800 |
| | | | | | | C3H6 | 13,100 |
| | | | | | | C3H8 | 1,600 |
| | | | | | | C4H8 | 5,600 |
| | | | | | | C4H10 | 0,800 |
| | | | | | | C5H8 | 1,800 |
| | | | | | | C5H10 | 1,400 |
| | | | | | | C5H12 | 0,600 |
| | | | | | | C6H12 | 1,600 |
| | | | | NA | 900 | H2 | 13,500 |
| | | | | | | CH4 | 22,800 |
| | | | | | | CO | 13,800 |
| | | | | | | CO2 | 7,600 |
| | | | | | | C2H4 | 22,500 |
| | | | | | | C2H6 | 4,000 |
| | | | | | | C3H6 | 9,200 |
| | | | | | | C3H8 | 0,300 |
| | | | | | | C4H8 | 4,200 |
| | | | | | | C4H10 | 0,300 |
| | | | | | | C5H8 | 0,600 |
| | | | | | | C5H10 | 0,600 |
| | | | | | | C5H12 | 0,400 |
| | | | | | | C6H12 | 0,200 |
| | | | USA mix PLASTICS | NA | 500 | H2 | 0,000 |
| | | | | | | CH4 | 5,900 |
| | | | | | | CO | 33,000 |
| | | | | | | CO2 | 25,500 |
| | | | | | | C2H4 | 5,000 |
| | | | | | | C2H6 | 3,800 |
| | | | | | | C3H6 | 8,800 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C3H8 | 3,100 |
| | | | | | | C4H8 | 2,900 |
| | | | | | | C4H10 | 1,900 |
| | | | | | | C5H8 | 6,500 |
| | | | | | | C5H10 | 1,400 |
| | | | | | | C5H12 | 0,000 |
| | | | | | | C6H12 | 2,200 |
| | | | | NA | 700 | H2 | 6,800 |
| | | | | | | CH4 | 14,500 |
| | | | | | | CO | 13,400 |
| | | | | | | CO2 | 5,100 |
| | | | | | | C2H4 | 18,600 |
| | | | | | | C2H6 | 7,600 |
| | | | | | | C3H6 | 15,600 |
| | | | | | | C3H8 | 1,600 |
| | | | | | | C4H8 | 8,700 |
| | | | | | | C4H10 | 1,000 |
| | | | | | | C5H8 | 2,100 |
| | | | | | | C5H10 | 2,800 |
| | | | | | | C5H12 | 0,900 |
| | | | | | | C6H12 | 1,300 |
| | | | | NA | 900 | H2 | 14,600 |
| | | | | | | CH4 | 22,700 |
| | | | | | | CO | 10,200 |
| | | | | | | CO2 | 4,200 |
| | | | | | | C2H4 | 27,100 |
| | | | | | | C2H6 | 3,500 |
| | | | | | | C3H6 | 10,000 |
| | | | | | | C3H8 | 0,400 |
| | | | | | | C4H8 | 4,900 |
| | | | | | | C4H10 | 0,400 |
| | | | | | | C5H8 | 0,700 |
| | | | | | | C5H10 | 0,700 |
| | | | | | | C5H12 | 0,400 |
| | | | | | | C6H12 | 0,200 |
| Aylón, E., Murillo, R., Fernández-Colino, A., Aranda, A., García, T., Callén, M.S., Mastral, A.M. | pilot | Fast pyrolysis | rubber from old tyres | NA | 600 | H2 | 30,400 |
| | | | | | | CH4 | 23,270 |
| | | | | | | CO | 2,380 |
| | | | | | | CO2 | 2,900 |
| | | | | | | N2 | 9,930 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | H2S | 1,550 |
| | | | | | | OTHER | 29,570 |
| Alcazar-Ruiz, A., Sanchez-Silva, L., Dorado, F. | lab | Fast pyrolysis | 1.5:1 OP/PE OP=Olive Pomace | NA | 500 | CH4 | 29,260 |
| | | | | | | CO | 13,577 |
| | | | | | | CO2 | 26,367 |
| | | | | | | C2H2 | 13,750 |
| | | | | | | C2H4 | 10,347 |
| | | | | | | C2H6 | 6,699 |
| | | | | NA | 550 | CH4 | 29,451 |
| | | | | | | CO | 8,838 |
| | | | | | | CO2 | 26,548 |
| | | | | | | C2H2 | 15,572 |
| | | | | | | C2H4 | 12,857 |
| | | | | | | C2H6 | 6,734 |
| | | | | NA | 600 | CH4 | 40,132 |
| | | | | | | CO | 14,286 |
| | | | | | | CO2 | 17,038 |
| | | | | | | C2H2 | 5,982 |
| | | | | | | C2H4 | 16,652 |
| | | | | | | C2H6 | 5,910 |
| | | | | NA | 650 | CH4 | 34,088 |
| | | | | | | CO | 13,039 |
| | | | | | | CO2 | 17,631 |
| | | | | | | C2H2 | 13,160 |
| | | | | | | C2H4 | 12,993 |
| | | | | | | C2H6 | 9,089 |
| | | | | NA | 700 | CH4 | 15,293 |
| | | | | | | CO | 13,126 |
| | | | | | | CO2 | 28,941 |
| | | | | | | C2H2 | 21,640 |
| | | | | | | C2H4 | 10,457 |
| | | | | | | C2H6 | 10,543 |
| | | | 1:1.5 OP/PS OP=Olive Pomace PS=Polystyrenes | NA | 500 | CH4 | 50,590 |
| | | | | | | CO | 24,860 |
| | | | | | | CO2 | 10,010 |
| | | | | | | C2H2 | 9,740 |
| | | | | | | C2H4 | 2,480 |
| | | | | | | C2H6 | 2,320 |
| | | | | | 550 | CH4 | 51,030 |
| | | | | | | CO | 21,740 |
| | | | | | | CO2 | 10,090 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | C2H2 | 9,800 |
| | | | | | | C2H4 | 2,480 |
| | | | | | | C2H6 | 4,860 |
| | | | | NA | 600 | CH4 | 53,540 |
| | | | | | | CO | 0,683 |
| | | | | | | CO2 | 22,361 |
| | | | | | | C2H2 | 14,615 |
| | | | | | | C2H4 | 1,556 |
| | | | | | | C2H6 | 7,245 |
| | | | | NA | 650 | CH4 | 44,874 |
| | | | | | | CO | 0,436 |
| | | | | | | CO2 | 22,321 |
| | | | | | | C2H2 | 26,372 |
| | | | | | | C2H4 | 0,436 |
| | | | | | | C2H6 | 5,561 |
| | | | | NA | 700 | CH4 | 95,717 |
| | | | | | | CO | 1,622 |
| | | | | | | CO2 | 0,680 |
| | | | | | | C2H2 | 0,743 |
| | | | | | | C2H4 | 0,880 |
| | | | | | | C2H6 | 0,358 |
| Czajczyńska, D., Krzyżyńska, R., Jouhara, H. | pilot | Fast pyrolysis | waste tyre | 2.3% | 500 | H2 | 20,520 |
| | | | | | | CH4 | 24,460 |
| | | | | | | CO | 3,230 |
| | | | | | | CO2 | 8,730 |
| | | | | | | H2S | 3,640 |
| | | | | | | OTHER | 39,420 |
| Klejnowska, K., Pikoń, K., Ścierski, W., Skutil, K., Bogacka, M. | lab | NA | Preconsumer Pharmaceutical Blisters | NA | 400 | H2 | 86,790 |
| | | | | | | CH4 | 3,570 |
| | | | | | | CO | 1,790 |
| | | | | | | CO2 | 2,140 |
| | | | | | | N2 | 2,880 |
| | | | | | | OTHER | 2,830 |
| Shi, K., Yan, J., Menéndez, J.A., Luo, X., Yang, G., Chen, Y., Lester, E., Wu, T. | lab | Microwave -assisted SLOW pyrolysis | Bamboo (biomass) | 3.7 % | 600 | H2 | 29,600 |
| | | | | | | CH4 | 1,000 |
| | | | | | | CO | 44,300 |
| | | | | | | CO2 | 23,400 |
| | | | | | | OTHER | 1,700 |
| | | | | | 700 | H2 | 43,400 |
| | | | | | | CH4 | 4,600 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | CO | 34,300 |
| | | | | | | CO2 | 16,800 |
| | | | | | | OTHER | 0,900 |
| | | | | | 800 | H2 | 48,200 |
| | | | | | | CH4 | 6,400 |
| | | | | | | CO | 29,100 |
| | | | | | | CO2 | 14,300 |
| | | | | | | OTHER | 2,000 |
| | | SLOW PYROLYSIS | | | 600 | H2 | 11,700 |
| | | | | | | CH4 | 15,700 |
| | | | | | | CO | 44,000 |
| | | | | | | CO2 | 24,200 |
| | | | | | | OTHER | 4,400 |
| | | | | | 700 | H2 | 15,100 |
| | | | | | | CH4 | 16,000 |
| | | | | | | CO | 45,300 |
| | | | | | | CO2 | 18,000 |
| | | | | | | OTHER | 5,600 |
| | | | | | 800 | H2 | 21,400 |
| | | | | | | CH4 | 16,700 |
| | | | | | | CO | 42,400 |
| | | | | | | CO2 | 13,900 |
| | | | | | | OTHER | 5,600 |
| | | Microwave-assisted SLOW pyrolysis | Gumwood (biomass) | 4.8 % | 600 | H2 | 38,400 |
| | | | | | | CH4 | 5,500 |
| | | | | | | CO | 41,500 |
| | | | | | | CO2 | 13,000 |
| | | | | | | OTHER | 1,600 |
| | | | | | 700 | H2 | 41,800 |
| | | | | | | CH4 | 4,600 |
| | | | | | | CO | 37,700 |
| | | | | | | CO2 | 14,700 |
| | | | | | | OTHER | 1,200 |
| | | | | | 800 | H2 | 47,600 |
| | | | | | | CH4 | 5,600 |
| | | | | | | CO | 35,100 |
| | | | | | | CO2 | 10,000 |
| | | | | | | OTHER | 1,700 |
| | | SLOW PYROLYSIS | | | 600 | H2 | 11,600 |
| | | | | | | CH4 | 14,600 |
| | | | | | | CO | 53,100 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | CO2 | 15,400 |
| | | | | | | OTHER | 5,300 |
| | | | | | 700 | H2 | 13,400 |
| | | | | | | CH4 | 17,000 |
| | | | | | | CO | 57,000 |
| | | | | | | CO2 | 7,200 |
| | | | | | | OTHER | 5,400 |
| | | | | | 800 | H2 | 21,300 |
| | | | | | | CH4 | 14,900 |
| | | | | | | CO | 49,400 |
| | | | | | | CO2 | 9,200 |
| | | | | | | OTHER | 5,200 |
| | | Microwave-assisted SLOW pyrolysis | Pine (biomass) | 3.6 % | 600 | H2 | 42,400 |
| | | | | | | CH4 | 4,000 |
| | | | | | | CO | 38,200 |
| | | | | | | CO2 | 14,200 |
| | | | | | | OTHER | 1,200 |
| | | | | | 700 | H2 | 43,200 |
| | | | | | | CH4 | 3,800 |
| | | | | | | CO | 38,000 |
| | | | | | | CO2 | 14,000 |
| | | | | | | OTHER | 1,000 |
| | | | | | 800 | H2 | 46,000 |
| | | | | | | CH4 | 5,900 |
| | | | | | | CO | 33,400 |
| | | | | | | CO2 | 12,900 |
| | | | | | | OTHER | 1,800 |
| | | SLOW PYROLYSIS | | | 600 | H2 | 15,300 |
| | | | | | | CH4 | 13,400 |
| | | | | | | CO | 47,200 |
| | | | | | | CO2 | 19,800 |
| | | | | | | OTHER | 4,300 |
| | | | | | 700 | H2 | 16,900 |
| | | | | | | CH4 | 15,500 |
| | | | | | | CO | 49,400 |
| | | | | | | CO2 | 13,200 |
| | | | | | | OTHER | 5,000 |
| | | | | | 800 | H2 | 21,200 |
| | | | | | | CH4 | 16,700 |
| | | | | | | CO | 45,200 |
| | | | | | | CO2 | 12,600 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | OTHER | 4,300 |
| | | Microwave -assisted SLOW pyrolysis | Rosewood (biomass) | 5.6 % | 600 | H2 | 32,600 |
| | | | | | | CH4 | 8,700 |
| | | | | | | CO | 36,200 |
| | | | | | | CO2 | 21,400 |
| | | | | | | OTHER | 1,100 |
| | | | | | 700 | H2 | 43,000 |
| | | | | | | CH4 | 4,000 |
| | | | | | | CO | 41,700 |
| | | | | | | CO2 | 10,300 |
| | | | | | | OTHER | 1,000 |
| | | | | | 800 | H2 | 46,300 |
| | | | | | | CH4 | 5,600 |
| | | | | | | CO | 38,000 |
| | | | | | | CO2 | 8,600 |
| | | | | | | OTHER | 1,500 |
| | | SLOW PYROLYSIS | | | 600 | H2 | 0,800 |
| | | | | | | CH4 | 22,500 |
| | | | | | | CO | 67,100 |
| | | | | | | CO2 | 3,200 |
| | | | | | | OTHER | 6,400 |
| | | | | | 700 | H2 | 5,200 |
| | | | | | | CH4 | 21,200 |
| | | | | | | CO | 62,700 |
| | | | | | | CO2 | 3,800 |
| | | | | | | OTHER | 7,100 |
| | | | | | 800 | H2 | 20,000 |
| | | | | | | CH4 | 15,300 |
| | | | | | | CO | 49,300 |
| | | | | | | CO2 | 9,500 |
| | | | | | | OTHER | 5,900 |
| Waheed, Q.M.K., Nahil, M.A., Williams, P.T. | lab | Fast pyrolysis | WOOD | 6.02 % | 750 | H2 | 26,910 |
| | | | | | | CH4 | 11,290 |
| | | | | | | CO | 45,120 |
| | | | | | | CO2 | 11,350 |
| | | | | | | OTHER | 5,330 |
| | | | | | 850 | H2 | 27,460 |
| | | | | | | CH4 | 10,890 |
| | | | | | | CO | 47,100 |
| | | | | | | CO2 | 9,690 |
| | | | | | | OTHER | 4,860 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | 950 | H2 | 29,210 |
| | | | | | | CH4 | 11,240 |
| | | | | | | CO | 45,940 |
| | | | | | | CO2 | 9,340 |
| | | | | | | OTHER | 4,270 |
| | | | | | 1050 | H2 | 31,010 |
| | | | | | | CH4 | 9,330 |
| | | | | | | CO | 48,740 |
| | | | | | | CO2 | 7,810 |
| | | | | | | OTHER | 3,110 |
| | | | RICE HUSK | 6.31 % | 750 | H2 | 21,840 |
| | | | | | | CH4 | 11,920 |
| | | | | | | CO | 45,010 |
| | | | | | | CO2 | 15,060 |
| | | | | | | OTHER | 6,170 |
| | | | | | 850 | H2 | 25,320 |
| | | | | | | CH4 | 10,650 |
| | | | | | | CO | 46,170 |
| | | | | | | CO2 | 12,980 |
| | | | | | | OTHER | 4,880 |
| | | | | | 950 | H2 | 27,830 |
| | | | | | | CH4 | 8,940 |
| | | | | | | CO | 48,310 |
| | | | | | | CO2 | 11,330 |
| | | | | | | OTHER | 3,590 |
| | | | | | 1050 | H2 | 30,300 |
| | | | | | | CH4 | 8,670 |
| | | | | | | CO | 49,400 |
| | | | | | | CO2 | 8,650 |
| | | | | | | OTHER | 2,980 |
| | | | FORESTRY RESIDUE | 6.81 % | 750 | H2 | 23,700 |
| | | | | | | CH4 | 11,620 |
| | | | | | | CO | 43,800 |
| | | | | | | CO2 | 15,600 |
| | | | | | | OTHER | 5,280 |
| | | | | | 850 | H2 | 26,500 |
| | | | | | | CH4 | 9,700 |
| | | | | | | CO | 46,600 |
| | | | | | | CO2 | 12,600 |
| | | | | | | OTHER | 4,600 |
| | | | | | 950 | H2 | 29,050 |

| Source | Scale | Pyrolysis Technology | Feedstock | Moisture Yield | Temperature | Syngas Component | Vol % |
|---|---|---|---|---|---|---|---|
| | | | | | | CH4 | 9,140 |
| | | | | | | CO | 48,070 |
| | | | | | | CO2 | 10,450 |
| | | | | | | OTHER | 3,290 |
| | | | | | 1050 | H2 | 30,530 |
| | | | | | | CH4 | 9,620 |
| | | | | | | CO | 46,610 |
| | | | | | | CO2 | 9,480 |
| | | | | | | OTHER | 3,760 |
| Gao, N., Quan, C., Eller, Z., Toth, O., +A126:E127Miskolczi, N., Al-asadi, M. | lab | Fast pyrolysis | MPW (Municipal Plastic Waste) | 0.8% | 500 | H2 | 12,700 |
| | | | | | | CH4 | 6,400 |
| | | | | | | CO | 9,300 |
| | | | | | | CO2 | 10,900 |
| | | | | | | C2-C6 | 60,700 |
| | | | | | 900 | H2 | 42,000 |
| | | | | | | CH4 | 5,700 |
| | | | | | | CO | 20,100 |
| | | | | | | CO2 | 7,400 |
| | | | | | | C2-C6 | 24,800 |

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