UNIVERSITA' DEGLI STUDI DI PAVIA

FACULTY OF ENGINEERING DEPARTMENT OF ELECTRICAL, COMPUTER AND BIOMEDICAL ENGINEERING

MASTER DEGREE IN INDUSTRIAL AUTOMATION ENGINEERING

Innovative Energy Recovery from End-of-Life Tires in Romania: Logistics-Driven Automation for Gripping and Continuous Feeding in Pyrolysis, Combustion and Gasification

Supervisor:
Prof. Stefano Farnè

Candidate:
Pardis Aliakbari
s.n.: 513656

Academic year 2024/2025

Acknowledgments

I want to sincerely thank my supervisor for his support and guidance, Professor Stefano Farnè, for his invaluable guidance, encouragement, and support throughout the development of this thesis. His expertise and insightful feedback greatly enriched this work.

My heartfelt appreciation goes to my husband, whose emotional and technical support was essential during the writing of this thesis. His patience, motivation, and constant encouragement made this journey much easier.

Finally, I am deeply thankful to my family for their unconditional love, support, and belief in me. Their unwavering support has been a source of strength throughout my academic path.

Abstract

The continuous growth of end-of-life tires (ELT) represents a significant environmental and logistical challenge worldwide. Due to their non-biodegradable nature, large volume, and resistance to natural degradation, waste tires create long-term storage, safety, and pollution problems when landfilled or stockpiled. At the same time, tires contain a high amount of recoverable energy, which makes them a valuable resource rather than merely a waste stream. As conventional disposal routes become increasingly restricted, waste-to-energy solutions have gained attention as a sustainable alternative.

Among the available waste-to-energy technologies, pyrolysis and gasification are considered particularly promising because they allow controlled energy recovery while also producing reusable material outputs. However, existing studies show that the technical performance of these processes is strongly influenced by non-chemical factors such as feedstock preparation, feeding stability, storage conditions, and operational continuity. Experimental investigations demonstrate that high proportions of waste tires can lead to practical difficulties, including unstable feeding, material blockages, ash agglomeration, and interruptions in continuous operation. In addition, the reviewed evidence indicates that feasibility is shaped by system-level constraints beyond the reactor, including the capacity of gas cleaning and residue handling systems to meet compliance requirements under throughput variability. Downstream planning is also critical: pyrolysis yields multiple output streams (oil, gas, char, and recovered steel) that require safe storage and reliable routing, and tire-derived products may require conditioning or upgrading to satisfy offtake specifications. These challenges indicate that technological success depends not only on the conversion process itself, but also on the logistical system that supports it.

This thesis focuses on the logistics-oriented evaluation of waste tire-to-energy systems, with particular attention to Pyrolysis, Gasification and Combustion pathways. The analysis emphasizes collection networks, transportation flows, storage safety, pre-treatment requirements, and the operational constraints that arise when handling large quantities of tire waste. Rather than examining chemical reactions or material compositions, the study adopts an industrial automation and logistics perspective, in line with the Master's programme in Industrial Automation Engineering at the University of Pavia. From an automation viewpoint, the thesis also highlights monitoring and control challenges typical of industrial thermal systems: because internal conditions are not always directly measurable, practical operation may rely on external measurements combined with known wall/lining characteristics and redundancy in sensing to estimate internal states and verify stability. Sustainability evidence discussed in the thesis further shows that environmental performance depends strongly on how conversion plants are integrated, especially when internal energy integration is achieved (e.g., using non-condensable gases for on-site heat demand) and transport distances and handling burdens are minimised.

The application context of this work is Romania, a country that generates a substantial volume of waste tires each year while still facing limitations in domestic processing capacity. Existing

industrial actors such as Gravita Europe, together with related companies including Geocycle Romania (Holcim Group) and equipment suppliers such as Beston Machinery, illustrate how organised logistics chains can support tire-to-energy recovery at industrial scale. The Romanian context also highlights the importance of positioning new conversion capacity alongside established recovery routes and industrial users, so that offtake pathways and compliance-related operating burdens are addressed within the overall system design. By linking literature findings with the Romanian case, this thesis demonstrates how well-designed logistics systems can improve process stability, environmental performance, and overall feasibility of pyrolysis- and gasification-based tire-to-energy plants. To support this system-level evaluation, the thesis develops a transparent reasoning framework that connects product-yield ranges, energy content, and recurring constraints (logistics, emissions control, and residue management); an illustrative calculation shows that, under mid-range assumptions, the oil and char fractions can represent on the order of 3×10^4 MJ per tonne of tires (about 9 MWh_{th}/t, using 1 MWh = 3,600 MJ), highlighting both the magnitude of recoverable energy and the need for reliable industrial integration.

This thesis has received limited assistance from an artificial intelligence language model (OpenAI) to enhance grammatical accuracy and linguistic clarity. The conceptual development, analyses, and conclusions are fully based on research conducted on authoritative articles.

Contents

List of Figures

List of Tables

List of Abbreviations

AFM Environmental Fund Administration (Romania)

AFR Alternative Fuels & Raw Materials

BAT Best Available Techniques

BET Brunauer–Emmett–Teller (specific surface area)

CAPEX Capital expenditure

CO Carbon monoxide

CO_2 Carbon dioxide

DTA Differential thermal analysis

DTG Derivative thermogravimetry

ELT End-of-life tires

EU European Union

FGC Flue-gas cleaning

GCV Gross calorific value

GIS Geographic information system

HCl Hydrogen chloride

HFO Heavy fuel oil

HG Government Decision (Romania)

HHV Higher heating value

HHVd Higher heating value (dry basis)

H_2O Water

H_2S Hydrogen sulfide

HV Heating value

INR Indian rupees

LCA Life cycle assessment

LCIA Life cycle impact assessment

LCV Lower calorific value

LHV Lower heating value

MSW Municipal solid waste

$\mathbf{MWh}_{th}$ Megawatt-hour (thermal)

NCG Non-condensable gas

$\mathbf{NO}_2$ Nitrogen dioxide

$\mathbf{NO}_x$ Nitrogen oxides

$\mathbf{Nm}^3$ Normal cubic metre

$\mathbf{O}_2$ Oxygen

OPEX Operating expenditure

OUG Emergency Ordinance (Romania)

PAHs Polycyclic aromatic hydrocarbons

PLC Programmable Logic Controller

PM Particulate matter

PNGD National Waste Management Plan (Romania)

R3 Recovery operation R3 (recycling/reclamation of organic substances)

$\mathbf{SO}_2$ Sulfur dioxide

TDF Tire-derived fuel

TG Thermogravimetry / thermogravimetric curve

tkm Tonne-kilometre

TPO Tire pyrolysis oil

TPG Tire pyrolysis gas

VOCs Volatile organic compounds

WI BREF Waste Incineration Best Available Techniques Reference Document

WT Waste tires

WtE Waste-to-energy

Chapter 1

Introduction

1.1 Background and Motivation

End-of-life Tires represent one of the most challenging waste streams in modern industrial and municipal waste management systems. Their complex structure, high durability, and resistance to natural degradation make them unsuitable for conventional disposal methods such as landfilling. Unlike organic waste, Tires do not decompose naturally and can persist in the environment for long periods if not properly managed. Large stockpiles of waste tires occupy valuable land, pose serious fire hazards, and create long-term environmental risks through air, soil, and water pollution. The continuous growth of vehicle ownership and transportation activities has further intensified this problem, leading to steadily increasing volumes of waste tires each year [1, 2, 3].

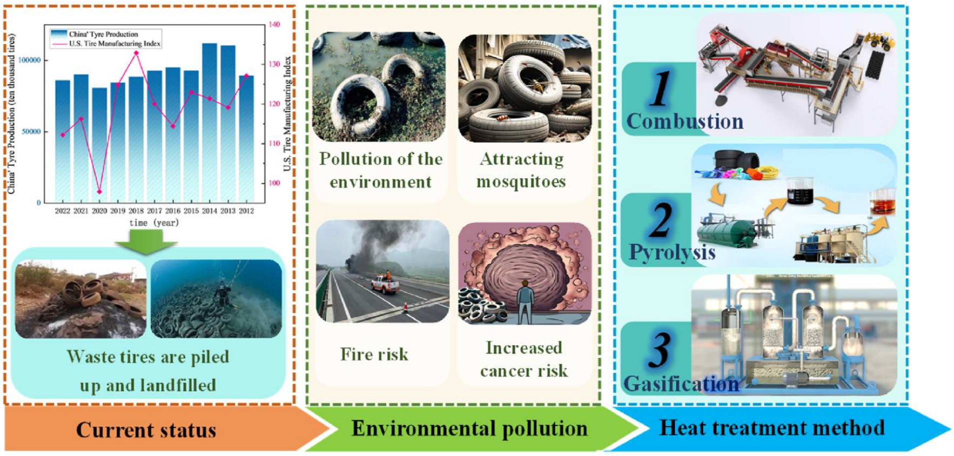


Figure 1.1: Current status of waste tires, environmental impacts, and main heat-treatment methods [2].

At the same time, waste tires contain a significant amount of recoverable energy. Their energy content is higher than that of many other waste materials and is comparable to that of conventional industrial fuels. This characteristic has encouraged the development of waste-to-energy (WtE) solutions that aim to reduce waste volumes while simultaneously recovering useful energy. Rather than treating waste tires solely as a disposal problem, they can be viewed as a secondary resource within an integrated energy and material recovery framework[2]. This shift in perspective supports broader sustainability and circular economy objectives[1, 4, 3].

Table 1.1: Physicochemical characteristics of waste tires and other fuels (received basis) [2].

Material	**C (%)**	**H (%)**	**N (%)**	**S (%)**	**HV (MJ/kg)**
Tires	81.79	7.99	0.48	1.81	38.3
Tires	86.70	8.10	0.40	1.40	36.2
Tires	82.80	7.60	0.50	1.30	36.5
Tires (car)	83.92	6.83	0.78	0.92	38.6
Tires (truck)	83.20	7.70	1.50	1.44	33.4
Tires (motorcycle)	75.50	6.75	0.81	1.44	29.18
Municipal solid waste	15–30	2–5	0.2–1.0	0.02–0.1	8.9–13.4
Wood	49.50	5.50	0.20	0.10	16.7–19.0
Bituminous coal	73.10	5.50	1.40	1.70	34.0
Lignite	56.40	4.20	1.60	–	26.8

Thermal conversion technologies have emerged as important options for waste Tire valorisation. Among these technologies, pyrolysis and gasification have attracted particular attention because they allow controlled processing under specific operating conditions, enabling both energy recovery and material reuse. Compared to direct combustion, these processes offer improved operational control and greater flexibility in managing outputs. However, practical experience shows that the success of pyrolysis and gasification systems depends not only on the conversion technology itself but also on the supporting logistics and operational infrastructure [1, 2].

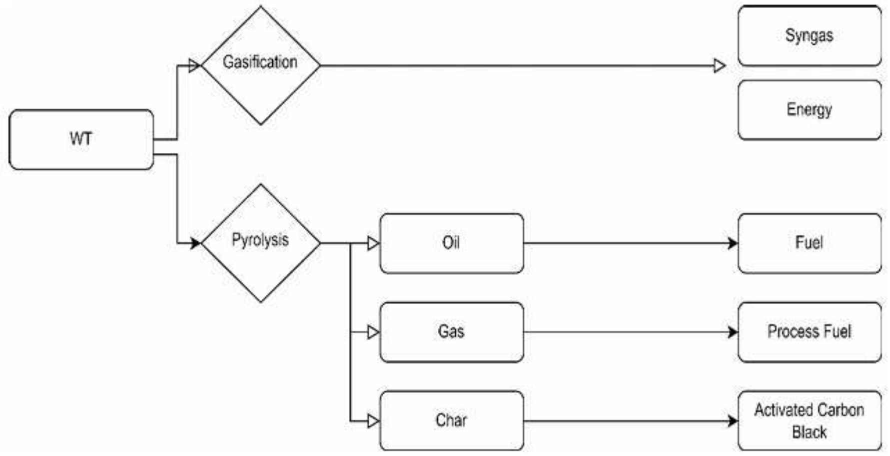


Figure 1.2: Thermochemical waste-tire (WT) treatment methods and main product pathways [3].

1.2 Role of Logistics in Tire-to-Energy Systems

From a logistics and industrial automation perspective, waste Tire-to-energy plants must be considered as integrated systems rather than isolated processing units. Their performance and reliability are strongly influenced by upstream and downstream logistics activities, including Tire collection, transportation, storage, pre-treatment, and continuous feeding into the conversion unit. Any disruption in these activities can directly affect process stability and overall plant efficiency.

Waste Tires present specific logistical challenges due to their size, elasticity, irregular shape, and heterogeneous composition. Inadequate preparation or inconsistent feed quality can lead to feeding interruptions, mechanical blockages, and unstable operating conditions. Experimental studies have shown that these issues become more pronounced as the proportion of waste tires increases, often requiring manual intervention to maintain operation. Such interventions increase operational costs and reduce system reliability, highlighting the critical role of logistics planning. [4]

Logistics considerations also extend to storage and safety management. Improper storage of waste tires can increase fire risk and environmental exposure, while insufficient buffering capacity may disrupt continuous plant operation. Transportation logistics influence not only cost but also supply reliability, particularly for facilities that require steady material inflow to maintain stable thermal conditions. Furthermore, downstream logistics related to the handling, storage, and distribution of process outputs must be integrated into plant design to ensure efficient and compliant operation.

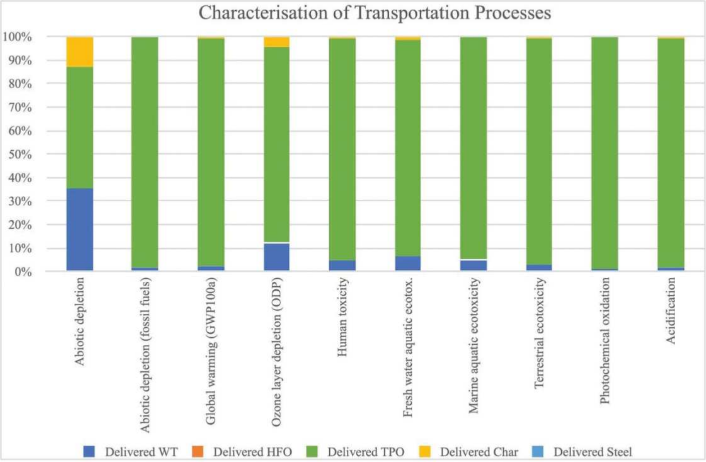


Figure 1.3: Characterisation of transportation processes (environmental-impact contribution by transport stage) [1].

Table 1.2: Transportation distances and transport work (tkm) used for waste-tire fast pyrolysis logistics [1].

Input/Output stream	**Amount (kg)**	**Distance (km)**	**Output (tkm)**
Delivered WT	1056	2.0	2.1
Separated steel	190	4.9	0.93
Char	320.76	13.2	4.2
TPO	375.03	6.3	2.3

Flue-gas flow as an operational variable linking process control and downstream capacity. From logistics perspective, stable operation depends not only on moving solid tires into the conversion unit, but also on managing the gaseous stream that leaves it. The volumetric rate of flue gas and its composition are essential inputs for determining and monitoring emissions. This implies that operating choices that influence air supply and furnace conditions also influence downstream treatment load, because flue-gas flow and temperature determine the capacity required for heat recovery and gas-cleaning stages. In system terms, the conversion reactor and the downstream treatment line must be coordinated as a single throughput-constrained chain rather than independent units. [5]

Link between logistics-driven throughput variability and combustion stability (rotary kiln model). From a logistics viewpoint, waste inflow variability and feeding-rate decisions translate directly into thermal stability constraints in the conversion unit. A full-scale rotary kiln modelling study shows that operational behaviour changes when the waste input rate is varied, and that stable performance requires coordinated adjustment of operating conditions to preserve complete burnout while maintaining useful heat recovery . This supports the thesis argument that collection, storage buffering, and feed scheduling are not external "support" activities, but variables that must be aligned with control capacity in the plant.

1.3 Operational Characteristics of Pyrolysis and Gasification

Pyrolysis and gasification differ in their operating conditions and output characteristics, yet both require stable and predictable material flows to function effectively. In pyrolysis systems, uniform feed size and controlled feeding rates are essential to maintain consistent thermal conditions and stable product generation. Variations in feedstock quality or supply can lead to fluctuations in output and complicate downstream handling and utilisation. [2, 3]

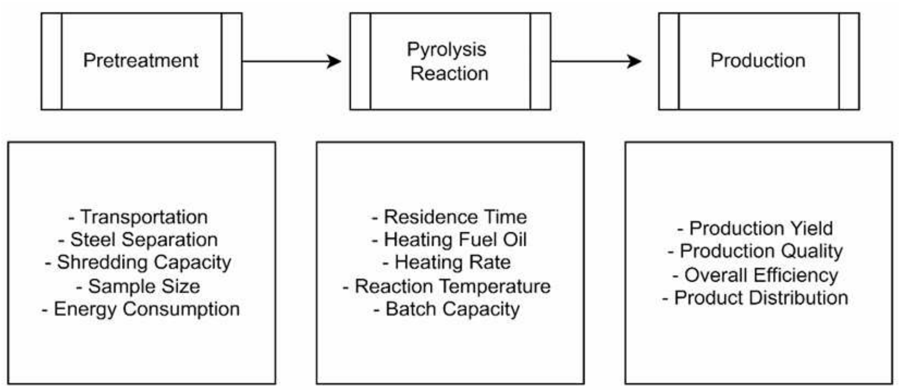


Figure 1.4: Stages of conventional pyrolysis and influential parameters across pretreatment, reaction, and production [3].

Gasification systems are similarly sensitive to feedstock properties and feeding stability. Stable operation requires consistent material characteristics to avoid temperature fluctuations and variations in gas composition. Studies have demonstrated that higher proportions of waste tires can lead to feeding instability, process interruptions, and increased formation of unwanted residues. These operational challenges reinforce the importance of coordinated logistics, automation, and process control strategies. [4]

From an industrial automation standpoint, both technologies benefit from advanced feeding systems, real-time monitoring, and integrated control mechanisms. Automation can reduce reliance on manual intervention, improve safety, and enhance operational consistency. However, automation systems are only effective when supported by a logistics chain capable of delivering material that meets defined quality and consistency requirements. [3]

Implications for monitoring strategy when direct measurements are difficult. Industrial thermal reactors do not always allow straightforward measurement of the most important internal variables. In a full-scale rotary kiln case, practical constraints motivate the use of external temperature measurements combined with known wall and lining characteristics to estimate internal conditions and verify stability. This observation is transferable to pyrolysis and gasification from an automation perspective: robust operation benefits from redundant sensing, estimation approaches, and control logic that can maintain stability even when direct measurements inside the reactor are constrained.

1.4 Romanian Context and Industrial Relevance

Romania provides a relevant context for examining waste tire–to–energy systems. The country generates a substantial volume of end-of-life tires (ELT) each year, while domestic processing capacity remains limited. This imbalance has resulted in challenges such as incomplete collection, illegal dumping, and reliance on export solutions. These conditions underline the need for domestic recovery infrastructure that can handle waste tires efficiently and sustainably.

Several industrial actors already operate within the Romanian waste management and energy recovery landscape. Gravita Europe operates a waste tire processing facility, demonstrating the technical feasibility of industrial-scale recovery. Geocycle Romania, part of the Holcim Group, plays a role in organised waste collection and the use of alternative fuels in energy-intensive industries. Equipment suppliers such as Beston Machinery provide technological solutions that support the industrial implementation of pyrolysis-based systems. Together, these actors illustrate how logistics, technology, and market demand interact in practical waste tire–to–energy systems.

The Romanian case highlights the importance of strategic plant location, proximity to waste sources, access to transportation infrastructure, and integration with industrial energy users. Without effective coordination of these elements, even advanced conversion technologies may struggle to achieve stable and economically viable operation.

1.5 Scope and Objectives of the Thesis

The purpose of this thesis is to analyse waste tire–to–energy systems from a logistics and industrial automation perspective, with a specific focus on pyrolysis and gasification technologies. The study does not aim to investigate chemical reaction mechanisms or material compositions. Instead, it concentrates on operational constraints, material flows, and system-level interactions that influence real-world performance.

By combining insights from the scientific literature with a Romanian case-study perspective, this thesis seeks to demonstrate that effective logistics planning and industrial automation are essential enablers of successful waste tire–to–energy systems. The findings are intended to support the development of scalable and sustainable solutions that transform waste tires from an environmental challenge into a reliable energy resource.

Chapter 2

Literature Review

2.1 Introduction

The rapid increase in end-of-life tires presents important environmental, economic, and logistical challenges. The management and valorisation of end-of-life tires is a growing challenge for modern waste logistics systems [2]. In many regions the large annual generation of tires creates pressure on collection, transport, storage and final treatment infrastructures; this in turn stimulates interest in energy recovery routes that can reduce landfilling and create value from a waste stream that is otherwise difficult to recycle [2]. Due to their durable and complex material structure, waste tires do not degrade naturally and landfilling is widely considered an undesirable option because it consumes land, increases fire risk, and creates long-term pollution hazards [2]. Alternative reuse routes such as retreading or incorporation into construction materials (e.g., asphalt, concrete, athletic-field infill) face limitations because of safety concerns and the potential release of harmful compounds during use, such as volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) [2, 3].

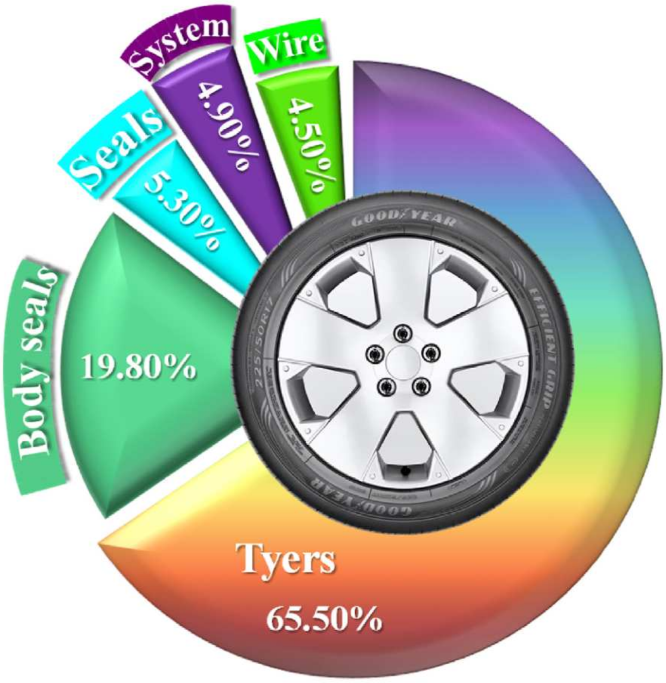


Figure 2.1: Main component structure of waste tires (WT) [2].

Despite these disposal challenges, waste tires represent a significant resource. Their mass composition is dominated by carbon, hydrogen and oxygen, giving them a high calorific value comparable to certain fossil fuels [2]. The literature and the experimental results summarized in the source document emphasize that tires have a high energy potential compared with typical lignocellulosic biomass fuels [4]. This makes them attractive as supplements to biomass in co-combustion and co-gasification schemes, but the higher energy density and different physical behaviour of rubber/plastics create specific logistic and operational impacts [4]. If recovered carefully, the energy contained in WT can be converted into useful forms (electricity, heat, or chemical feedstocks), which can help reduce dependence on conventional fossil fuels and lower the environmental burden of waste disposal [2].

From a logistics viewpoint, waste-tire energy projects are not only about choosing the best conversion technology but also about arranging the flows and handling steps that make the technology viable in practice. Key logistics issues that recur in the experimental work include: (i) the need for sorting and size reduction of incoming tires to avoid damage to equipment; (ii) difficulties with automated feeding when high shares of polymeric wastes are mixed with biomass; (iii) increased need for operator intervention and preventive maintenance where ash agglomeration or fused residues form; and (iv) limits on feasible blend ratios because of feeding, residence-time and stability constraints in the reactors [4]. These points indicate that successful deployment requires attention to upstream operations (collection, pre-treatment, and quality control) as much as to the conversion unit itself [4]. For example, higher heating value fuels tend to reduce the required feed mass flow but increase the risk of ash fusion and feed-blocking in pellet- or screw-fed boilers; as a result, feeding systems and storage must be designed to accommodate differences in bulk density, particle size and melting/softening behaviour [4].

Another logistics theme is the trade-off between maximizing waste diversion from landfill and maintaining process stability. Experimental findings show that mixtures with moderate shares of tire-derived material can improve energetic output, but beyond certain thresholds the feeding and process stability problems increase sharply [4]. From a logistics and systems-design perspective, this implies that collection and blending strategies must be intentionally engineered: incoming streams should be characterized and possibly pre-blended or pre-treated to ensure the conversion plant receives a consistent, machine-friendly fuel [4]. Where automatic feeding becomes unreliable, operational costs increase because of manual interventions and downtime, which erodes the overall environmental and economic gains of energy recovery [4].

Quality control, material preparation and contamination removal are further logistics concerns raised by the experimental work. The authors report manual removal of metals and mechanical screening to reach a preferred particle size range prior to thermal conversion. These sorting steps are essential to prevent equipment damage and to reduce unwanted by-products [4].

Finally, emissions and residue management have direct logistic ramifications. Combustion of tire material can lead to higher concentrations of certain pollutants (notably sulfur-containing emissions and fused ash) which in turn require additional flue-gas treatment and ash handling infrastructure [4]. The experimental results indicate that, without adequate mitigation measures, pollutant limits can be exceeded for high shares of polymeric waste, therefore logistics planners must factor in the capacity and cost of emissions control and ash processing when sizing the overall system [4].

In summary, the body of experimental evidence reviewed here points to two central conclusions from a logistics perspective: (1) waste tires are an energetically attractive feedstock for co-processing with biomass, and (2) Practical logistics: especially pre-treatment, feeding reliability, and residue./ Emissions handling: strongly determine whether that energetic potential can be converted into a reliable, compliant and cost-effective process [4, 2]. The remainder of this literature review will keep these logistics concerns as a guiding thread while examining the technical options (combustion, pyrolysis, gasification) and their operational implications in greater detail [2].

2.1.1 Thermal-chemical treatment

Thermal-chemical treatment is identified in the reviewed literature as a promising pathway for recovering energy and materials from WT. Three principal thermal-chemical methods are highlighted: combustion, pyrolysis, and gasification. Each method applies heat under different conditions and thus yields different products and environmental footprints. Combustion is the most direct means of volume reduction and energy recovery but raises significant concerns due to emissions of sulfur and nitrogen oxides and other toxic gases. Pyrolysis—thermal decomposition in an oxygen-free environment; Produces solid char, liquid oil, and gaseous products that can be further used or upgraded. Gasification converts tire material into a synthesis gas (syngas) composed of light, energy-rich gases under controlled atmospheres [2].

The reviewed work further notes that, before this comprehensive review, there was a lack of studies that jointly examine treatment methods, product applications, and the key technological challenges across all three thermal-chemical routes. That gap restricts broader understanding and practical adoption of WT-to-energy systems. This literature review therefore aims to offer an integrated overview of the three routes and their product applications, and to identify the main limitations and research directions needed to move WT thermal-chemical utilization toward sustainable deployment [2].

From a logistics and industrial automation point of view, central to the present thesis, the thermal-chemical processes do not operate in isolation. Effective WT valorization requires coordinated systems for collection, transport, pre-treatment (shredding, screening and metal/textile separation), safe storage, and downstream product handling and distribution.

Feedstock heterogeneity and variability of arrival influence plant design, inventory policies, and automation needs; likewise, the choice among combustion, pyrolysis, or gasification substantially affects requirements for emission control, product purification, and market linkage. The reviewed literature underscores that adapting technologies to handle WT complexity and integrating logistical and control systems are essential for operationally and economically viable WT-to-energy plants [2].

2.1.2 Thermal-Chemical Treatment Methods of Waste Tires

Thermal-chemical treatment methods convert waste tires (WT) into usable energy and materials through controlled heating processes. According to the reviewed literature, the three principal thermal-chemical methods are combustion, pyrolysis, and gasification. Each method operates under different thermal conditions and produces distinct sets of products with unique environmental and logistical implications. These methods have become increasingly important as WT are recognized as a high-energy, carbon-rich resource rather than mere waste [2].

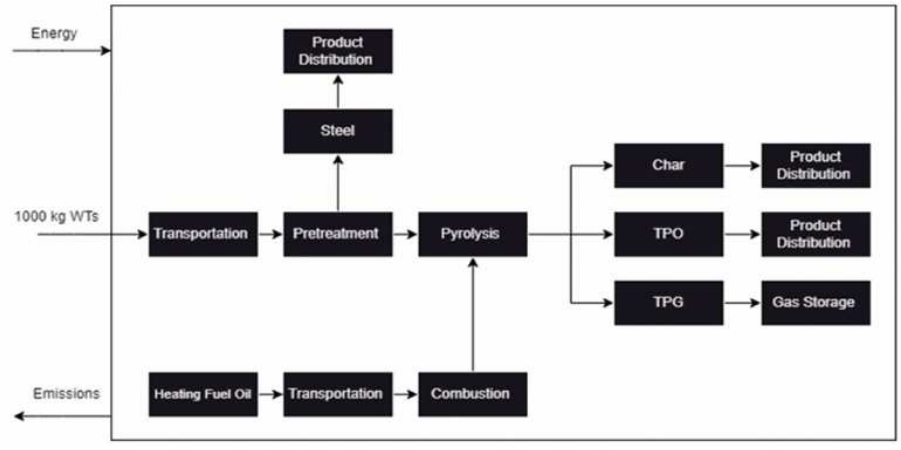


Figure 2.2: System boundaries for pyrolysis with HFO combustion [1].

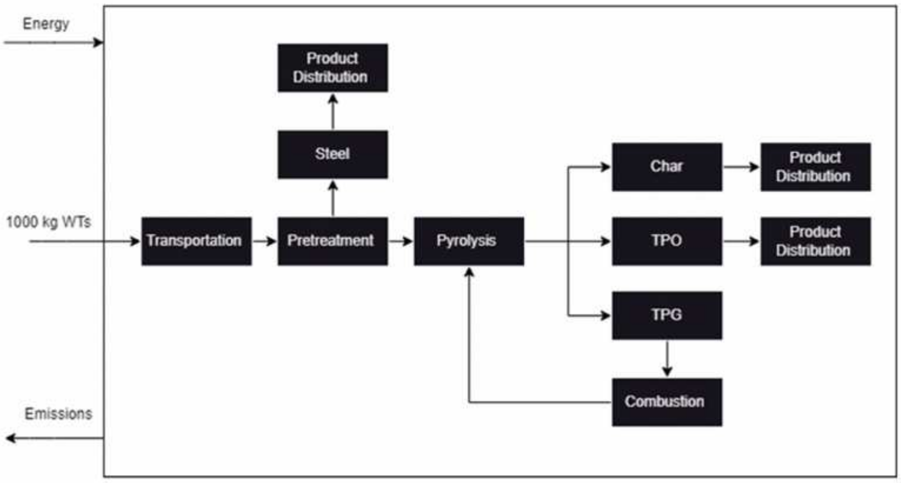


Figure 2.3: System boundaries for pyrolysis with NCG combustion [1].

Combustion

Combustion is the simplest and fastest thermal-chemical treatment method for WT. It involves burning WT in the presence of oxygen, rapidly reducing their volume while releasing heat that can be used for industrial processes such as cement production or heat generation. The literature highlights that waste tires have a very high carbon and hydrogen content, resulting in a calorific value close to that of certain grades of coal. This energy makes WT a potential substitute fuel in high-temperature industries [2].

However, combustion also presents serious environmental challenges. Direct burning of WT releases significant amounts of carbon dioxide, carbon monoxide, water vapour, and harmful pollutants such as sulfur oxides, nitrogen oxides, and polycyclic aromatic hydrocarbons. These emissions pose health risks and therefore require advanced emission control systems. Experimental studies cited in the reviewed paper show increasing emissions of sulfur dioxide and nitric oxide at higher temperatures and ventilation rates [2, 4]. Although co-combustion of WT with other materials (such as biomass or waste plastics) is feasible and can partially reduce fossil fuel consumption, the environmental risks associated with pollutant emissions remain a key limitation. As a result, combustion is typically considered a transitional rather than a long-term sustainable method for WT energy recovery [2, 4].

Pyrolysis

Pyrolysis is presented in the reviewed literature as one of the most promising methods for WT treatment. It involves heating WT *in the absence of oxygen*, which prevents combustion and instead causes the rubber materials to thermally decompose into oil, gas, and solid char. This process is valued because it enables the recovery of multiple useful products and significantly reduces the volume of tire waste [2, 3].

The paper outlines four major categories of pyrolysis [2, 3]:

- **Hydrothermal liquefaction**
- **Microwave pyrolysis**
- **Supercritical fluid pyrolysis**
- **Traditional pyrolysis** (including catalytic pyrolysis and co-pyrolysis)

Different pyrolysis conditions affect the quality and quantity of the resulting products. Factors such as temperature, reactor type, heating rate, and catalytic materials determine the oil yield, gas composition, and char properties. For instance, microwave pyrolysis provides more uniform heating and has been shown to increase product yield compared to conventional methods [2, 3].

Table 2.1: Temperature and heating-rate sets in different reactors (waste-tire pyrolysis) [3].

Reactor	**Heating Rate (°C/min)**	**Temperature (°C)**	**Optimal Temp. (°C)**	**Max. Yield (wt.%)**
Fixed-Bed	10–15	1000–1300	1000	34.4 (Oil)
Fixed-Bed	10	400–900	∼850	∼45 (Gas)
Rotary Bed	5–60	550	—	67 (Gas)
Rotary Kiln	Nm	400–1050	550	44 (Oil)
Lab-scale	14	400–750	500	43.6 (Oil)
Rotary Bed	15	420–500	500	45 (Oil)
Photothermal	60–600	425–575	575	57.5 (Oil)
This study	Rotary Kiln	10	450–850	45.2 (Oil)

Co-pyrolysis—processing WT together with materials such as biomass or soapstock—can create synergistic effects that improve oil yield and quality. Similarly, catalytic pyrolysis can enhance product selectivity and reduce contaminants. These advantages make pyrolysis a key focus for future research and development [2, 3].

Gasification

Gasification is another thermal-chemical method that partially oxidizes WT under controlled atmospheres to produce *syngas*, a mixture of light, energy-rich gases such as hydrogen, carbon monoxide, and methane. Gasification generally occurs at high temperatures and transforms the organic fraction of WT through both primary decomposition and secondary cracking and reforming reactions [2].

The composition of syngas depends strongly on the gasifying agent [2]:

- Air gasification produces mainly carbon monoxide and methane.
- Steam gasification favours reactions producing carbon dioxide and methane.
- Gasification in carbon dioxide increases the reactivity of carbon in WT.

Gasification can be performed in several reactor types, such as fixed beds, fluidized beds, spray beds, and rotary kilns. The literature notes that fixed bed gasification is more economical, while fluidized beds generally achieve better performance and higher syngas quality [2].

Emerging techniques such as *chemical looping gasification* show potential for lowering tar formation and improving gas purity, but these are still largely in the research and simulation stages. Tar reduction remains a significant challenge, as it affects gas quality and downstream applications [2].

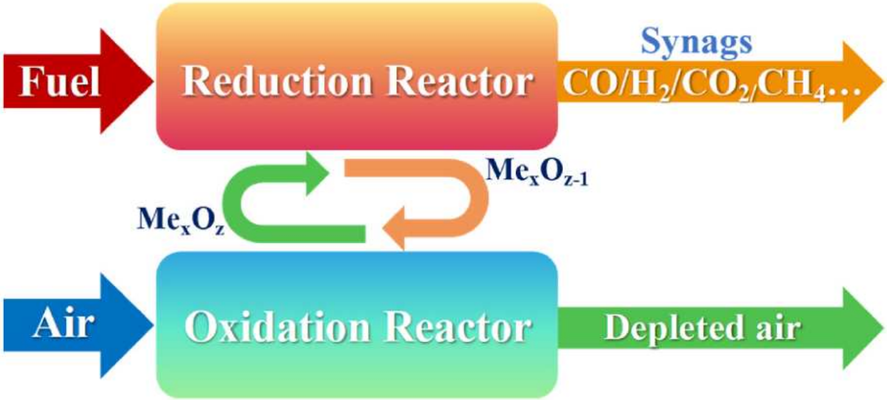


Figure 2.4: Reaction mechanism of chemical looping gasification for WT [2].

Overall, gasification presents advantages such as hydrogen-rich gas production and reduced environmental impact compared to direct combustion. However, improvements in syngas purity and fuel synthesis technologies are required before large-scale industrial deployment becomes feasible [2].

2.2 WT Thermal-Chemical Utilization Techniques

The thermal-chemical utilization of waste tires (WT) has gained significant global attention because these technologies convert WT into energy and valuable products while reducing the environmental burden associated with disposal. The reviewed literature identifies three primary utilization techniques: combustion, pyrolysis, and gasification. Each technique requires specific operating conditions and yields a distinct set of useful outputs. These technologies form the core of current WT-to-energy strategies [2].

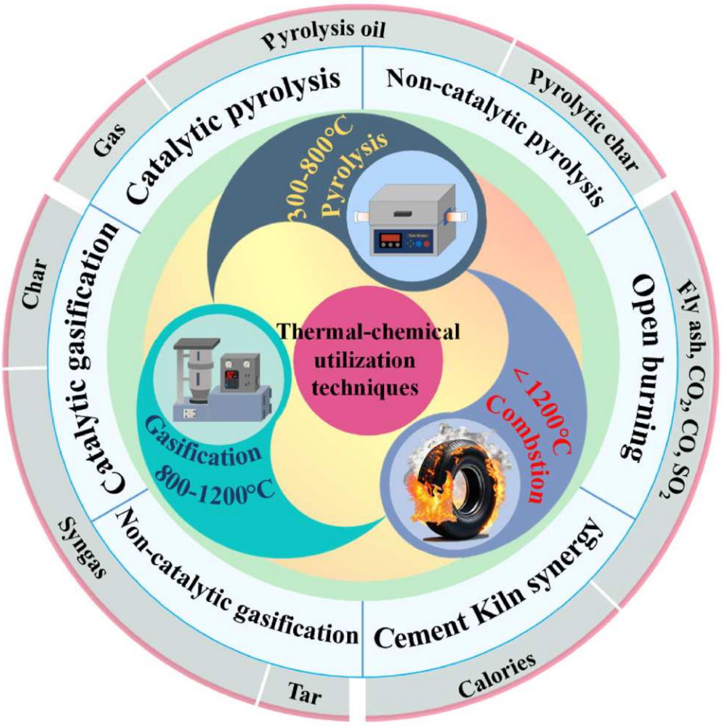


Figure 2.5: Thermal-chemical utilization techniques and typical products from WT conversion [2].

2.2.1 Combustion Utilization

Combustion is the most straightforward utilization technique, as WT can be burned directly to recover heat. The high carbon and hydrogen content of WT gives them a calorific value comparable to low-grade coal, making them suitable substitutes for industrial fuels. Combustion therefore finds applications in facilities such as cement kilns and waste-to-energy plants, where high thermal demand exists [2].

Cement kilns as a high-temperature combustion route for tire-derived fuel (TDF)

Waste Tires have high energy potential and are often converted into tire-derived fuel (TDF), typically by shredding. A major industrial outlet for TDF in the European context is the cement industry, where waste Tires can be co-combusted with coal and, in some cases, even fed as whole Tires. This use is enabled by the high operating temperatures in cement kilns (reported as above 1200 °C), which support complete burnout of Tire components.

An important operational implication for residue handling is that the mineral ash and steel cord from Tires can become incorporated into the clinker matrix rather than forming a separate disposal stream, without seriously degrading clinker properties. The same source frames this kiln pathway as environmentally safe in comparison to coal combustion, emphasizing that the cement-kiln environment and high-temperature conditions are central to the feasibility of using Tires as an alternative fuel [6].

However, despite its ease of implementation, combustion has a narrow application scope due to the emission of harmful pollutants, including sulfur oxides, nitrogen oxides, and particulate matter. These pollutants must be carefully treated before release. Although co-firing WT with other fuels can reduce some operational costs and fuel consumption, the environmental concerns limit widespread adoption of combustion as a long-term WT utilization strategy. The reviewed paper emphasizes that while combustion rapidly eliminates waste tires and produces energy, its environmental impact remains its major drawback [2].

Although combustion is often described at a general level as direct oxidation for energy recovery, industrial implementations typically rely on controlled reactor configurations designed to handle heterogeneous wastes safely and continuously. For this reason, the following subsection briefly describes a rotary kiln combustion layout with a secondary post-combustion chamber, since it provides a representative reference model for controlled thermal treatment and highlights the operational requirements that influence stability and emissions control [7, 8].

Rotary Kiln Combustion and Post-Combustion Chamber Operation

This part briefly expands the combustion pathway by describing a rotary-kiln-based configuration with a secondary post-combustion chamber, since this design is frequently used for heterogeneous waste and provides a controlled reference point for thermal treatment systems [7].

A rotary kiln incineration system is commonly described as a suitable configuration for heterogeneous waste because the primary chamber is an inclined rotating cylindrical tube lined with refractory materials. The movement of the cylinder around its axis supports the continuous advancement of the waste, while primary air is introduced in the initial part of the cylinder to sustain oxidation. In the reference full-scale plant discussed in the literature, the installation is organized as a two-chamber system, composed of a primary rotary kiln and a secondary chamber that completes the gas-phase combustion before the exhaust stream proceeds to downstream devices such as energy recovery and flue-gas treatment units [7].

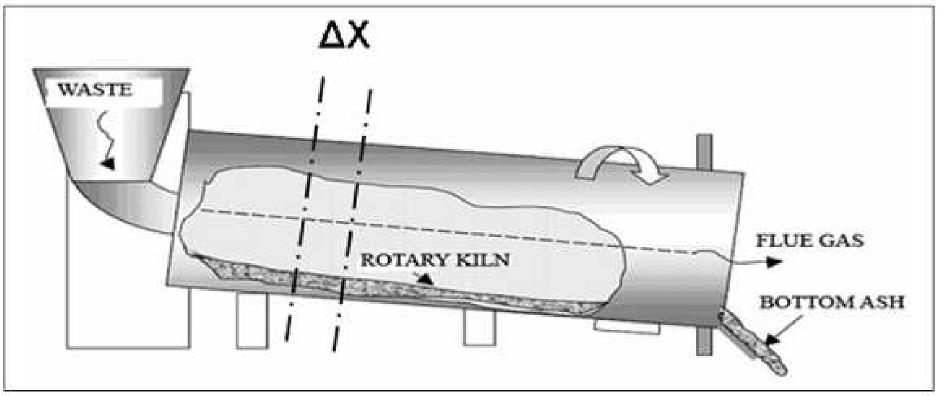


Figure 2.6: Rotary kiln combustion chamber (schematic from the full-scale reference plant) [7].

Inside the kiln, the waste undergoes staged conversion, beginning with drying and devolatilization, followed by progressive oxidation of the remaining solid fraction. As the material advances along the inclined kiln, residues reach the terminal section and are discharged as bottom ash. In the same configuration, the produced flue gases exit the kiln and enter the post-combustion chamber,

Table 2.2: Rotary kiln characteristics of the full-scale reference plant [7].

Parameter	**Value**
Kiln internal diameter (m)	2.65
Kiln length (m)	10
Refractory material thickness (cm)	22
Refractory material thermal properties (W m^{-1} K^{-1})	0.53 (400°C); 0.72 (800°C); 0.84 (1000°C)
Insulator material thickness (cm)	9.8
Insulator material thermal properties (W m^{-1} K^{-1})	$2.9 - 0.0006 \cdot T$ (K)
Air temperature (°C)	15
Convection coefficient with the external wall (W m^{-2} K^{-1})	18
Waste temperature in the first volume (°C)	660
Air temperature in the first volume (°C)	670
Waste flow rate (kg h^{-1})	1690
Excess air ratio	1.8
Waste residence time (min)	120

where gas-phase reactions are completed, providing an additional safeguard for achieving stable and complete combustion prior to the subsequent treatment units [7].

The same study emphasizes that stable operation is closely linked to temperature monitoring and thermal control, but also recognizes the practical limitations of measuring temperatures directly inside the rotating kiln because of rotation, flame presence, and high internal temperatures. As an alternative, external wall temperatures can be measured using an infrared temperature probe and combined with the known kiln wall material system to estimate internal temperatures and validate operating conditions. In the reported full-scale case, temperature profiles along the kiln length show that the final section reaches the highest internal temperatures, while external wall temperatures remain substantially lower, illustrating the insulating role of the lining system and its relevance for thermal stability and energy efficiency [7].

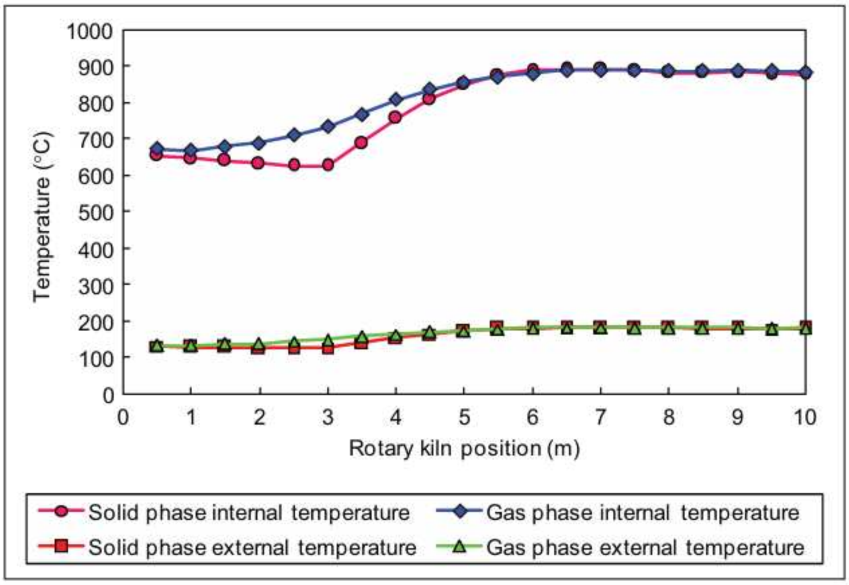


Figure 2.7: Model temperature profiles showing internal vs external of the solid and gaseous phase [7].

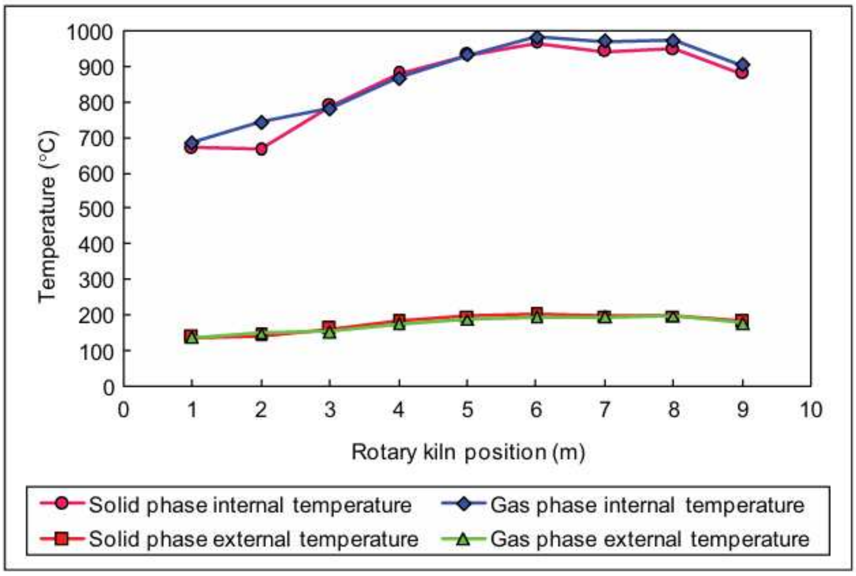


Figure 2.8: Measured external wall temperatures (IR) and the corresponding calculated internal temperatures. [7].

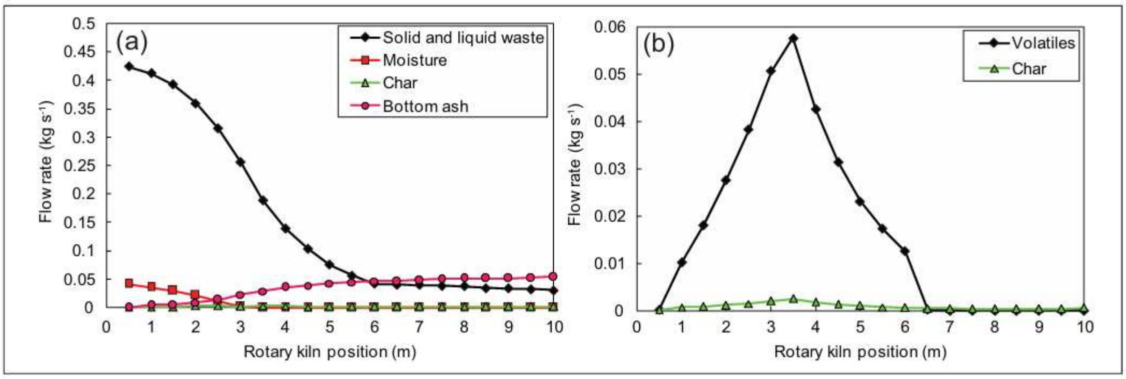


Figure 2.9: (a)Solid phase flow rates. (b)Char and volatile flow rates [7].

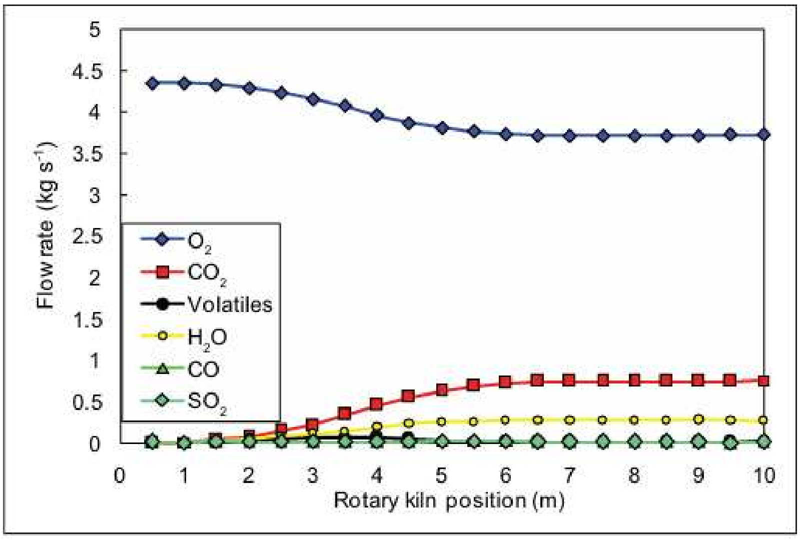


Figure 2.10: Gas phase flow rate trends(O_2:oxygen; CO_2:carbon dioxide; H_2O:water; CO:carbon monoxide; SO_2:sulphur dioxide and volatiles) [7].

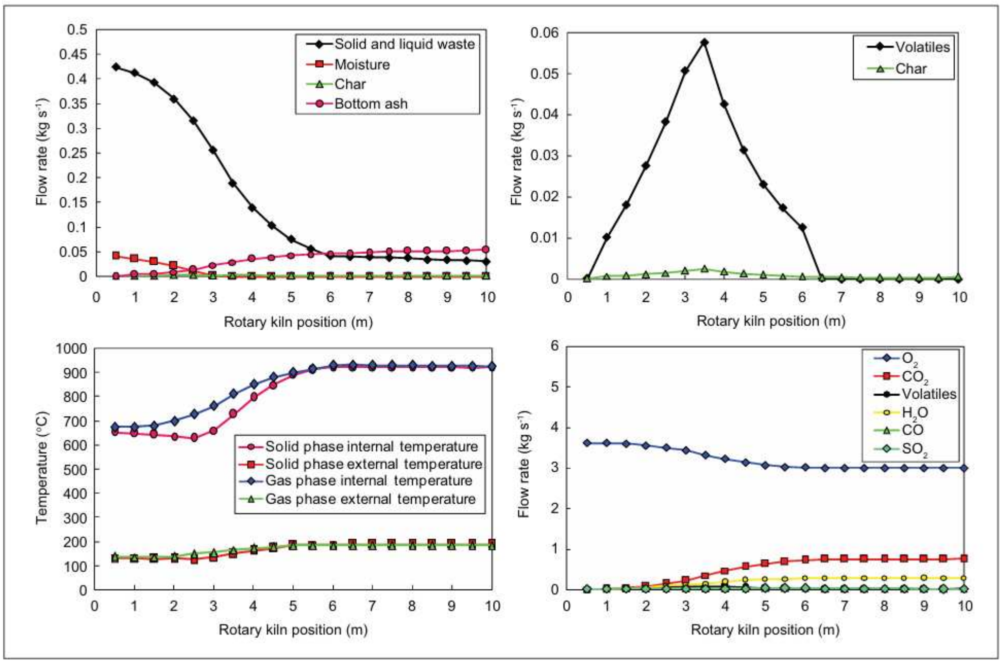


Figure 2.11: Model results for an excess air ratio of 1.35; O_2:oxygen; CO_2:carbon dioxide; H_2O:water; CO:carbon monoxide; SO_2:sulphur dioxide and volatiles (solid/gas trends and temperature response) [7].

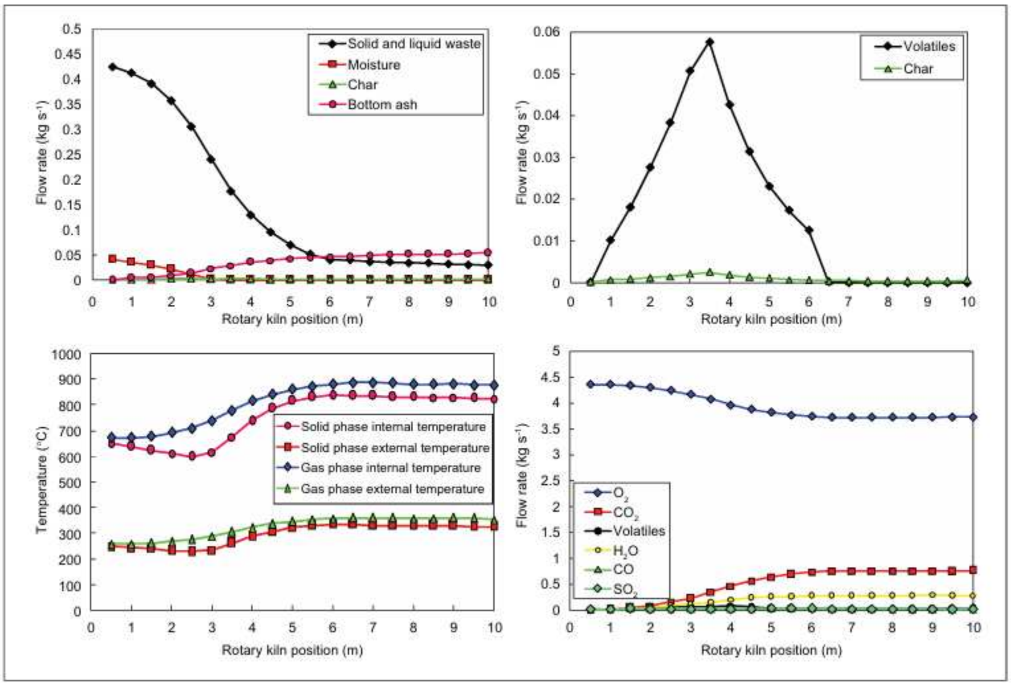


Figure 2.12: Model results for an excess air ratio of 1.; O_2:oxygen; CO_2:carbon dioxide; H_2O:water; CO:carbon monoxide; SO_2:sulphur dioxide and volatiles (solid/gas trends and temperature response) [7].

Beyond descriptive system layout, the article provides evidence that combustion behaviour depends strongly on operating and design parameters that are directly connected to logistics and automation control strategies. The authors assess how variations in waste input rate affect the formation of intermediate solid fractions during conversion, reporting that increased waste feeding produces greater quantities of volatile and carbonaceous fractions available for combustion and results in higher kiln temperatures. This supports the practical implication that throughput adjustments must be coordinated with thermal stability requirements, particularly in continuous feeding systems [7].

The study also identifies the excess air ratio as a crucial operating parameter for maintaining complete combustion while maximizing energy recovery. Insufficient air supply is associated with incomplete combustion and increased quantities of incompletely burned material in the discharged ash, whereas very high air supply values promote completion of combustion but can reduce kiln temperatures through cooling, lowering overall heat recovery. These findings are directly relevant to process control in industrial applications, because air supply and feeding must be balanced to avoid instability, efficiency losses, and increased residue-handling burdens [7].

Table 2.3: Parameter variation used for sensitivity analysis [7].

Parameter	**Actual properties**	**Elaboration 1**	**Elaboration 2**
Waste flow rate (kg h^{-1})	1690	2100	1300
Excess air ratio	1.8	1.35	2.25
Refractory thickness (cm)	22	12	16.5
Refractory conductivity (W m^{-1} K^{-1})	$2.9 - 0.0006 \cdot T$	$5 - 0.0009 \cdot T$	$3.63 - 0.00075 \cdot T$
Insulating thickness (cm)	9.8	6	7.5
Insulating conductivity at 400°C (W m^{-1} K^{-1})	0.53	0.8	0.663
Insulating conductivity at 800°C (W m^{-1} K^{-1})	0.72	1.1	0.90
Insulating conductivity at 1000°C (W m^{-1} K^{-1})	0.84	1.4	1.05

BAT operating requirements and control practices (WI BREF). In addition to the rotary kiln design description, the Waste Incineration BAT Reference Document (WI BREF) provides an operational framing for how stable combustion is ensured in industrial practice. The document describes waste incineration as a set of overlapping stages that typically include heating and drying, release of volatile fractions, intermediate conversion of solids to gases, and final oxidation of combustible gases at elevated temperature. Because these stages can occur simultaneously, the Waste Incineration Best Available Techniques Reference Document (WI BREF) emphasizes the importance of furnace design and control engineering to stabilize combustion and limit the formation of undesirable by-products [8].

This table 2.4 compares various incineration chamber designs by looking at their geometric characteristics, how well they suit different waste types, and other practical aspects,such as specific air supply requirements.

Split-flow systems are used mainly in larger furnaces, since they enable additional secondary-air mixing in the central areas of the furnace. In smaller furnaces, sufficient mixing can often be achieved by injecting the secondary air through the side walls. A well-balanced combustion chamber design ensures that the gases released from the waste are thoroughly mixed and held at a high enough temperature for long enough in the combustion chamber, so the combustion process can be completed fully. This principle applies to all incineration processes [8].

For kiln-based systems, the WI BREF highlights that combustion quality depends on maintaining adequate temperature, sufficient time at temperature, and appropriate oxygen availability in the hot zone. It also describes the operational role of auxiliary burners, which are used during start-up to heat the system before waste feeding begins and can be switched on automatically dur-

Table 2.4: Comparison of the features of some different incineration chamber designs [8].

Type	Design features	Comments
Co-current or parallel flow	• Exit to combustion chamber at end of furnace • Gas flow in same direction as waste movement	• Suited to higher LHV wastes • Evolved gases pass through maximum temperature zone with long retention time • Primary air heating required in ignition zone
Countercurrent or counter-flow	• Exit to combustion chamber at start of furnace • Gas flow opposite to waste movement	• Suited to low-LHV / high-moisture / high-ash waste (hot gases assist drying) • Higher secondary air requirements for gas burnout
Medium current or centre-flow	• Exit to combustion chamber in middle of furnace	• Compromise for wide spectrum of waste • Secondary air / configuration important to ensure gas burnout
Split-flow	• Exit in middle position but split by central section	• Central section aids retention; allows additional secondary air injection locations • Mainly used for very large furnaces

ing operation if the combustion temperature falls below a specified threshold. During shutdown, auxiliary burners can be used to maintain temperature until the system no longer contains unburnt waste. This Best Available Techniques (BAT) description aligns with the supervisor's emphasis on continuous temperature control and on maintaining high-temperature residence conditions in the post-combustion stage [8].

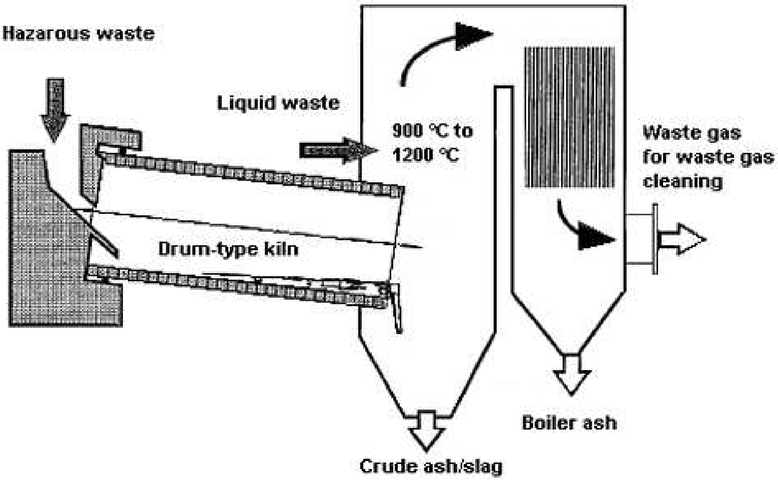


Figure 2.13: Rotary (drum-type) kiln with post-combustion chamber (schematic) [8].

BAT framing for treatment of gaseous, solid, and liquid streams (WI BREF). Beyond the furnace itself, the WI BREF frames incineration plants as integrated systems in which the combustion zone and post-combustion chamber are followed by engineered downstream units for energy recovery and emissions control. In this approach, gaseous streams leaving the combustion system are routed through flue-gas treatment stages designed to control acid gases, particulate matter and other pollutants, while solid residues (e.g., bottom ash and fly ash) are handled through dedicated discharge and management systems. Where wet flue-gas treatment is applied, the WI BREF also recognizes that wastewater streams may be generated and therefore require appropriate treatment and management to avoid shifting impacts from air emissions to water discharge. From a logistics and automation viewpoint, this reinforces that stable combustion is inseparable from reliable handling of outputs, including controlled discharge of solids and the management of liquid streams arising from gas treatment [8].

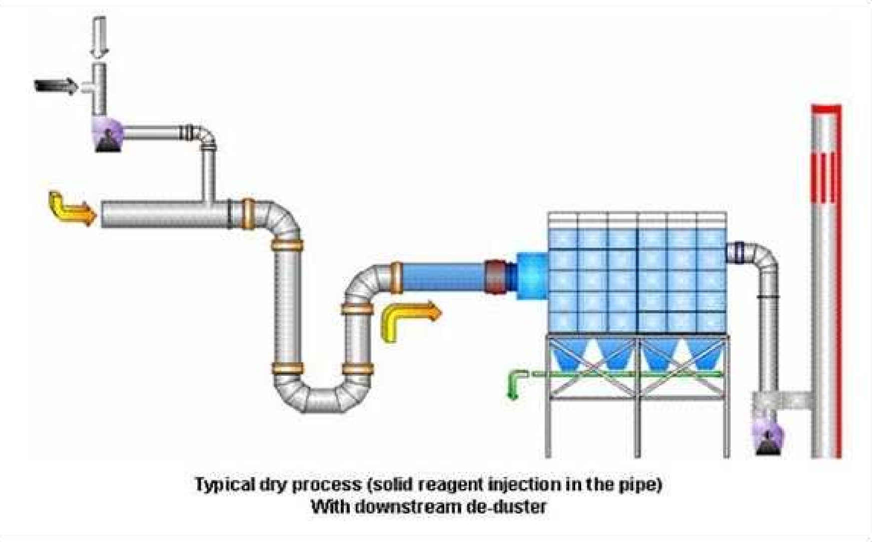


Figure 2.14: Typical design of a semi-wet flue-gas cleaning (FGC) system [8].

Finally, the refractory and insulation design is not only a structural requirement, but also a key operational variable. Changes in lining thickness and thermal properties affect heat dispersion through the kiln wall, which can delay combustion progression and reduce internal temperatures. Good-quality refractory and insulation materials reduce thermal dispersion and improve energy recovery, while lower-performing materials may be selected when operational constraints require lower chamber temperatures to limit damage risks such as corrosion, thermal stress, or accelerated lining consumption. This reinforces the thesis conclusion that stable combustion is an integrated outcome of design decisions, feed management, and control strategies rather than a function of the reactor alone [7].

This configuration illustrates that effective combustion performance depends not only on the oxidation reaction itself, but also on stable feeding, temperature monitoring, sufficient residence time for complete burnout, and reliable management of bottom ash and exhaust gases. These system requirements are closely connected to logistics and automation design, and they also provide a useful comparison point for the operational constraints discussed later for pyrolysis and gasification pathways [7, 8].

Excess-air management as an automation lever for stable combustion and compliance. In addition to furnace geometry, stable and homogeneous combustion in waste-to-energy practice is strongly influenced by how air input is controlled during operation. A design-oriented study on waste incineration emissions shows that the excess-air ratio is a key driver affecting the required combustion-air flow, the total flue-gas flow, and the flue-gas temperature. As excess air increases, the total mass flow of gases increases while the flue-gas temperature can decrease due to the cooling and dilution effect of additional air. This creates an operational trade-off that is directly relevant to industrial automation: the plant must keep conditions in a window that supports complete burnout and regulatory compliance, while also protecting energy recovery performance. The same study notes that real facilities operate within a practical range of excess-air settings that maintain furnace temperatures suitable for meeting regulatory expectations, reinforcing the supervisor's emphasis on continuous monitoring and active control to avoid unstable or incomplete combustion [5].

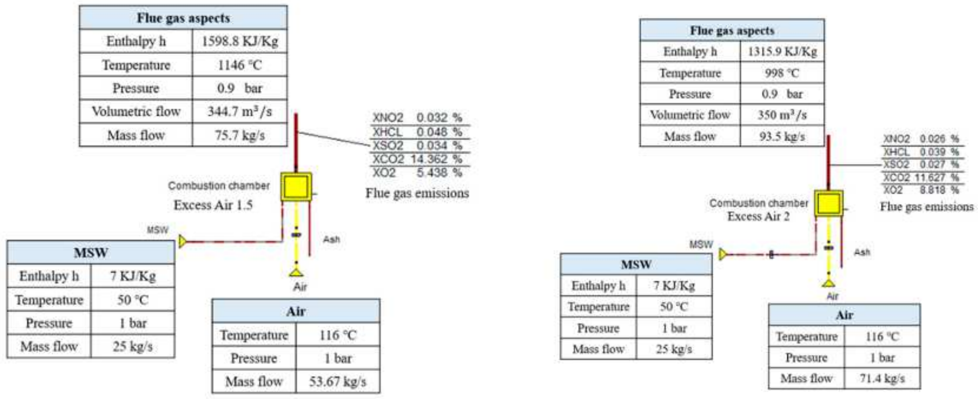


Figure 2.15: Ebsilon furnace simulation at two excess-air ratios [5].

The excess-air ratios considered are 1.5 (left side of the figure) and 2.0 (right side of the figure). This comparison illustrates the effect of the excess-air ratio on the required combustion-air mass flow rate, the flue-gas volumetric flow rate, the flue-gas temperature, and the resulting emissions for the same MSW mass flow rate.

[5].

Flue gas density has a significant impact when quantifying CO_2 emissions. As is widely known, flue gas becomes less dense as its temperature rises, which results in higher CO_2 emissions. This also directly affects the air ratio (excess air to stoichiometric air) in the combustion chamber (furnace): emissions decrease as the air ratio increases. For any waste incineration process, operating at 800 °C is preferable to operating at 1000 °C in terms of emissions, especially CO_2 emissions, while higher temperatures are generally preferred from an energy standpoint [5].

The results indicated that when the flue gas temperature was about 70 °C, its density was 1.3 kg/m^3 and the CO_2 emissions reached their lowest value, at 77 kg/s. In contrast, when the flue gas temperature rose to 1200 °C, the density dropped to 0.24 kg/m^3 and the CO_2 emissions increased to 203 kg/s[5].

This figure 2.17 provides a theoretical illustration showing that when the air ratio increased to 8, CO_2 emissions fell to their minimum value of 77 kg/s, whereas the maximum value of 203 kg/s occurred when the air ratio was around 1.2. For a real waste incineration plant, the optimal operating air ratio is typically 2–2.5, as this helps maintain the flue gas temperature in the furnace at about 900 °C, which is the ideal level required to comply with regulations [5].

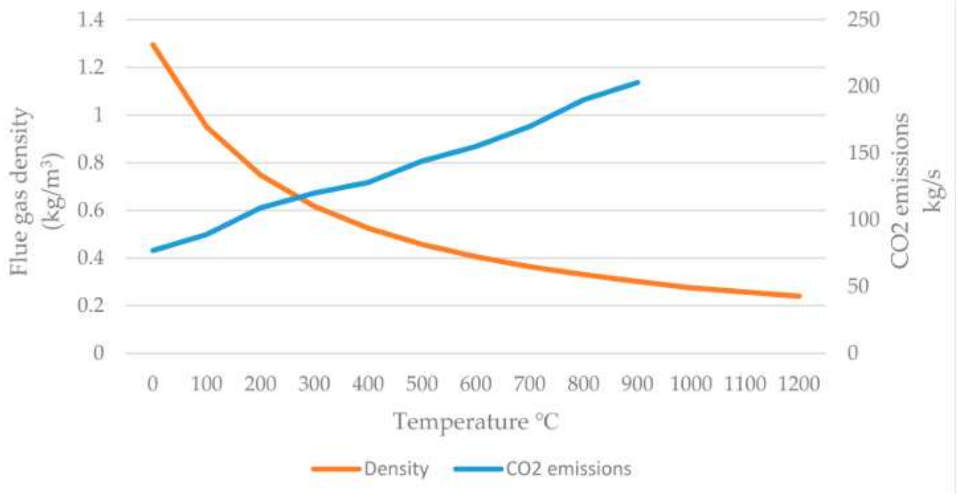


Figure 2.16: Flue gas temperature and density with CO_2 emissions (Ebsilon simulation) [5].

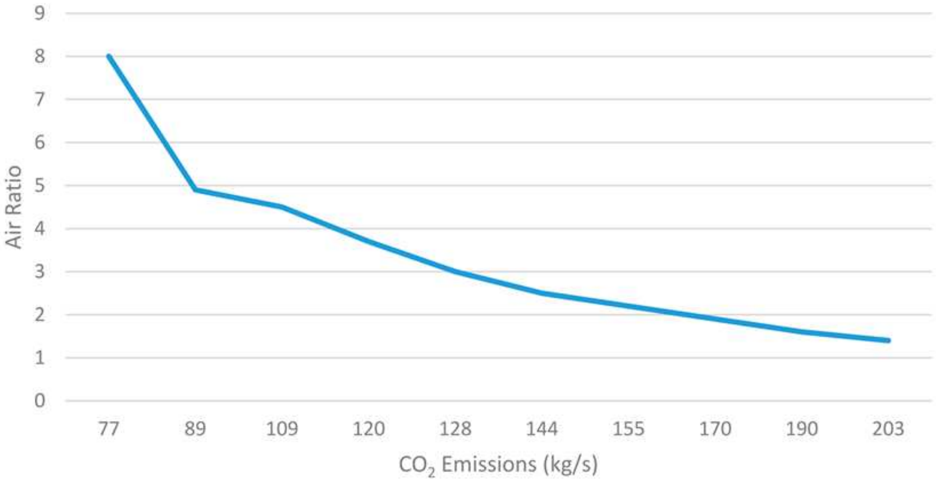


Figure 2.17: Air ratio and CO_2 emissions [5].

From post-combustion completion to engineered flue-gas treatment: implications for plant logistics. The same work frames incineration plants as integrated systems where the combustion chamber is only the first stage of an emissions-managed chain. It proposes two complementary design-phase approaches to estimate flue-gas load and emissions: a simplified calculation approach suitable for early design screening and a process-simulation approach that can represent downstream treatment stages. In the proposed system layout, hot flue gases leaving the combustion zone pass through energy-recovery steps (boiler/heat-exchanger equivalents) and then through a sequence of treatment units. These include particulate removal, staged treatment for gaseous pollutants, and optional capture-oriented stages in the tail end of the line. From a logistics and operations viewpoint, this integrated chain matters because each treatment stage introduces additional supply and handling requirements (for example, reagent delivery, residue collection, and maintenance planning), and the sizing of these downstream units depends on the upstream operating regime, especially excess-air control and the resulting flue-gas flow rate. This supports the thesis argument that stable combustion and environmental performance are achieved not only by reactor operation, but also by reliable downstream handling capacity and coordinated process control across the full plant line [5].

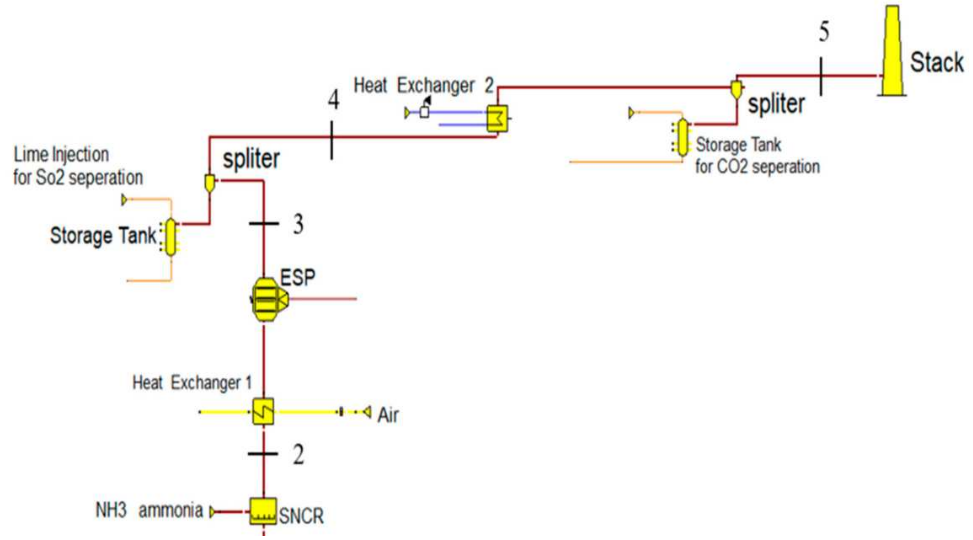


Figure 2.18: Flue-gas cleaning system chain for the proposed incineration facility (Ebsilon simulation) [5].

Table 2.5: Results obtained from the simulation of the flue-gas emissions cleaning system for 25 kg/s of MSW [5].

MSW (kg/s)	**Air (kg/s)**	**Air (°C)**	**Excess air**	**Flue gas flow (m^3/s)**	**Flue gas temp (°C)**	**CO_2 (mg/Nm^3)**	**NO_2 (mg/Nm^3)**	**SO_2 (mg/Nm^3)**	**HCl (mg/Nm^3)**	**Point**
25	51.5	120	1.5	310.5	1146	258514.40	749.90	890.20	717.00	1
25	51.5	120	1.5	310.5	1146	258514.40	180.00	890.20	717.00	2
25	51.5	120	1.5	137.4	325	258514.40	180.00	890.20	717.00	3
25	51.5	120	1.5	137.4	325	258514.40	180.00	44.50	7.16	4
25	51.5	120	1.5	85.0	129	6023.90	180.00	44.50	7.16	5
25	68.6	180	2.0	337.0	998	209294.70	606.80	720.50	580.00	1
25	68.6	180	2.0	337.0	998	209294.70	145.40	720.50	580.00	2
25	68.6	180	2.0	166.0	325	209294.70	145.40	720.50	580.00	3
25	68.6	180	2.0	166.0	325	209294.70	145.40	35.80	5.60	4
25	68.6	180	2.0	104.0	129	4728.20	145.40	35.80	5.60	5
25	85.8	190	2.5	375.0	931	175855.40	509.40	604.70	486.00	1
25	85.8	190	2.5	375.0	931	175855.40	122.30	604.70	486.00	2
25	85.8	190	2.5	195.0	325	175855.40	122.30	604.70	486.00	3
25	85.8	190	2.5	195.0	325	175855.40	122.30	30.30	4.80	4
25	85.8	190	2.5	124.0	129	3892.30	122.30	30.30	4.80	5

Kiln-related use of waste tires and temperature-dependent pollutant formation

Waste tires are widely discussed in the waste-to-energy literature as a high-calorific fuel that can be used in industrial combustion applications, including cement kilns and other rotary kiln operations[9]. In this context, the kiln pathway is attractive because waste disposal and energy recovery can be achieved simultaneously, and the steel reinforcement contained in tires may partially substitute the iron requirement in cement raw materials[9]. However, tire-derived fuel (TDF) differs from conventional fuels in combustion behaviour and ash chemistry, and reported kiln-scale challenges include poor heat distribution, unstable precalciner operation, blockages in preheater cyclones, build-ups in kiln riser ducts, increased gaseous emissions (SO_2, NO_x, CO), and dustier kiln operation[9].

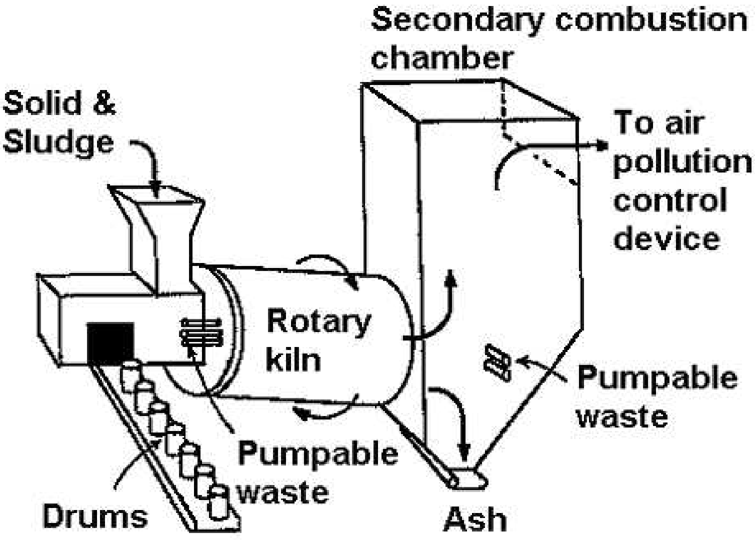


Figure 2.19: Schematic of a rotary kiln incineration system [8].

A key implication for kiln-based systems is that pollutant formation depends strongly on combustion temperature and oxygen availability[9]. The literature distinguishes between low-temperature, oxygen-limited burning (e.g., open burning piles where temperatures around ~600°C may occur) and engineered waste-incineration furnaces which can operate at much higher firebox temperatures (reported around ~1200°C)[9]. Because incomplete combustion at low temperature is associated with elevated toxic gas and particulate emissions, kiln configurations that maintain sufficiently high temperature and stable oxidation conditions are central for reducing incomplete-combustion products[9].

To clarify how temperature influences gaseous and solid pollutants from tire combustion, the investigations show waste-tire combustion under controlled laboratory conditions across a firebox temperature window of 650–900°C, measuring flue-gas components (CO, CO_2, NO_x, SO_2) and capturing solid-phase pollutants on a quartz/fiberglass filter for morphology and PAH analysis[9]. Although the experiments were not performed in a full-scale cement kiln, the temperature-controlled results provide directly relevant evidence for kiln practice because kilns and post-combustion chambers must be managed to suppress incomplete combustion and minimize toxic organic by-products while maintaining stable operation[9].

Gaseous emissions as temperature-dependent control targets. During tire combustion, the time-evolution of flue-gas components shows identifiable phases: CO maxima indicating ignition behaviour, while CO_2 and NO_x maxima (together with an O_2 minimum) indicate the intense combustion phase[9]. Importantly for combustion control, the CO signal exhibits a characteristic *double-peak* behaviour for tires[9]. The analysis links this to staged decomposition/oxidation of different tire constituents, and to the influence of $CaCO_3$ filler decomposition, which can contribute additional CO formation through interactions between released CO_2 and remaining fixed carbon under hot conditions[9]. From an automation viewpoint, this supports the need for continuous temperature monitoring and active air/fuel control (as emphasized in kiln BAT discussions) because the combustion process can shift between regimes with different pollutant-formation tendencies even when the same waste stream is used[9].

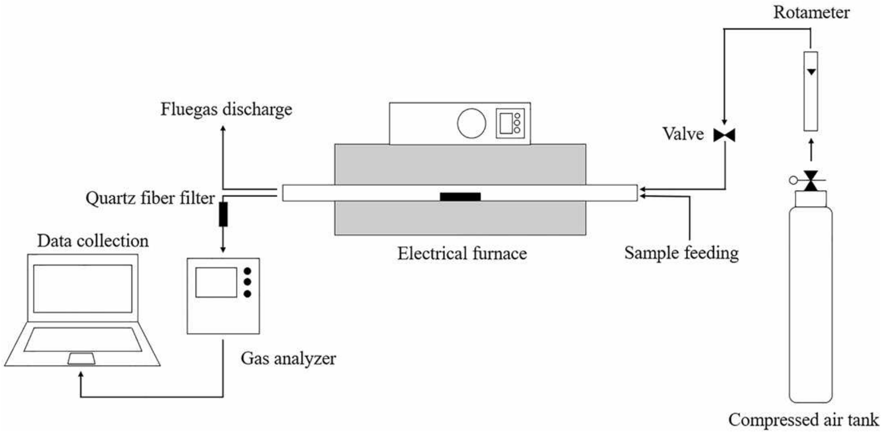


Figure 2.20: Schematic of the combustion experiments with flowing medium [8].

Across the investigated temperature range, the study reports that CO emissions decrease after ~700°C, while CO_2 emissions increase and NO_x exhibits a temperature-dependent maximum (reported near ~750°C in the emission-factor trends)[9]. SO_2 emission-factor values increase steeply up to around ~750°C in the reported results[9]. These observations are operationally relevant to kiln and post-combustion design because they show how emission control requirements can tighten as operating temperature changes, and they reinforce that air management and thermal stabilization are not only efficiency levers but also compliance levers[9].

Solid pollutants and PAHs as indicators of incomplete-combustion risk. Beyond gaseous pollutants, the study characterizes solid particles captured from the flue gas and reports that the emitted solids form spherical particles compressed into a reticular (network-like) structure, with the structure becoming denser as firebox temperature increases[9]. This temperature dependence is relevant for downstream gas-cleaning logistics because particle size distribution and morphology affect filtration, deposition, and maintenance needs in real plants[9].

Also a strong temperature effect on solid-phase polycyclic aromatic hydrocarbons (PAHs): the total concentration of PAHs on the collected solids decreases markedly as temperature increases (reported as dropping from a high level at 650°C to much lower values at higher temperatures)[9]. In addition, the PAH profile shifts with temperature: lower temperatures are associated with a higher share of multi-ring (heavier) PAHs, while higher temperatures are dominated by PAHs with fewer rings[9]. Since PAHs are often treated as harmful toxic compounds in waste-combustion contexts, this provides direct supporting evidence for the supervisor's recommendation to ensure high-temperature residence conditions (particularly in post-combustion zones) to destroy harmful organics and reduce the risk of incomplete-combustion by-products[9].

Relevance to kiln + post-combustion operation in tire-to-energy systems. Taken together, kiln-related discussion and the temperature-dependent pollutant evidence support three thesis-relevant implications for rotary-kiln-based tire combustion systems:[9]

- **Combustion stability and emissions are coupled:** kiln operation must be stabilized with adequate temperature and oxygen availability to avoid incomplete combustion that elevates CO and toxic organic pollutants.
- **Temperature management changes pollutant regimes:** as temperature changes, the balance among $CO/CO_2/NO_x/SO_2$ and the solid-phase pollutant profile changes, meaning that continuous monitoring and control (air ratio, auxiliary firing where needed) are critical.
- **Downstream treatment and maintenance depend on solids:** particle morphology and pollutant partitioning influence filtration load and cleaning frequency, linking combustion choices to logistics of maintenance and residue handling.

2.2.2 Pyrolysis Utilization

Pyrolysis is a highly promising WT utilization technique because it converts tires into three valuable products: gas, oil, and char. The process occurs in an oxygen-deficient environment, preventing combustion and enabling controlled decomposition of rubber polymers. The literature categorizes pyrolysis into several subtypes, including hydrothermal liquefaction, microwave pyrolysis, supercritical fluid pyrolysis, catalytic pyrolysis, and co-pyrolysis [2, 3].

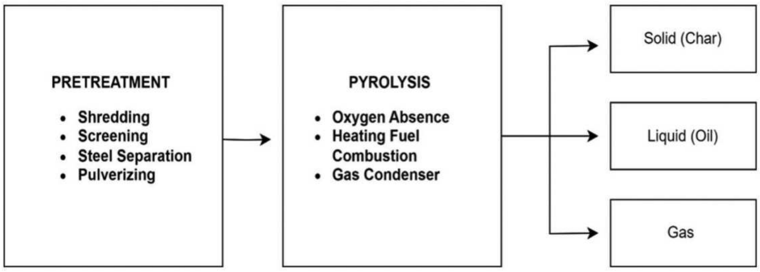


Figure 2.21: Stages of conventional pyrolysis process [1].

For a rotary-kiln pyrolyser, the slow rotation of an inclined kiln is highlighted as an operational advantage because it promotes mixing of the waste and can yield more uniform pyrolysis products. In addition, the residence time is described as a variable that can be regulated to reach operating conditions suited to the desired conversion behaviour; An automation-relevant control lever, analogous to "time-at-temperature" constraints discussed for combustion systems. [6].

Each pyrolysis route has distinct benefits. Microwave pyrolysis offers rapid and uniform heating, often increasing product yield compared to conventional methods. Hydrothermal and supercritical pyrolysis methods provide deeper decomposition but require high-performance reactors. Catalytic pyrolysis enhances product quality and reduces contaminants, while co-pyrolysis creates synergistic effects when WT are processed with biomass or plastics [2, 3].

Pyrolysis products have multiple energy and industrial applications. Oil can be refined or blended as fuel; char can be upgraded into activated carbon or used for environmental remediation;

and gas can serve as a heating fuel or be processed into higher-value materials. These diverse outputs position pyrolysis as a central technique in sustainable WT utilization [2, 3].

Innovation in tire pyrolysis reactor design: fixed-bed fire-tube heating and process optimization

An innovation-oriented experimental study proposed and tested a fixed-bed, fire-tube heated pyrolysis system for recovering liquid products from scrap tires [10]. In this work, scrap tires are treated as an important solid-waste stream, and pyrolysis is presented as a recovery route that produces a liquid fraction, a solid char fraction, and a non-condensable gas fraction under inert conditions [10]. The authors emphasize that reactor heating strategy and operating conditions strongly influence product yields and product quality, which is directly relevant for practical design and implementation [10].

The proposed setup uses internal fire-tubes that deliver heat inside the reactor, together with inert-gas purging and a condensation train for collecting the liquid fraction [10]. This heating configuration is discussed as a way to improve heat delivery and process stability, since insufficient or uneven heat transfer can increase incomplete conversion in larger tire pieces, while excessive secondary cracking at higher severity can shift yield from condensable liquids toward permanent gases [10].

The study reports that temperature, feed size, and vapor residence time act as key operational levers [10]. Over the tested range, the liquid yield increases with temperature up to an optimum region and then decreases at higher temperatures, consistent with increased secondary cracking of vapors into non-condensable gases [10]. The authors also show that feed size influences the balance between incomplete decomposition, in larger pieces, and secondary reactions, in smaller pieces, while longer vapor residence time tends to promote secondary reactions that reduce liquid yield and increase gas yield [10]. These results support a practical interpretation of "innovation" as the ability to control the process in a narrow operating window where decomposition is complete but excessive cracking is limited.

Beyond the reactor itself, the work reinforces that tire pyrolysis must be treated as a multi-stream system [10]. The liquid fraction is discussed in terms of fuel-related indicators, but the study also highlights constraints that motivate upgrading before broad fuel use, including issues linked to impurity content [10]. The non-condensable gas fraction is discussed as potentially useful for supplying process heat, supporting the concept of internal energy integration [10]. The char fraction is described as a stream with potential uses either as a fuel or as a precursor for higher-value carbon materials, which implies that storage, quality control, and downstream routing of char are important design considerations [10].

Although the study does not analyse rotary kilns, it provides transferable design logic that complements kiln-based thermal treatment discussions in this thesis: stable heat delivery, residence-time control, and integrated handling of gaseous, liquid, and solid outputs are decisive for practical waste-to-energy performance [10].

Table 2.6: Previous applications of pyrolysis using different feedstocks [3].

Feedstock	**Temp. (°C)**	**Max. Yield (%)**	**Remarks/Highlights**
Wastepaper	300–450	48.3 (TPO)	Heating rate of 10 to 30 °C/min. Oil yield increased from 42.18 to 48.3% once heating rate increased. No highlights on environmental performance.
Municipal Solid Waste (MSW)	500–600	40 (TPG)	Considerable carbon reduction impacts on both process and power generation. Pyrolysis showed higher impact than gasification. Ecosystem impact was the highest compared to the other impact categories.
Waste Tire (WT)	370–570	51.4 (TPO)	TPO yield reached 51.4% at 500 °C. Aromatic and aliphatic compounds were main components. Aliphatic compounds slightly decreased from 370 to 570 °C. Aromatic compounds slightly increased from 370 to 570 °C.
Waste Tire (WT)	400/500/600	57.1 (TPO)	Reaction temperature increase (400 to 600 °C) increased gas yield. Char yield decreased from 40.7% to 38.7%. Carbon content increased from 84.29% to 88.74%. Sulfur content decreased from 1.08% to 0.63%.
Waste Tire (WT)	400	41 (TPO)	Pyrolysis oil had high heating value. High volatile content. High ash content.
Waste Tire (WT)	450	54.5 (TPG)	Pyrolysis-based gasification produced 54.5% TPG. TPG used as fuel in the diesel engine.
Waste Tire (WT)	480–700	— (Nm)	Pyrolysis emerged as the most environmentally friendly scenario among other scenarios. Pyrolysis showed the highest net benefits with maintained recovery of valuable products.
Electrical and Electronic Waste	800	39 (TPG)	High tar yield was produced at 800 °C. High carbon transformation.
Sewer Sludge	500	70 (Char)	Char yield increased at higher moisture content. Gas yield increased with lower moisture content. High nitrogen contents were in gas products.
Agricultural Waste	600	— (Nm)	Gasification was more harmful to the environment than pyrolysis. Separation stage in fast pyrolysis was the most detrimental. Pyrolysis showed fewer emissions and energy consumption than gasification.

Rotary kiln reactors for waste-tire pyrolysis: continuous processing logic and control variables

Beyond cement-kiln co-combustion, rotary kilns are also discussed as a reactor option for *continuous* waste-tire pyrolysis. While fixed-bed reactors are widely used because of simplicity, their typical operating mode is less aligned with continuous industrial throughput. The literature therefore reports that the push toward continuous processing has contributed to the development and use of rotary kiln and fluidized-bed pyrolysis systems [6].

2.2.3 Gasification Utilization

Gasification converts WT into a synthesis gas composed mainly of hydrogen, carbon monoxide, methane, and light hydrocarbons. This process requires high temperatures and the presence of controlled gasifying agents, such as air, steam, carbon dioxide, nitrogen, or oxygen. Gasification proceeds through multiple stages: primary decomposition into hydrocarbons and carbonaceous solids, followed by secondary cracking, reforming, and carbon gasification reactions to generate syngas [2].

The syngas composition depends heavily on the gasifying medium. Air gasification produces more carbon monoxide and methane; steam gasification favours carbon dioxide and methane formation; and carbon dioxide gasification increases carbon reactivity. Reactor type also affects performance, with fluidized bed gasifiers offering improved conversion efficiency compared to fixed beds, while fixed beds remain more economical [2].

Innovative approaches such as chemical looping gasification offer potential for improved tar removal and enhanced syngas purity, although these methods remain in early development stages. Gasification can produce hydrogen-rich fuels and can support heat and power generation as well as chemical production. Despite these advantages, challenges remain regarding syngas purification, tar reduction, and fuel synthesis, which must be addressed for broader commercial application [2].

2.3 WT Thermal-Chemical Products Application

Thermal-chemical conversion of waste tires (WT) produces a wide range of products that can be utilized across energy, industrial, and environmental applications. These products differ significantly depending on whether the process is combustion, pyrolysis, or gasification. The reviewed literature organizes WT-derived products into solid, liquid, and gas phases, each with specific application pathways and economic potential.

Table 2.7: WT thermal-chemical products and their applications [2].

Technology	**Product**	**Main ingredient**	**Application**
Combustion	Resources	Heat as energy source	Cement production, combustion power generation
Combustion	Wastes	Toxic gases, particulate matter, heavy metals	Preparation of geopolymer (solidified contaminants)
Pyrolysis	Gas	Hydrocarbons, H_2, CO, CO_2, H_2S	Gas fuels, chemical materials
Pyrolysis	Oil	Aliphatic + aromatic hydrocarbons, hydroxyl compounds	Diesel and other liquid fuels
Pyrolysis	Char	Carbon, ash, sulfur	Activated carbon, ink pigments, solid fuels
Gasification	Syngas	Mainly H_2, CH_4, CO, CO_2	Hydrogen purification, gas fuel
Gasification	Char	Fly ash, bottom ash, carbon residue	Adsorbent preparation, catalyst
Gasification	Tar	Alkynes, cycloalkanes, N/O/S compounds	Tar reforming to hydrogen

The ability to turn WT into useful outputs not only reduces environmental burdens but also supports the development of circular economy strategies [2].

2.3.1 Products of Combustion

Combustion of WT generally produces two main types of products: a *gas phase* and a *solid phase*. The gas phase consists mainly of carbon dioxide, carbon monoxide, and other gaseous pollutants such as sulfur oxides and nitrogen oxides. These gases contain heat energy that can be captured for industrial uses. Due to their high calorific value, the heat released from WT combustion can be used in cement kilns and waste-to-energy power plants. In these applications, WT serve as an alternative fuel, substituting part of the primary energy input [2].

The solid-phase product of WT combustion is known as fly ash. Fly ash from WT contains heavy metals and other contaminants. Despite these pollutants, it can be used beneficially after proper stabilization. Fly ash can serve as an ingredient in geopolymer production or cement formulations, where it helps immobilize heavy metals and reduces the need for virgin raw materials. In future applications, WT fly ash concrete may achieve acceptable performance standards for broader industrial use [2].

Operationally relevant interpretation of gas- and solid-phase outputs in kiln systems. Beyond classifying outputs as gas or solids, kiln-based studies emphasise that output behaviour depends on operating choices. The rotary kiln modelling results illustrate how solid fractions evolve along the reactor length toward the final solid residue stream, and how air management influences the gas-phase conditions relevant to completeness of burnout and downstream energy recovery. For logistics design, this supports treating ash discharge, residue staging, and flue-gas routing as capacity-constrained subsystems that must remain aligned with feeding and air-control strategy [7].

While combustion products have certain energy and industrial uses, their overall application potential remains limited by environmental and regulatory constraints. This is because significant emissions control measures are required to manage harmful gases and particulate pollutants generated during the combustion process [2].

2.3.2 Products of Pyrolysis

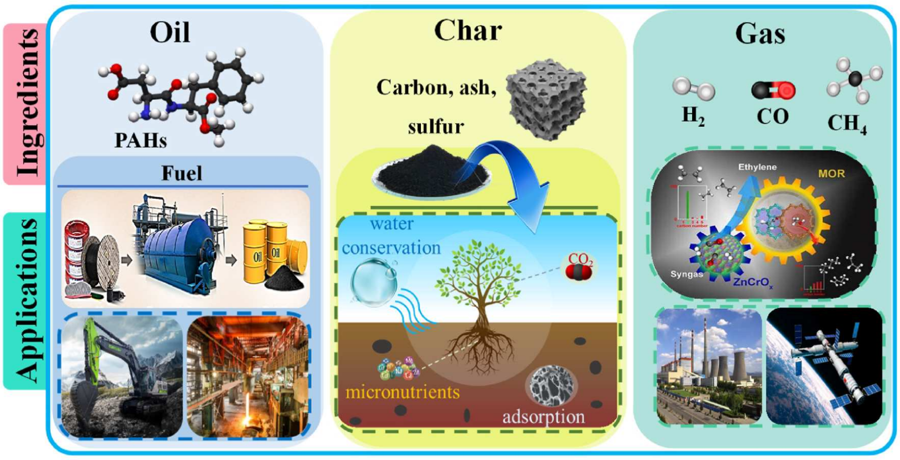


Figure 2.22: Products applications of WT pyrolysis [2].

Pyrolysis produces three major product streams: gas, oil, and char. These products are highly versatile and form the basis of many studies on WT valorization [2, 3].

Pyrolysis Gas

The gaseous phase of WT pyrolysis contains hydrogen, carbon monoxide, carbon dioxide, hydrogen sulfide, methane, ethylene, and other light hydrocarbons. These gases possess high calorific value and can be burned directly as a fuel for heating or energy generation. Their energy potential can be significantly improved by removing carbon dioxide, which increases the heating value of the syngas. Pyrolysis gas can also serve as a feedstock for chemical synthesis or be refined into higher-value energy carriers [2, 3].

Table 2.8: Chemical composition and mixture densities of the pyrolysis gas [1].

Component	Primary data (% vol.)	Density (kg/m^3)	Mixture density
Methane	31.56	0.65600	0.2070336
Hydrogen	20.80	0.08375	0.01742
Ethane	13.60	1.3562	0.1844432
Carbon dioxide	12.20	1.9770	0.241194
Carbon monoxide	7.10	1.1450	0.081295
Propane	4.83	2.0098	0.09707334
Propene	2.84	1.8100	0.051404
Ethylene	2.15	1.1780	0.025327
1-Butene	1.36	2.6748	0.03637728
2-Fumaric acid	1.39	1.6250	0.0225875
Butane	0.92	2.4800	0.022816
Nitrogen	0.87	1.1900	0.010353
Isobutane	0.31	2.5100	0.007781
Cis-2-butene	0.07	4.2830	0.0029981
Pentane	0.06	3.1780	0.0019068

Temperature plays a central role in gas composition: hydrogen production increases with rising temperature, and the decomposition of long-chain molecules generates free radicals and monomers. Certain volatile by-products, such as isoprene and stirene, may appear and then decline as temperature changes. Slow pyrolysis tends to favor hydrogen production compared to fast pyrolysis, reflecting differences in reaction pathways [2, 3].

Pyrolysis Oil

Pyrolysis oil is one of the most important products due to its potential to replace conventional fuels. The oil primarily consists of long-chain hydrocarbons and can be upgraded through purification or refining processes. Purified pyrolysis oil may be used directly as a fuel or blended with diesel for internal combustion engines. It also serves as a source of valuable chemicals, depending on its composition. According to the reviewed literature, pyrolysis oil properties are influenced by factors such as temperature, catalysts, heating rate, and reactor type. This variability allows optimization for targeted industrial uses [2, 3].

Pyrolysis Char

Char is a solid residue rich in carbon and has a wide range of industrial applications. Char can be upgraded into high-value activated carbon used for filtration, environmental remediation, and gas purification. Due to its high carbon content (up to 85 wt% in some gasification-related processes), char can also be used as an adsorbent, reinforcing filler, or precursor for advanced carbon materials. The growing interest in char upgrading methods aims to expand its market potential, noting that recovered carbon black (rCB) can be improved further for specialized applications such as CO_2 capture [2, 3].

Implications for solid outputs: char/ash quality as a handling and upgrading driver. The same review emphasises that the solid-phase product, char and pyrolytic carbon black, can contain substantial ash compared with virgin carbon black, and that ash levels depend on reactor type and process conditions. This matters logistically because higher ash fractions affect downstream handling, storage and transport, and the feasibility/cost of upgrading routes such as activated-carbon production. The article reports that ash originates both from Tire additives and from dirt on waste Tires, reinforcing the importance of upstream cleaning and feedstock quality control [6].

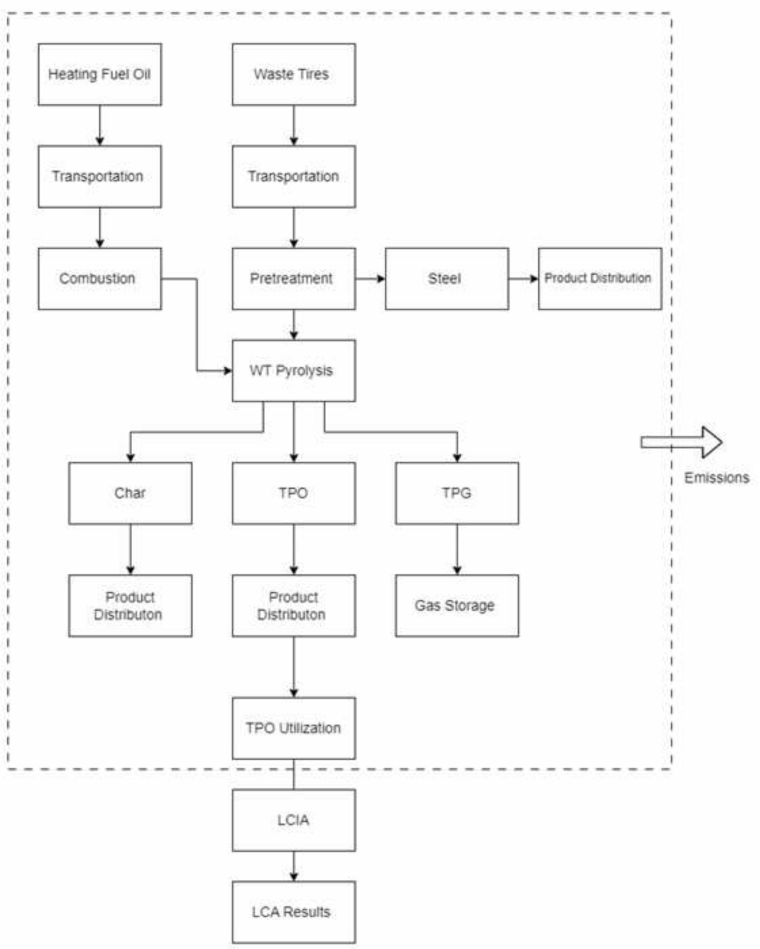


Figure 2.23: System boundary for waste-tire fast pyrolysis to produce heavy fuel oil (HFO), highlighting transport, pretreatment, process, and product handling [3].

2.3.3 Products of Gasification

Gasification produces three main product categories: syngas, char and tar. Each has specific uses depending on its composition and quality [2].

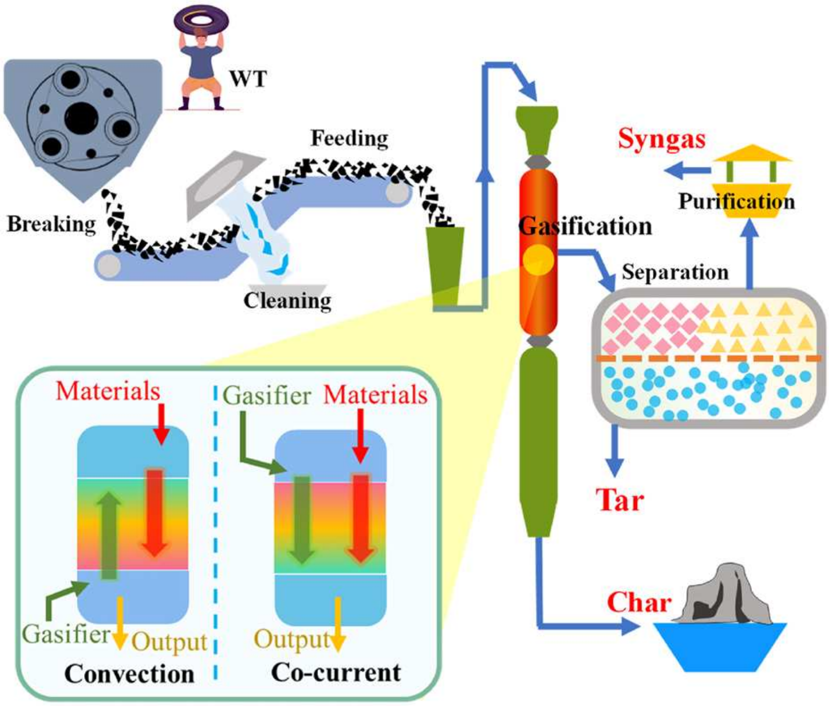


Figure 2.24: Gasification reaction systems and reactors [2].

Syngas

Syngas is the principal product of gasification and consists primarily of hydrogen, carbon monoxide, and methane. It can be used directly as a fuel for electricity and heat generation or as a feedstock for producing chemicals such as methanol, ammonia, or synthetic fuels. The reviewed paper describes syngas as a clean energy source with great potential, although its calorific value and purity must often be improved through gas cleaning and upgrading technologies. Syngas from WT also provides a route for hydrogen recovery, making it attractive for future energy systems [2].

Char

Similar to pyrolysis char, gasification char is rich in carbon and has wide industrial applications. It can be used in activated carbon production or be incorporated into metallurgical and environmental processes. Despite sometimes being overlooked in research, char from gasification represents a valuable resource given its stability and carbon content [2].

Tar

Tar is a heavy, complex by-product composed of high-molecular-weight hydrocarbons. Tar has a very limited application range because of its complex structure and low stability. In most cases, tar must be removed or processed further because it can foul equipment and complicate syngas utilization. The paper notes that tar reduction remains one of the major challenges in gasification systems and that catalytic reforming may provide promising solutions [2].

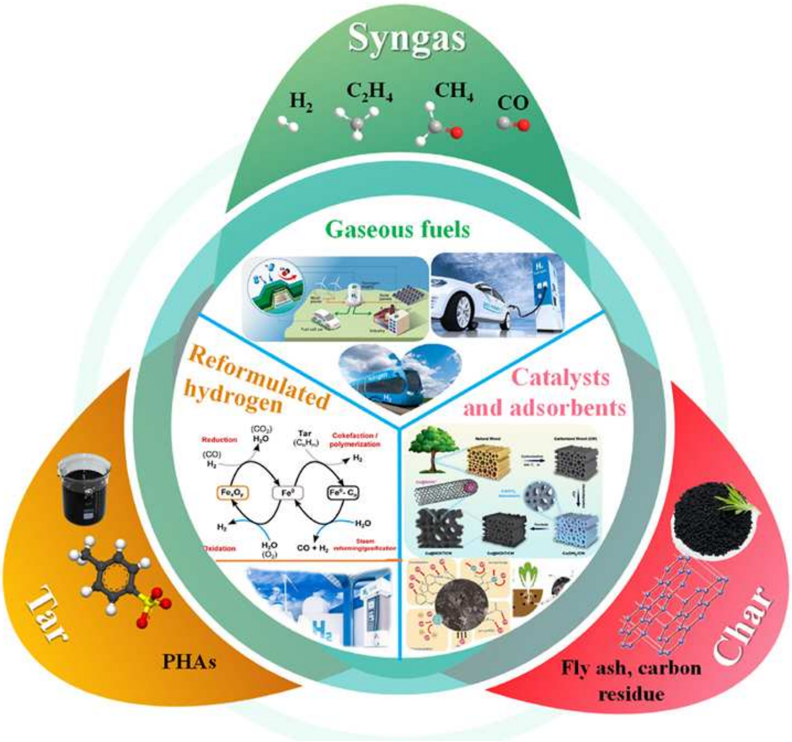


Figure 2.25: Applications of WT Gasification products [2].

Overall, the products from combustion, pyrolysis, and gasification offer diverse applications across energy, chemical, and material industries. Among them, pyrolysis and gasification products -especially oils, syngas, and char- are highlighted as having the highest long-term value and lowest environmental impact [2].

2.4 Materials and Methods

This section (Figure 2.26) describes the materials and procedures used in the thermal conversion tests of waste tires mixed with biomass. The objective of these methods was to understand how tires behave during combustion, pyrolysis, and gasification, and how these behaviours influence the practical logistics of operating an energy-recovery system. The article on which this review is based carried out laboratory scale and pilot-scale tests using controlled mixtures of tires and forest biomass. These procedures highlight several logistical issues such as fuel preparation, pre-treatment, and handling constraints that directly affect the feasibility of a tire-to-energy plant. Gasification and combustion tests were carried out using tires and a blend of crushed plastic and rubber waste from outdoor luminaires. Because it was difficult to run the experiments using only this waste, it was mixed with forest biomass for the tests.[4].

2.4.1 Waste Tire Preparation and Characterization

Tire material was obtained in fragmented form (between 1-4 cm after screening) because the reactors used in the study required uniform particle size. Mechanical screening was therefore necessary to remove oversized pieces and ensure that the fuel could be fed safely and consistently into the reactors without blocking or damaging mechanical components. Where necessary, manual sorting was performed to remove metal reinforcement materials, which are commonly present in tires and can cause operational failures if not removed [4] (Table 2.9).

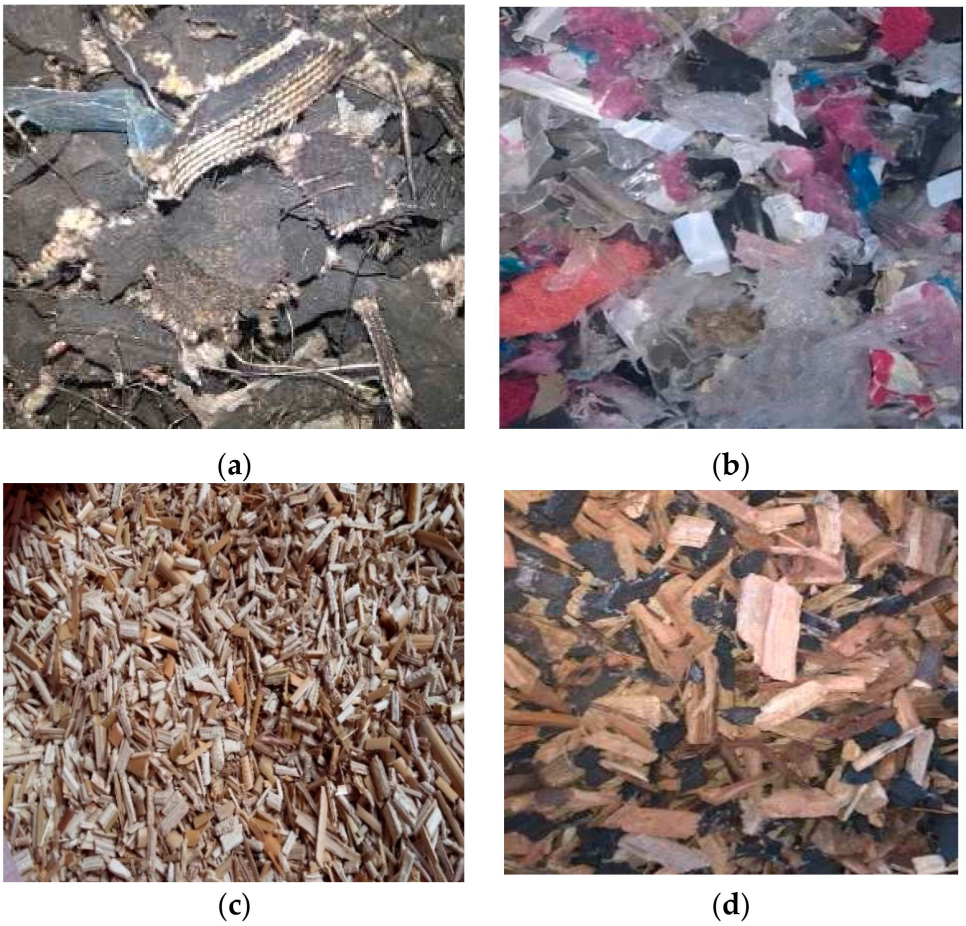


Figure 2.26: Raw materials selected for co-gasification in the reactor: (a) waste tires; (b) plastic–rubber waste; (c) Miscanthus biomass; (d) Acacia biomass. Reproduced [4].

Table 2.9: Biomass analysis (proximate/ultimate analysis and HHV). Reproduced [4].

Category	**Parameter**	**Acacia**	**Miscanthus**	**Used tires**	**Plastics & rubbers**
Proximate	Moisture (%)	9.8	14.2	0.5	0.6
Proximate	Volatile matter (%)	72.6	70.8	59.3	92.1
Proximate	Fixed carbon (%)	17.0	14.2	31.6	0.7
Proximate	Ashes (%)	0.4	0.8	8.5	6.6
Ultimate	Nitrogen (%)	0.09	0.55	0.6	0.6
Ultimate	Carbon (%)	46.7	43.1	81.6	72.3
Ultimate	Hydrogen (%)	5.8	5.5	0.7	7.4
Ultimate	Sulphur (%)	0.00	0.04	1.9	0.6
Ultimate	Oxygen (%)	46.1	50.8	7.1	12.5
	HHV (MJ/kg)	20.1	18.0	32.3	38.1

The residues were evaluated for heating value and basic composition through standard laboratory analyses. Although the exact numerical values are not reproduced here, the article confirms that waste tires show high energy content and contain organic compounds that support efficient energy recovery. This high energy density has important logistics implications: smaller mass flows are needed for the same heat output, but feeding systems must be capable of handling the dense and rubbery texture of tire fragments [4].

2.4.2 Combustion Tests

Combustion experiments were carried out in a multi-fuel pellet boiler (steel construction, with automatic feeding and air control systems). The boiler was initially operated with 100% biomass to reach stable operation at approximately 500 °C, after which controlled mixtures of biomass and tire fragments were introduced. The percentage of tires in the mixture was gradually increased until technical limitations of the boiler prevented further testing [4].

(a) (b)

Figure 2.27: Boiler operation and gas analyzer location: (a) multi-fuel boiler in operation; (b) portable gas analyzer [4].

During the tests, several operational conditions were continuously monitored, including:

- combustion chamber temperature,
- inlet and outlet water temperature,
- airflow and air temperature,
- water flow rate used for heat extraction,
- flue gas composition.

These tests were designed not only to measure energetic performance but also to observe real operational challenges related to logistics and process stability. For example, higher tire percentages led to feeding irregularities, ash clumping, and the need for manual intervention—issues that logistics planning must consider when selecting equipment or designing pre-processing steps [4].

Flue gas analysis was carried out using a portable gas analyzer equipped with sensors to measure oxygen, carbon monoxide, carbon dioxide, sulfur dioxide, and nitrogen oxides. The data collected from these instruments allowed the study to assess environmental emissions and identify pollutant trends linked to the presence of tires in the mixture. These results are critical for determining the type of emission-control infrastructure required in a full-scale facility [4].

2.4.3 Combustion of Waste Tires

The combustion tests showed that adding tire material to biomass increases the power output of the system. When tire content reached 40% and 60%, the boiler produced significantly higher thermal power compared to biomass alone. This is because tires have a much higher energy content than typical biomass fuels. However, this energetic improvement came with operational challenges that have strong logistics implications [4].

A key observation was the difficulty in automatic fuel feeding as tire content increased. At mixtures above 40% tires, feeding interruptions and blockages occurred frequently, and constant operator intervention was necessary to ensure continuous operation. This indicates that industrial systems using high tire fractions would require reinforced feeding mechanisms or additional preprocessing steps such as shredding or pelletizing to prevent disruptions [4].

Another major issue was the formation of fused and aggregated ash. Tires contain compounds that, when burned, melt and agglomerate, forming heavy clumps inside the combustion system. These clumps can block air channels, restrict fuel movement, and force shutdowns if not manually removed. From a logistical standpoint, this means that systems running on tires require robust ash-handling routines, frequent cleaning cycles, and trained personnel to avoid downtime [4].

Regarding emissions, sulfur dioxide (SO_2) levels increased continuously with higher tire fractions. This is consistent with the high sulfur content of tires. At 60% tire mixture, SO_2 levels exceeded regulatory limits, highlighting the need for substantial flue-gas cleaning equipment. Logistics planning must therefore include the integration of scrubbers or similar systems, which influence cost, facility layout, and maintenance routines [4].

Nitrogen oxide (NO and NO_x) emissions also rose slightly but remained relatively stable due to the high temperatures reached during combustion. Their behaviour depended partly on the size of tire particles fed into the system. Larger particles tend to produce more NO_x, meaning that uniform, reduced particle size can improve emissions performance. This again points to the logistical importance of proper shredding and size control before combustion [4].

Overall, combustion results demonstrate that while tires significantly increase power production, they introduce feeding, ash, and emissions challenges that require strong logistical planning. Systems with high tire content must incorporate advanced feeding technologies, strict pretreatment, and enhanced gas-cleaning solutions [4].

2.4.4 Gasification Tests

Gasification experiments were performed using a downdraft gasifier, the AllPowerLabs PP20 Power Pallet, which includes a biomass silo, a drying system using recirculated hot gas, and an internal combustion engine for power generation. The unit requires well-prepared and uniform fuel, making the correct pre-treatment of tire fragments an essential logistics requirement [4].

Each gasification test began with 100% acacia biomass to achieve steady operation at around 800 °C. Mixtures containing increasing percentages of tire material were then introduced. Tests continued until the process became unstable, the flare was no longer visible, or feeding problems occurred. These stopping conditions are important indicators of the maximum practical tire share that a drying and feeding system can handle without significant operator intervention [4].

During the gasification tests, the following parameters were measured:

- temperatures in the oxidation and reduction zones of the reactor
- reactor pressure and pressure drop across the filter
- airflow rate
- fuel feed rate
- syngas composition collected at stabilization and at shutdown.

Syngas samples were collected from the particulate filter and stored in sealed bags for laboratory analysis. Gas chromatography was used to identify the major gas components, allowing assessment of the heating potential of gases produced from tire-containing mixtures. From a logistics perspective, syngas composition influences the design of downstream cleaning systems, gas storage, and power generation units [4].

2.4.5 Gasification of Waste Tires

Gasification tests provided detailed insight into the behaviour of tire-containing mixtures under high-temperature, low-oxygen conditions. The downdraft gasifier used in the study was able to operate smoothly with moderate tire percentages, but increasing the tire share above 40% caused significant instability, similar to the combustion tests. The flame signal disappeared, and feeding problems occurred, forcing the test to stop. This shows that logistics planning must limit tire content or ensure robust feeding technologies for reliable operation [4].

At tire shares of 20%, the syngas produced reached its highest quality, with a better heating value and higher concentrations of useful gases. When tire percentages increased beyond this optimal point, the calorific value of the syngas began to decline. This decline was associated with incomplete conversion and increased amounts of unreacted material remaining inside the reactor. This means that for an industrial plant, excessive tire content not only destabilizes operations but also reduces the quality of output gas, undermining energy efficiency [4].

Feeding behaviour again played a decisive role. As tire percentages increased, the fuel feeding rate decreased despite the higher energy content of the material. This reduction was linked to difficulties in maintaining continuous flow through the hopper and feeding screw. Tire fragments tend to clump or deform under heat, which reduces feed consistency. These findings demonstrate that gasification systems relying on tires require enhanced hopper designs, vibration-assisted feeding, or fuel pre-conditioning to avoid blockages [4].

Syngas composition reflected the influence of tire content. Mixtures containing tires produced gases with moderate levels of carbon monoxide, hydrogen, methane, and small amounts of ethylene. These components confirm that tires can successfully be converted into usable syngas, but the proportion of tire material must remain within stable operational limits. A key observation was that hydrogen and carbon monoxide concentrations tended to increase at moderate tire contents but then declined at higher shares because of process instability [4].

Ash-related issues were also significant. Similar to combustion, fused ash formed inside the gasifier with high tire concentrations. These agglomerates obstructed the air flow and fuel descent, forcing shutdowns. Therefore, ash management becomes a central logistical concern for any facility co-processing tires in a gasifier [4].

Overall, the gasification results emphasize that tires can serve as a viable feedstock for syngas production but only when blended with biomass at controlled proportions. Process stability, feeding systems, and ash handling strongly limit the maximum share of tires [4].

2.4.6 Pyrolysis of Waste Tires

Pyrolysis of tires produces useful gas and liquid fractions, although pyrolysis requires carefully controlled thermal conditions and consistent feeding of clean, uniform tire particles. While pyrolysis may offer flexible fuel products, it also requires separate handling systems for oils, gases, and solid char. These requirements imply complex logistics involving cleaning, storage, and transportation steps that increase the overall system cost compared to combustion or gasification. [4, 2, 3].

The gas fraction tends to be rich in useful components, while the solid fraction retains unconverted carbon. Tire pyrolysis generally produces less hydrogen than gasification but more condensable liquids.[4, 2].

From a logistics perspective, pyrolysis differs significantly from combustion and gasification because [4, 2]:

- it requires separate storage and handling of liquid products
- the solid char must be collected and transported for reuse or disposal,
- the reactor does not tolerate metal contamination requiring strict pre-sorting of tires.

In addition, pyrolysis systems need stable feeding of uniformly sized tire pieces, which reinforces the need for controlled shredding operations. These requirements strongly influence the design of the logistics chain of a tire-to-energy plant. [4, 2].

2.4.7 Comparison Across the Three Thermal Processes

Across combustion, pyrolysis, and gasification, several common patterns emerge [4]:

- Tires provide high energy output but reduce feeding reliability without proper pre-treatment.
- Fused ash formation is a recurring operational issue in both combustion and gasification.
- Gasification performs best with moderate tire shares (around 20%), while combustion can tolerate slightly higher levels but requires more manual intervention.
- Pyrolysis produces more liquid products but requires the most controlled feeding conditions.

From a logistics standpoint, the choice of thermal process determines the structure of the entire supply chain. Combustion requires strong emission-control systems, pyrolysis requires liquid-handling facilities, and gasification requires stable feeding and gas-cleaning equipment. The results clearly show that the practical feasibility of each method depends not only on energy performance but also on logistics compatibility at industrial scale [4].

2.4.8 Logistics-Relevant Observations from the Methods

Across all methods, several logistical considerations emerge:

- **Fuel Preparation**: Size reduction and metal removal are mandatory before thermal processing to protect equipment.
- **Feeding Reliability**: High tire shares cause feeding interruptions, meaning that full-scale plants must invest in robust feeding systems or limit tire proportions.
- **Ash Handling**: Tires produce fused ash that can obstruct air and fuel systems, requiring enhanced ash-management logistics.

- **Emission Control**: High sulfur content in tires increases the need for gas-cleaning infrastructure, influencing plant layout and permitting.
- **Process Stability**: Tests were frequently stopped due to instabilities, demonstrating that the operational window for tire mixtures is limited by practical logistics constraints[4].

Model-based insight into throughput flexibility, control levers, and maintenance-related constraints. In addition to experimental work, literature also provides model-based evidence that operational flexibility is bounded by stability and compliance constraints. Rotary kiln modelling indicates that moderate variations in feed input can be feasible without violating required operating limits, but only when air supply and thermal conditions are managed to avoid incomplete burnout and loss of useful heat recovery.

Lining and insulation design is not only a structural choice: it influences heat dispersion, internal thermal behaviour, recoverable energy, and the risk of accelerated wear that can increase maintenance burden and downtime. From a logistics and automation perspective, these findings reinforce that throughput planning, control tuning, and maintenance scheduling must be treated as a coupled system [7].

Overall, the methods adopted in the article provide a clear understanding of how waste tires behave under different thermal processes and what logistical measures must be considered when designing a tire-to-energy system [4].

2.5 Automatic systems for gripping tires and feeding them into the furnace consisting of the rotating drum

Industrial rotating-drum furnaces (rotary kilns) require a feeding system that can (i) transfer bulky, heterogeneous solids safely from storage into the kiln inlet and (ii) meter the input to support stable thermal operation. The Waste Incineration Waste Incineration Best Available Techniques Reference Document (WI BREF) describes the rotary kiln as an inclined rotating cylindrical vessel in which the solid waste is conveyed by gravity as the kiln rotates, and it states that solid materials are usually introduced through a non-rotating hopper. The same reference provides practical examples of automated handling and charging hardware that directly match the concept of "gripping and feeding" into a rotary drum. In bunkers, waste can be mixed and managed using bunker cranes (e.g., grab cranes), and crane operators can identify problematic discrete items that may cause loading/feeding problems and ensure that these items are removed, shredded, or blended as appropriate. For more controlled charging, the WI BREF describes a feed-equalising control concept in which solid bulk waste is fed into a hopper using a grab crane through horizontal feed gates (normally closed to prevent gas leakage), and then hydraulically operated feed screws continuously crush/feed the material into the feed chute through fire doors. The fire doors are explicitly used to prevent backdraught and associated hopper fires, while hopper level measurement provides interlocks that stop upstream charging at high level and slow the screws at low level so that a buffer layer remains in the hopper as a barrier against gas leakage/backdraught . These elements (grab crane/gripper → sealed gates → hopper buffer → positive metering by screws/ram-type devices → fire doors/airlock) represent a technically grounded template for automated feeding of bulky solids such as tires into a rotary-drum furnace.

Tire-pyrolysis case studies further reinforce why automated feeding systems for rotating-drum reactors typically include upstream pre-treatment to make the material feedable and to protect equipment. In an industrial horizontal rotary pyrolysis kiln reactor described in the literature, waste tires are injected into the reactor only after a pretreatment stage [3]. The pretreatment stage includes shredding the tires into scraps, passing the material through a magnetic separation station to remove steel, and then pulverizing the rubber into finer particles; the study also notes that the power consumption of connected equipment such as conveyor belts, the magnetic separator, and the shredding machine is part of the pretreatment-stage demand [3]. Although this example is a pyrolysis application, the mechanical logic is directly transferable to rotary-drum furnaces more generally: pre-treatment (size reduction + steel removal) reduces bridging, improves bulk-flow behaviour, and enables more reliable metering through hoppers and screw/ram feeders before the material enters the rotating drum.

Finally, experimental combustion results show that tire-containing fuels can become difficult to feed automatically when tire share is high, which is a key operational reason to adopt reinforced gripping and dosing equipment. In co-combustion tests using a boiler with automatic feeding and air-control systems, It was reported that, for mixtures containing 40% and 60% tires, automatic boiler feeding became difficult, and constant operator intervention was required [4]. This finding supports the design implication that whole tires and tire-rich mixtures tend to cause feeding interruptions and blockages unless the system includes robust handling (e.g., grab/gripper-based charging), adequate hopper design/buffering, positive displacement metering (screws/ram feeders), and/or additional pre-processing such as shredding or pelletizing [4]. In summary, combining the WI BREF feeding architecture for rotary kilns with tire-specific pretreatment and the documented feeding-instability evidence [3, 4] provides a coherent justification and literature-supported description of automatic systems for gripping tires and feeding them into rotating-drum furnaces.

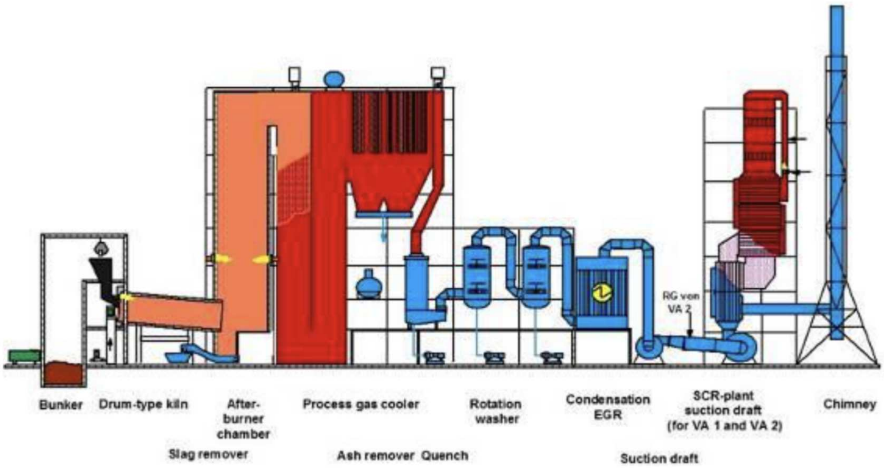


Figure 2.28: Example of a rotary (drum-type) kiln plant for hazardous waste incineration the WI BREF) [11].

2.5.1 Fully automated tire transport system ensures continuous feed of waste tires

Cement production requires high energy input, so HeidelbergCement aims to reduce the use of primary fuels such as coal by substituting alternative fuels, including waste tires [12]. The rubber's calorific value is described as being comparable to hard coal, and the steel reinforcement can be incorporated mineralogically into the cement, lowering the need for additional ferrous corrective materials [12]. According to the report, Beumer Group supplied a fully automated system that sorts, separates, and regulates tires of varying sizes and weights and delivers them to the rotary kiln inlet; the supplier also carried out the installation and provided the steel structure. As a result, the kiln is supplied with a constant material stream [12].

The plant director (Michael Becker) explains that each tonne of waste tires used replaces an equal amount of hard coal [12]. The company is headquartered in Heidelberg and is presented as a market leader with eight cement plants and three grinding plants. Waste tires are described as well suited for production due to their high heat content [12]. About 20,000 t of hard coal are said to be used annually at the plant to provide roughly 20% of the total required heat, which is stated to correspond to 20 million tires; this is presented as the basis for substituting primary fuel with tires as a secondary fuel [12].

The tires used include both production waste from manufacturers and end-of-life tires from trucks and cars [12]. Consequently, the report highlights wide variability: diameters from 300 mm to 1600 mm and widths from 100 mm to 400 mm, with average masses of about 8 kg for car tires and around 60 kg for truck tires [12].

To supply the rotary kiln inlet, HeidelbergCement previously operated two separate conveying solutions: one for smaller/lighter car tires and another for larger/heavier truck tires [12]. This arrangement was considered insufficiently efficient; car tires were reportedly placed individually by hand into a hook lift and then conveyed to the kiln inlet, while heavy truck tires were handled using an excavator before joining the transport stream [12]. The new fully automated system is presented as improving occupational safety and working conditions while also increasing performance, and prior positive experience with Beumer solutions at other sites is given as a factor in selecting the provider [12]. The report also states that Beumer supplies customised systems covering the full chain from receipt and unloading of deliveries through storage, sampling, conveying, and sorting of solid alternative fuels; the main requirements for the tire transport system were reliable operation across tire sizes, ease of maintenance, and comprehensive support. An eight-week window was scheduled for installation and commissioning [12].

The report describes a project timeline that began with an initial meeting in January 2015; the solution was developed and presented by April 2015, an offer was prepared by July 2015, and the contract was awarded at the end of that month., and work began at the start of August [12]. Beyond technical details, the fact that Beumer took responsibility for both supply and installation is emphasised [12]. The delivered scope is listed as including a feeding and dosing box for the wheel loader, hook separators, separating lines for Tires, and a flat belt conveyor with corrugated side walls (including a conveyor bridge), plus a tire transport system to the preheater tower and a tire sluice, along with various checking devices [12]. Assembly is stated to have begun in February 2016; the team integrated an electrical control system provided by the customer and was responsible for the steel structure and mechanics [12].

For continuous kiln feeding, wheel loaders take Tires from the collection area and load them into a feeding and sorting box [12]. The box volume is given as 140 m^3, intended to provide sufficient material for one shift. A hydraulically driven moving floor with plate fins conveys tires toward the outlet, while photocells installed at different heights monitor the fill level [12]. When a tire reaches the discharge area, a hook separator takes over, turns the tire upward, changes its direction at the drive station, and releases it onto a roller conveyor [12]. The hook separator is described as operating only when the roller conveyor issues a release signal and the photocell at the hook separator indicates the position is clear, preventing tires from dropping on top of one another [12]. The impact when the tire falls is stated to help drain water collected inside the tire and remove dirt. A checking device identifies tires that are damaged or still contain rims, and these are removed from the system [12].

Tires that pass inspection are conveyed from a timing roller conveyor to a flat belt conveyor with corrugated side walls, which provides an individual compartment for each tire [12]. A transfer chute in the discharge area guides the tires. The belt conveyor then transports the combustible material into the preheater tower [12]. A scale measures the mass of each tire on the conveyor; the value is recorded by the control system and used to regulate tire feeding [12]. The tires enter the tire sluice via an inlet chute, where an arched chute and a guide plate reorient them from a horizontal to a vertical position [12]. The report states that tires pass through the sluice one at a time, and at the rotary kiln inlet the flap valves are actuated so that only one is open at any moment to avoid heat losses and flashbacks (upper opens and closes, then the lower opens). A compressed-air tank is described as ensuring the flaps close in the event of a failure [12].

Installation and commissioning are reported to have been completed within the planned period [12]. The conveying capacity is stated as up to 3 t/h, corresponding to approximately 700 tires per hour, enabling the kiln to be supplied more quickly and with a continuous stream compared to the previous situation [12].

System engineering design (concept engineering to implementation)

Customer role: Heidelberg Materials / HeidelbergCement (plant owner and operator). In the ZKG plant report, HeidelbergCement is presented as seeking to reduce the use of primary fuels such as coal by using waste tires as an alternative fuel, noting that the kiln can then be supplied with a constant stream of material [12]. The report also highlights the practical constraints the operator faced: tires originate from both production waste and end-of-life car and truck tires and therefore vary significantly in size and weight, and the plant previously used two separate transport lines (one for car tires and one for truck tires), with manual hanging of tires into a hook lift and excavator handling of heavy truck tires [12]. The stated requirements for the new tire transport system were reliable operation across differently sized tires, easy maintainability, and comprehensive customer support, and the report notes that the electrical control system was provided by the customer and then integrated during implementation [12].

Complementing the plant-report description, Heidelberg Materials' AFR Policy states that the company aims to reduce consumption of fossil fuels and natural raw materials by co-processing waste-derived materials and that protocols and guidelines for transporting, unloading, storage, handling, analysing, and usage of AFR are in place and regularly reviewed, with health-and-safety rules and audits supporting responsible use [13]. The same policy defines co-processing as the controlled use of waste-derived alternative fuels and raw materials in clinker and cement production (burned as fuel and/or providing raw material), and defines pre-processing as preparing waste to make it suitable for co-processing [13]. On the corporate website, Heidelberg Materials defines alternative fuels as combustible materials used in place of fossil fuels in the clinker-burning process, explicitly listing used tires among examples [14]. This company describes the use of pre-processed and quality-controlled waste as alternative (secondary) fuels for clinker production and notes that high kiln temperatures and long retention times support complete burnout with low emissions, within official approval procedures [15].

System engineering role: BEUMER Group GmbH & Co. KG (system designer, supplier, and implementer). In the same ZKG report, BEUMER Group is described as supplying the fully automated system that sorts, separates, and regulates tires of different sizes and weights and feeds them to the rotary kiln inlet; the supplier is also reported to have taken over installation and provided the steel structure [12]. The report outlines the concept-to-implementation path: an engineering contract led to a developed solution and subsequent award, and BEUMER delivered the key mechanical subsystems (feeding and dosing box for wheel-loader charging, hook separators, separating lines, a flat belt conveyor with corrugated side walls including a conveyor bridge, a tire transport system to the preheater tower, a tire sluice, and checking devices) [12]. During assembly, the report states that BEUMER integrated the electrical control system supplied by the customer and was responsible for the steel structure and the mechanics [12]. The operating sequence described in the plant report connects directly to automated gripping/handling and controlled feeding: wheel loaders charge the feeding/sorting box; a moving floor conveys tires to discharge; a hook separator transfers tires to the conveying line under interlocked conditions; checking devices reject damaged tires or tires with rims; tires are conveyed in separated compartments and weighed for feed regulation; and a tire sluice with flap-valve sequencing at the kiln inlet limits heat losses and flashbacks [12].

BEUMER's cement-industry webpage on alternative fuels frames these functions as part of a system technology for co-processing tires, stating that continuous kiln operation requires continuous feeding and that an automatic handling system is recommended for large quantities [16]. The same page specifies key automation and handling elements: PLC-based electrical control; storage and supply functions controlled by photocells and sensors designed to tolerate dirt, dust, and temperature; and inspection switches on drives so a single segment can be handled manually in case of disturbance [16]. It also describes upstream and transfer logistics relevant to "gripping" and "feeding": scrap tires are handled after unloading primarily by a wheel loader or gantry crane with a polygon gripper; the stock area is sized as a buffer between discontinuous supply and continuous kiln consumption; steeply inclined conveyors transport tires to the defined inlet height at the preheater; and whole tires can be introduced via a swivel valve or a triple-flap arrangement in which the upper and central steps open/close to reduce heat loss and unwanted air entry while a lower step acts as a shutoff device for malfunctions [16].

The BEUMER website, on solid alternative fuels provides the same tire-specific system description and emphasises that the system technology for scrap tires covers the chain from tire supply and separation through rejecting improper tires and feeding the kiln, and that damaged tires and tires with rims are automatically rejected; it also describes that tires are turned during transport to remove dirt and water [17]. In addition, the brochure describes a flat belt conveyor with corrugated side walls lifting whole tires to the preheater feeding point and a hook lifter separating whole tires for controlled and continuous feeding, and it reiterates the PLC/sensor-based control of storage and supply functions [17].

2.6 Challenges and Prospects

Although thermal-chemical technologies for waste tire (WT) conversion have developed rapidly, the significant challenges remain before these methods can be deployed on a large industrial scale. These challenges appear across the entire WT value chain: from feedstock characteristics, process efficiency, and pollution control to product upgrading and market integration. At the same time, the literature identifies several promising research directions capable of improving efficiency, reducing environmental impacts, and enhancing the economic performance of WT-to-energy systems [2, 3].

This section summarizes the main challenges and future prospects associated with combustion, pyrolysis, and gasification of WT [2].

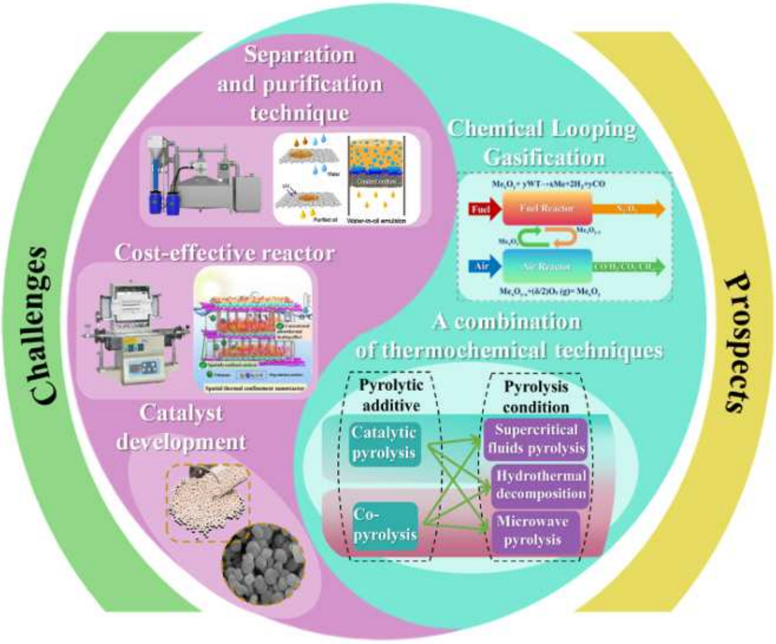


Figure 2.29: Challenges and prospects of WT thermal-chemical treatment [2].

2.6.1 Challenges

Feedstock Complexity and Variability

One of the most fundamental challenges is the heterogeneity of WT composition. Tires contain natural rubber, synthetic rubber, carbon black, steel, textile fibers, additives, oils, and various chemical stabilizers. These materials interact differently during thermal decomposition, making it difficult to standardize process conditions and predict product quality. Variability in tire type, age, and degree of wear further complicates processing. As a result, thermal-chemical systems must be flexible enough to handle diverse feedstocks without compromising efficiency or safety [2].

Table 2.10: Typical composition of passenger-car tires (approximate) [1].

Component	Amount (g)
Rubber	470
Carbon black	215
Steel	165
Clay	50
Zinc oxide	10
Fiber	55
Sulfur	10
Activated silica	25

Environmental Emissions and Pollutants

All three thermal-chemical routes present environmental challenges. Combustion emits sulfur oxides, nitrogen oxides, particulate matter, and potentially toxic organic compounds, requiring advanced emissions control technologies. Pyrolysis and gasification generate tar, sulfur-containing gases, and other pollutants that must be cleaned before products can be used. Tar formation in gasification remains a persistent obstacle, as it reduces syngas quality and causes operational issues such as pipe blockage and catalyst deactivation. These pollutants impose significant technical and regulatory burdens [2, 3].

Table 2.11: Emissions to air generated by combustion processes (heat supply by HFO vs NCG) [1].

HFO combustion		**NCG combustion**	
Emission	**Value (kg)**	**Emission**	**Value (kg)**
NO_x	0.3708	NO_x	0.082
CO	0.0193	CO	0.00432
Soot	0.2503	Soot	0.053
PM	0.3620	PM	0.0808
CO_2	24.18	CO_2	43.88

Combustion of pyrolytic gas: emissions limits and the need for downstream gas treatment. When pyrolysis products are combusted for energy recovery, the review stresses that the gas phase (pyrolytic gas / syngas) is a valuable fuel, but that its sulphur chemistry can create compliance challenges. Pyrolytic gas typically contains hydrocarbons, hydrogen, carbon oxides and sulphur compounds (notably H_2S). During combustion, H_2S is readily oxidized to SO_2, which can drive emissions above allowed limits if not treated.

For EU-sited plants, the article highlights a regulatory framing: if the substances resulting from pyrolysis are subsequently incinerated, then the system can fall under incineration-type emissions requirements (the review discusses this in the context of the Waste Incineration Directive definition). In reported measurements from combustion of gas-phase pyrolysis products, SO_2 and HCl are identified as problematic pollutants relative to limits, and the authors conclude that an acid-gas cleaning system is necessary. The review also argues that flue-gas cleaning should be included already at the investment-planning stage because it can be a major cost and design constraint [6].

Energy Consumption and Process Efficiency

Several thermal-chemical technologies require high operating temperatures, leading to substantial energy consumption. Achieving efficient heat transfer while minimizing energy losses remains a key challenge. In pyrolysis, uniform heating is difficult to maintain in large-scale reactors. In gasification, achieving full conversion and high-quality syngas requires carefully controlled conditions and sometimes specialized catalysts. Inefficient processes can make WT conversion economically uncompetitive compared to conventional fuels [2].

Table 2.12: Inventory of fast pyrolysis based on one ton of waste tires (WT) [1].

Category	**Sub-category**	**Value**	**Unit**	**Reference**
Raw material	Waste tire	1056	kg	Primary data
Energy	Electricity	102.9	kWh	Primary data
Energy	Heating fuel oil	104.3	kg	Primary data
Energy	NCG heat	940.68	MJ	Primary data
Emissions to air	NO_x	1.40	kg	Li et al. (2010)
Emissions to air	SO_2	3.55	kg	Li et al. (2010)
Emissions to air	CO_2	68.06	kg	Banar (2015)
Emissions to air	Dust	0.58	kg	Li et al. (2010)
Final waste flow	Plastic waste	52	kg	Primary data
Avoided products	TPO	160.38	kg	Primary data
Avoided products	Steel	190	kg	Primary data
Avoided products	Carbon black	187.51	kg	Primary data

Product Quality and Upgrading Requirements

Products from pyrolysis and gasification often require further purification or upgrading before they can be used commercially. For example [2, 3]:

- Pyrolysis oil may contain impurities such as sulfur or aromatic compounds that limit its direct use as a fuel.
- Syngas may contain tar, sulfur gases, and particulates requiring removal before use in engines or chemical reactors.
- Char may have lower quality than commercial activated carbon and often requires additional processing to reach market standards.

Without cost-effective upgrading technologies, product markets remain limited and reduce the economic viability of WT conversion [2].

Technological Readiness and Industrial Scaling

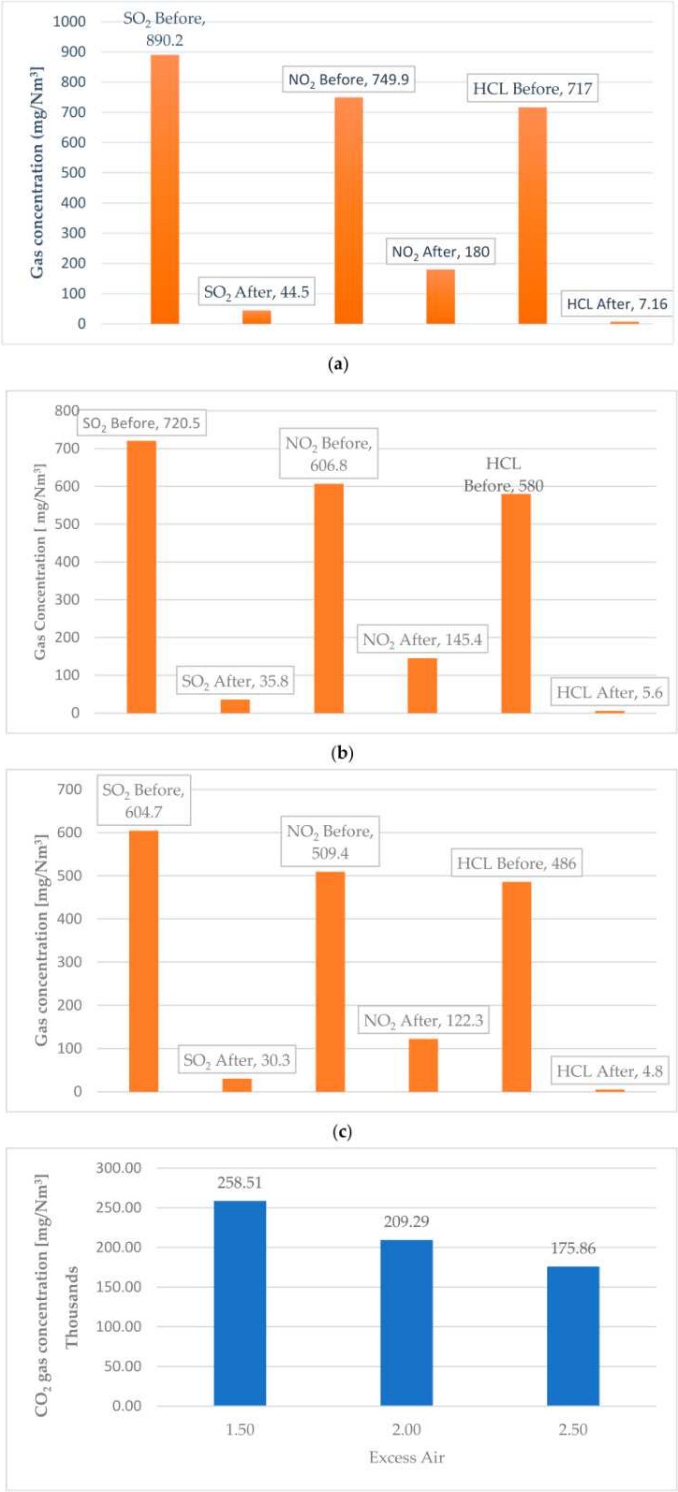
While combustion is already used industrially, pyrolysis and gasification technologies face obstacles in scaling up. Many studies remain at laboratory or pilot scale. Fluidized bed reactors, catalytic reforming units, and chemical-looping gasifiers show promise, but industrial deployment requires long-term reliability, stable performance, and manageable operational costs. Significant investment is needed to commercialize these technologies [2].

Economic and Market Limitations

Economic challenges include fluctuating WT supply, transportation costs, and variable product market prices. Furthermore, WT-derived products must compete with traditional fossil fuels and established industrial materials. Without supportive policies, subsidies, or carbon pricing, WT conversion may struggle to achieve economic stability. The literature notes that the lack of consistent product quality also limits industry acceptance [2].

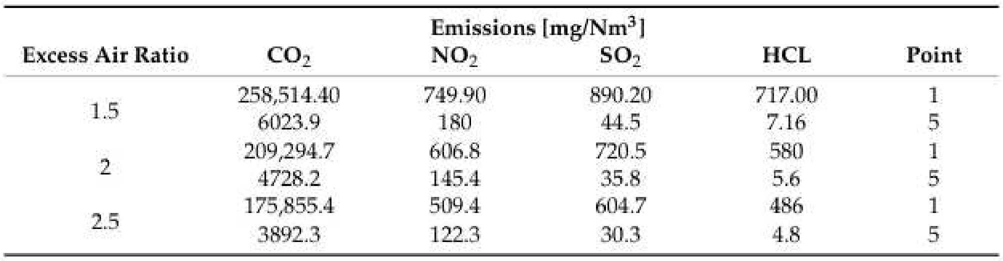
Challenges in emissions compliance: multi-stage treatment and operational trade-offs. Design-focused literature highlights that emissions control is not a single end-of-pipe step, but often a multi-stage system whose performance and cost depend on operating conditions and technology choices. In a study on flue-gas composition and treatment potential, the authors emphasise that flue-gas emissions and cleaning-system design remain an active and complex topic, with important environmental and economic trade-offs across alternative configurations. From a logistics viewpoint, this complexity creates recurring operational requirements, including reliable supply of treatment inputs, handling of residues, and maintenance planning across multiple stages, all of which must remain aligned with upstream combustion conditions and throughput [5].

Emission concentrations (SO_2, NO_2, HCl, and CO_2) before and after the treatment process are presented as a function of excess air: (a) excess air 1.5; (b) excess air 2; (c) excess air 2.5; (d) CO_2 emissions before the reduction process; and (e) CO_2 emissions after the reduction process. For NO_2 emissions, at an excess air ratio of 1.5 the concentration was reduced from 749 mg/Nm^3 to 180 mg/Nm^3, while at an excess air ratio of 2 it decreased from 606 mg/Nm^3 to 145 mg/Nm^3. With an excess air ratio of 2.5, the reduction was from 509 mg/Nm^3 to 122 mg/Nm^3. Table 15 summarizes the emission values of the flue gas cleaning system measured after the furnace at point 1 and upstream of the stack at point 5.



(d)

Figure 2.30: Example pollutant concentrations before and after flue-gas cleaning (SO_2, NO_x, HCl) for different excess-air cases, and CO_2 emissions trend [5].



	Emissions [mg/Nm^3]				
Excess Air Ratio	CO_2	NO_2	SO_2	HCL	Point
1.5	258,514.40	749.90	890.20	717.00	1
	6023.9	180	44.5	7.16	5
2	209,294.7	606.8	720.5	580	1
	4728.2	145.4	35.8	5.6	5
2.5	175,855.4	509.4	604.7	486	1
	3892.3	122.3	30.3	4.8	5

Figure 2.31: Summary of the performance results of the flue-gas emission control system [5].

2.6.2 Prospects

Despite these challenges, the literature expresses optimism regarding the future of WT thermal-chemical utilization. Several promising developments support long-term growth of these technologies [2, 3].

Advancements in Reactor Design

New reactor technologies such as microwave pyrolysis, catalytic pyrolysis reactors, and advanced fluidized bed gasifiers are improving product yield and reducing pollutant formation. Microwave-assisted pyrolysis, in particular, offers more uniform heating and higher efficiency, addressing key limitations of conventional pyrolysis systems. Chemical looping gasification is also highlighted as a promising future technology due to its ability to reduce tar formation and enhance syngas purity [2, 3].

Improved Catalysts and Reforming Technologies

Catalysts play a central role in enhancing product quality. Catalytic pyrolysis can improve oil composition, reduce contaminants, and increase production of desirable compounds. Likewise, catalytic gasification and tar reforming technologies are emerging as effective solutions to tar-related challenges. Research into robust, low-cost catalytic materials continues to expand, paving the way for higher-quality products [2, 3].

Char Upgrading and Material Applications

Char upgrading represents a major growth opportunity. Activated carbon production from WT char is expanding, and enhanced carbon materials show potential for environmental applications such as pollutant adsorption and carbon dioxide capture. Recovered carbon black (rCB) is becoming increasingly important in rubber reinforcement, composite materials, and energy storage devices. Such high-value markets can significantly boost the economic feasibility of WT conversion [2].

Syngas Utilization Pathways

Syngas can be used not only as a direct fuel but also as a feedstock for producing hydrogen, methanol, ammonia, and synthetic fuels. As global demand for clean fuels increases, hydrogen-rich syngas from WT gasification may play an important role in future energy systems. Research into syngas cleaning and upgrading technologies is expected to support this development [2].

Integration into Circular Economy Models

Thermal-chemical conversion aligns well with circular economy principles by recovering materials and energy from WT that would otherwise become environmental burdens. Pyrolysis oil, syngas, and char can be reintegrated into industrial processes, reducing reliance on virgin fossil resources. The reviewed literature emphasizes that integrating WT conversion systems into regional waste management and industrial networks will enhance both environmental and economic outcomes [2, 3].

Policy Support and Market Growth

Policies promoting waste recycling, renewable energy, and carbon reduction can accelerate adoption of WT conversion technologies. As regulatory frameworks tighten around landfilling and open burning, thermal-chemical methods become more attractive. Emerging carbon markets and environmental standards are likely to increase the demand for low-carbon fuels and recycled materials derived from WT [2].

Overall, while significant challenges remain, ongoing technological advancements, combined with growing environmental and economic pressures, are driving WT thermal-chemical utilization toward broader industrial adoption [2].

2.7 Waste management and innovation solutions

Waste-to-energy (WtE) facilities are widely used in modern waste-management systems to treat residual waste fractions for which recycling is technically or economically difficult, while simultaneously recovering useful energy. A key limitation of WtE, however, is that combustion-based treatment generates pollutant-bearing flue gas streams that must be cleaned before release. As emission requirements tighten, compliance increasingly depends not only on the main furnace, but also on the design and operation of the downstream flue-gas cleaning line, which becomes a coupled system handling gaseous pollutants, solid residues, and, in some configurations, liquid effluents [18].

2.7.1 Innovation driven by stricter emission targets

A central innovation driver in WtE is the move toward lower allowable emission targets for acid-related pollutants. When permissible limits are reduced substantially, the flue-gas treatment system must deliver higher removal efficiency under variable inlet conditions. Importantly, this does not always require an entirely new plant: in many cases the challenge is how to adapt an existing treatment line in a way that remains technically feasible, cost-effective, and operationally stable under realistic variability in waste feed and pollutant loads [18].

2.7.2 Three practical adaptation strategies for existing WtE plants

The literature identifies three broad strategies that plants can adopt to meet stricter emission targets. The first is intensification, where the plant keeps the existing dry treatment concept but increases the consumption rate of the reactant used for neutralizing acidic pollutants. This option is attractive because it can avoid major reconstruction; however, it is constrained by equipment capacities such as storage and feeding systems for reagents, and by operational limits of the filtration stage (e.g., limits related to pressure drop and stable operation) [18].

The second strategy is retrofitting, where an additional upstream removal step is added while keeping the main downstream dry system. In practice, this is implemented as an extra high-temperature injection step that partially reduces the acidic load before the existing duct treatment stage. This multi-stage approach can reduce the dependence on the more expensive downstream reactant, but it can increase the amount of process residues that must be collected and managed [18].

The third strategy is revamping, in which the dry system is replaced with a wet scrubbing concept. This option can provide high removal efficiency and can reduce reactant use for a given removal target, but it requires higher investment and introduces wastewater management as a core design issue. In addition, wet scrubbing can impose new integration constraints on the full flue-gas line, especially if downstream units require a minimum gas temperature or if local stack requirements make low-temperature release undesirable [18].

2.7.3 Integrated treatment of gaseous, solid, and liquid streams

A key contribution of the study is that it frames emission compliance as a cross-media waste-management problem rather than a purely gaseous-pollutant problem. In dry systems, pollutant removal is achieved by injecting powdered reactants into the flue-gas duct; the neutralization products, together with unreacted sorbent, become a solid residue stream that is captured by a fabric-filter stage and then managed as solid waste. As emission targets become stricter, higher reactant dosing is required, and therefore solid residue generation and disposal become increasingly important operational and logistics burdens [18].

In wet systems, removal is achieved by contacting flue gas with liquid streams in staged scrubbers. While this improves removal efficiency, it generates liquid effluents that contain absorbed pollutants and dissolved/entrained contaminants. The innovative direction highlighted in the literature is to avoid creating an external wastewater discharge stream by converting the scrubber effluent into a solid residue stream: after conditioning, the combined scrubber effluent can be introduced into hot flue gas in a dedicated drying step upstream of filtration, so that water is evaporated and the remaining salts/solids are captured in the fabric filter as a dry residue. This transforms a liquid-waste-management problem into a controlled solid-residue-management problem while maintaining the wet scrubbing removal performance. [18].

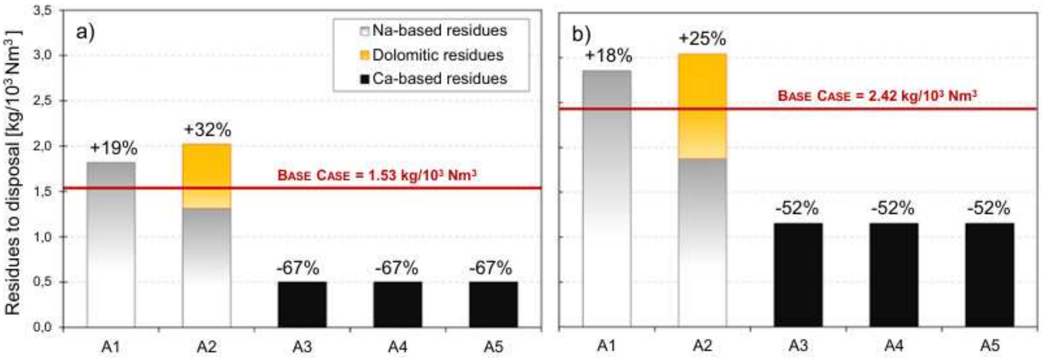


Figure 2.32: Generation of process residues per Nm^3 of treated flue gas for flue gas with (a) a low acid-gas load and (b) a high acid-gas load [18].

2.7.4 Operational trade-offs: cost, energy penalty, and layout constraints

The comparative assessment shows that stricter emission targets tend to increase total treatment costs across all options, but the ranking among options depends on site constraints and on inlet pollutant load characteristics. Intensification can be implemented with limited layout change, but it increases consumption of reactants and, correspondingly, the quantity of residues requiring handling and disposal. Retrofitting reduces reliance on downstream reactant consumption by sharing removal across stages, but it can increase residue flows and requires additional reagent handling infrastructure upstream [18].

Revamping to wet scrubbing can lower operating costs compared with dry options when the treated gas can be released without reheating, because wet scrubbing can achieve the required removal efficiency with less reactant excess and a different balance of process outputs. However, if the flue gas must be reheated after wet treatment (for example, due to constraints tied to stack release requirements or compatibility with downstream treatment units), the associated energy penalty can make wet revamping less economically attractive than the best dry-based alternatives. This highlights that compliance decisions are system-level decisions: the best technology is not determined only by removal efficiency, but by how the full chain behaves with respect to energy use, integration constraints, and downstream requirements [18].

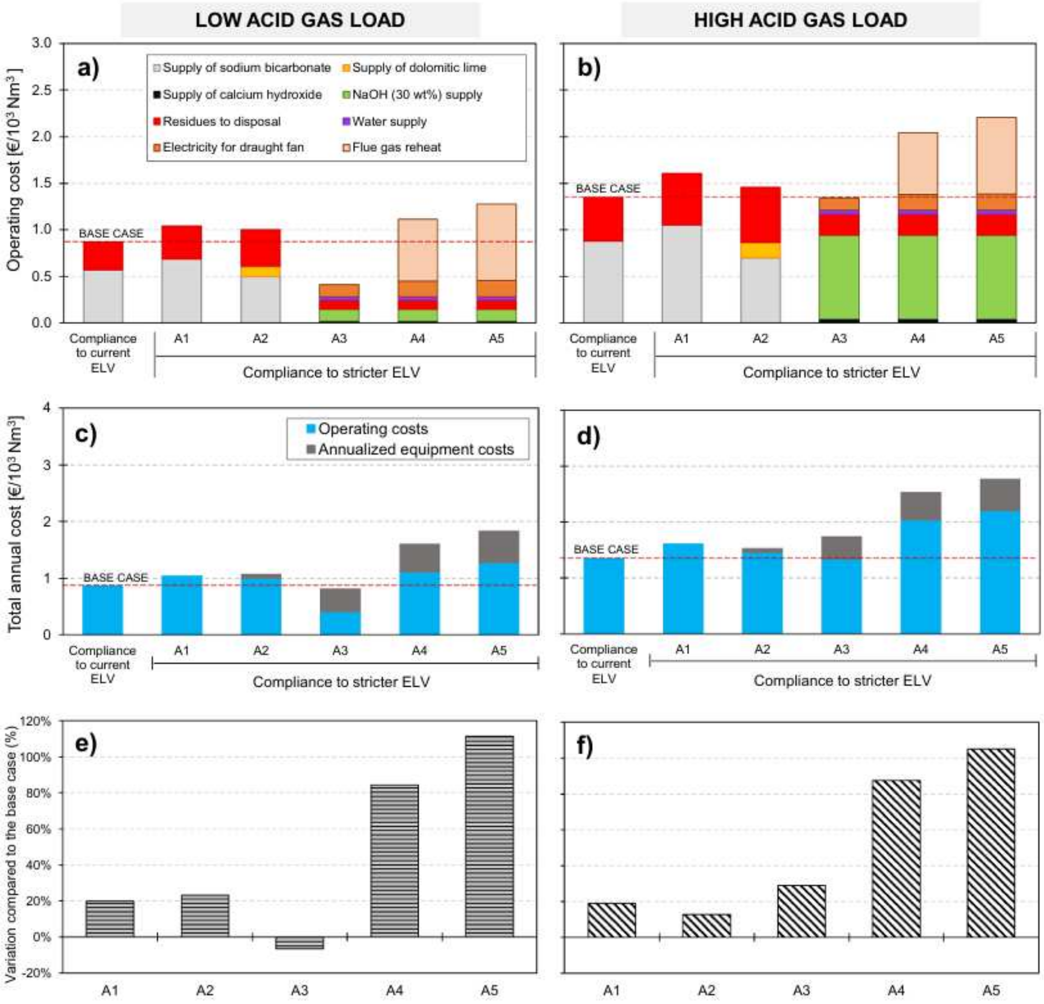


Figure 2.33: Techno-economic performance of the acid gas treatment alternative systems considered in the case-study [18].

2.7.5 Decision-support logic under variability and uncertainty

WtE operation is subject to variability in waste feed composition, which translates into variability in inlet pollutant loads to the cleaning system. As a result, decisions based on a single "average" condition can be misleading. A key innovation element is therefore the explicit consideration of variability and uncertainty in the evaluation of alternatives. By exploring cost-entry uncertainty and inlet-load variability, the analysis shows that the apparent ranking among options can shift depending on how pollutant loads and cost factors combine in real operation. This supports a planning approach where historical operating data (covering extended periods) and sensitivity analysis are used to guide robust selection of compliance strategies [18].

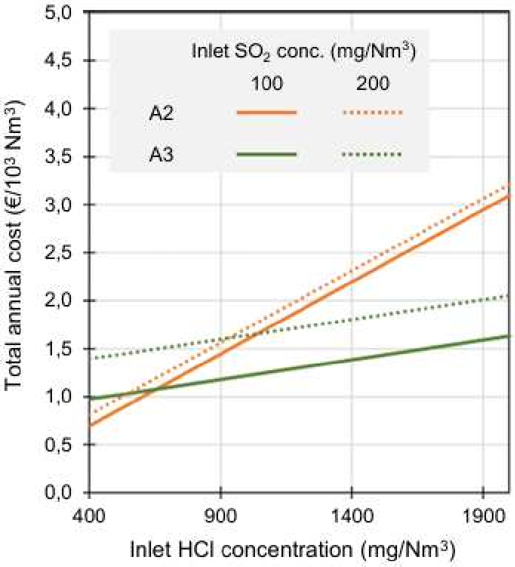


Figure 2.34: Effect of inlet HCl variability (and SO_2 level) on total annual cost: example comparison between alternatives (A2 vs A3) [18].

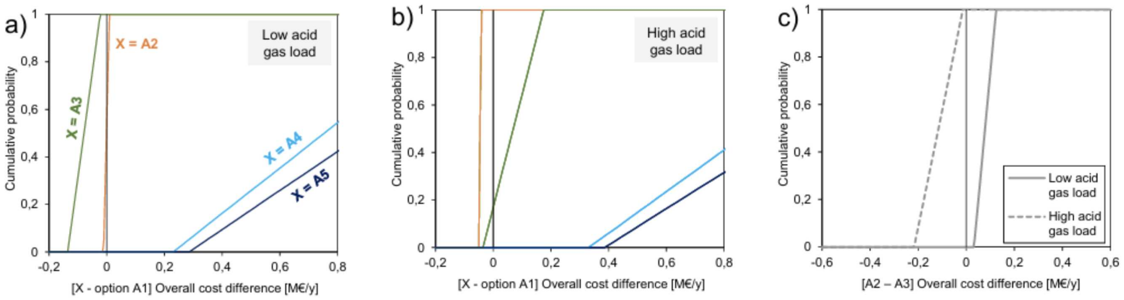


Figure 2.35: Results of sensitivity analysis: cumulative probability of the difference in terms of total annual cost between the alternatives A2 to A5 compared to alternative A1 for a) low acid gas load, b) high acid gas load. c) Comparison of alternative A2 with respect to alternative A3 in both acid gas load scenarios [18].

2.7.6 Relevance to tire-derived fuels and heterogeneous waste streams

For waste-tire-to-energy systems, these findings are directly relevant because tire-derived streams can increase variability and can alter the pollutant-loading regime of the flue gas compared with more homogeneous fuels. The literature therefore supports treating emissions compliance as a capacity-planning and logistics problem that spans: reagent procurement and storage, controlled dosing and automation, filtration and pressure-drop management, and residue handling for both solids and (where applicable) conditioned liquids converted to solids. In this framing, innovation is not limited to new reactor concepts; it also includes integrated, cross-media strategies that prevent shifting burdens from air emissions to water discharge and that allow plants to meet stricter targets through coherent redesign of the overall treatment chain [18].

2.7.7 Combustion emissions control and waste-stream treatment challenges for tire-derived fuels

A practical dimension of "waste management and innovation" in tire-to-energy systems is how operators prevent the formation and release of harmful pollutants when tires are used as a fuel. A dedicated experimental study examined waste-tire combustion at different furnace temperatures and monitored both gaseous pollutants and solid particles captured from the flue gas [9]. Even though the work is laboratory-scale, its findings are directly relevant to industrial practice because they show why modern plants rely on controlled combustion conditions and engineered downstream treatment rather than uncontrolled burning.

Table 2.13: Fuel properties of the waste-tire sample used in the combustion experiments (dry basis for ultimate analysis and HHV).

Property	**Value**
Moisture (% w/w)	0.50
Ash_d (% w/w)	7.78
C_d (% w/w)	85.11
H_d (% w/w)	7.41
N_d (% w/w)	0.47
S_d (% w/w)	1.33
HHV_d (MJ/kg)	38.44

The study positions tire combustion within the broader waste-management landscape, noting that waste tires are widely used as an auxiliary fuel in cement kilns and similar high-temperature installations, mainly because they have high energy content and can substitute part of conventional fuels [9]. At the same time, the article highlights why co-processing tires in kiln-type systems can be operationally sensitive: tires can disturb heat distribution, contribute to unstable operation in upstream zones, and create build-ups that lead to blockages and abnormal emissions [9]. From a systems viewpoint, this reinforces that waste-to-energy performance is not determined only by the furnace itself, but also by stable feeding, combustion control, and the reliability of the gas-path equipment that follows.

A central message of the study is that combustion temperature acts as a strong control lever for pollutant formation [9]. When temperatures are too low or combustion becomes incomplete, carbon monoxide and unburned organic compounds can increase, which raises the burden on any downstream treatment unit [9]. When temperatures are higher and oxidation is more complete, carbon monoxide and several harmful organic fractions decrease, but other pollutants (notably nitrogen-oxide-related emissions) can increase because hotter flames tend to promote their formation [9]. This is one reason industrial designs often separate the functions of (i) achieving stable burnout in the main chamber and (ii) ensuring destruction of remaining organics in a dedicated high-temperature post-combustion zone, while using monitoring and control loops to keep the system inside a safe operating window.

An important insight, that is often overlooked in simplified discussions: mineral constituents in tires can influence pollutant behaviour during combustion [9]. In particular, mineral fillers can transform at elevated temperatures and can partially retain sulfur-bearing pollutants by binding them into the solid residue stream rather than allowing them to remain in the gas phase [9]. For waste-management planning, this matters because it shows that the pollution-control problem

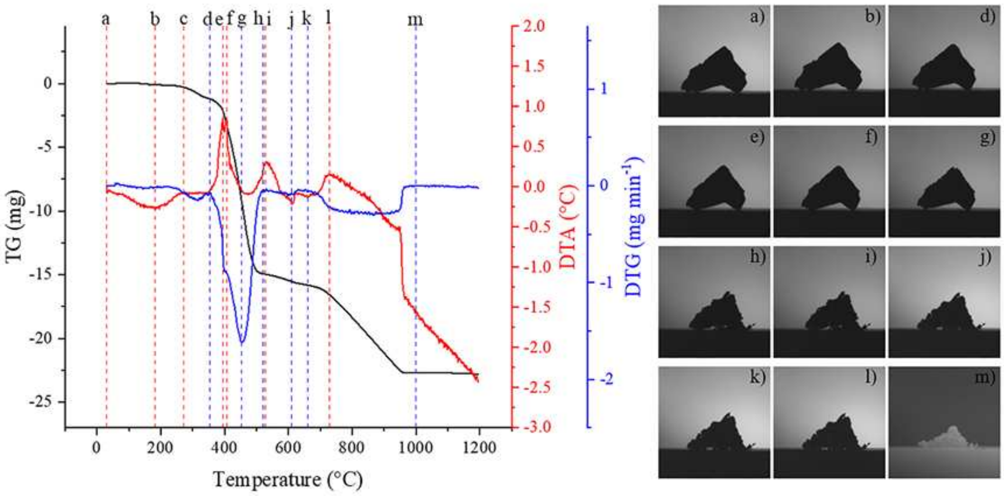


Figure 2.36: Derivatograms of tire and the deformation during heating [9].

is partly "shiftable" between streams: depending on operating conditions and fuel composition, more of a contaminant may end up in the solid residue, which then increases requirements for ash handling, residue characterization, and compliant disposal or utilization [9]. In other words, cleaner flue gas can come at the cost of a more contaminated solid fraction, so innovation must address gaseous and solid streams together rather than treating them as independent problems.

Beyond gases, the study documents that the solid particles carried by the flue gas change in quantity and character with temperature, and it evaluates hazardous organic compounds associated with these particles [9]. The reported behaviour indicates that higher-temperature conditions can reduce the overall amount of particle-bound hazardous organics, while also changing their distribution toward lighter fractions [9]. This supports an engineering logic that is consistent with industrial best practice: keep combustion sufficiently hot and well-mixed to limit formation of persistent toxic organics, then apply effective particulate removal so that particle-bound contaminants do not pass to the stack [9]. It also reinforces why plants that use tires or other difficult fuels typically require robust particulate control (for the solid stream) and, where needed, additional flue-gas treatment stages to address acid gases and other regulated pollutants (for the gaseous stream) [9].

Overall, innovative waste-to-energy solutions for tires are not only about choosing a conversion route, but also about integrating process control with downstream treatment across all waste streams [9]. Stable combustion conditions reduce the formation of harmful compounds at the source, while the plant's treatment chain must be sized and operated to manage both the flue gas and the solid residues produced under realistic throughput variations. This integrated view aligns with the thesis's logistics and automation focus: monitoring, control actions, residue routing, and maintenance planning are part of one connected system rather than separate tasks [9].

Treatment of gaseous, solid, and liquid streams in tire-to-energy systems. Taken together, the kiln-related pathways in this review reinforce a systems view that aligns with the thesis framing used elsewhere: (i) kilns can enable stable high-temperature destruction/energy recovery (cement-kiln co-processing), (ii) rotary kilns can support continuous conversion with controllable mixing and residence time (pyrolysis), and (iii) downstream treatment requirements remain essential,especially acid-gas control for sulphur-driven emissions from pyrolytic-gas combustion, and upgrading steps for oil/char quality when products are intended for higher-value applications [6].

While controlled combustion focuses mainly on stabilizing oxidation and treating the resulting flue gas and particulates, pyrolysis-based systems shift the waste-management task toward coordinated handling of three product streams (gas, oil, and char), each of which can require dedicated conditioning and compliance measures.

2.7.8 Integrated treatment of gaseous, solid, and liquid streams in waste-tire pyrolysis systems

Waste tire pyrolysis is often presented as a conversion technology, but from a waste management viewpoint it should be treated as an integrated multi-stream system that simultaneously generates a combustible gas stream, a liquid stream, and a solid stream. The practical feasibility of pyrolysis therefore depends not only on the reactor itself, but also on how these three streams are conditioned, handled, and either reused on-site or transferred safely to downstream users [6].

A key innovation-oriented concept highlighted by the review is the use of the produced gas as an internal energy source. The most common application of pyrolytic gas is to combust it in order to supply the heat demand of the pyrolysis process itself, which supports energy self-sufficiency and reduces reliance on external fuels [6]. However, the same source stresses that this internal energy loop immediately creates a waste management requirement: if the gas is burned, emissions performance and downstream treatment become central design constraints, not secondary issues. The tire pyrolysis gas is composed mainly of methane and other hydrocarbons containing 2 to 6 carbon atoms per molecule, along with carbon oxides, hydrogen, and small amounts of sulphur and nitrogen containing compounds [6].

Gaseous stream: from useful fuel to emissions-managed combustion. The sixth article explains that the composition and heating value of pyrolytic gas can make it a promising fuel, but it also reports that sulphur-related compounds in the gas can be a serious issue under conditions commonly discussed as favourable for tire pyrolysis [6]. The review connects this directly to regulatory framing by discussing how European Union (EU) waste-incineration rules define incineration plants broadly enough to include pyrolysis and gasification *when the resulting substances are subsequently incinerated*. In other words, a tire-pyrolysis plant that combusts its produced gas should be evaluated with an emissions-compliance mindset similar to waste-incineration systems [6].

Because published measurements on pollutants from combustion of pyrolytic gas are limited, the article highlights the importance of the few reported datasets that exist. It reports that while some measured pollutants remained below limits, other indicators associated with incomplete burnout and acid-gas formation were reported above permitted values, and the review concludes that an *acid-gas cleaning system* may be necessary [6]. Importantly for innovation and investment planning, the authors note that flue-gas cleaning can be one of the largest cost elements in waste-thermal systems and therefore should be considered already during the investment-design phase, rather than treated as an afterthought [6].

Gas-phase products at waste tires pyrolysis

Gas produced during the pyrolysis of waste tires is commonly referred to as pyrolytic gas, pyrogas, or syngas. Depending on the technology employed and the operating conditions, it can account for anywhere from a few percent to more than ten percent of the total products. This gas has a high heating value, reaching up to about 84 MJ/Nm^3 or 42 MJ/kg [**55**]. In general, the gas-phase products from waste tire pyrolysis consist of a mixture of paraffins and olefins (with other hydrocarbons also present), along with carbon oxides, hydrogen, and small amounts of sulphur- and nitrogen-containing compounds.

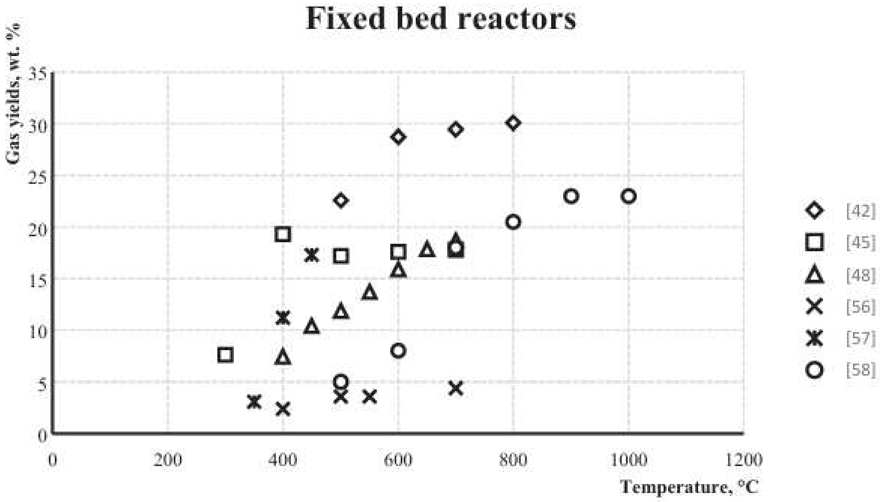


Figure 2.37: Gas yields according to the pyrolysis temperature [6].

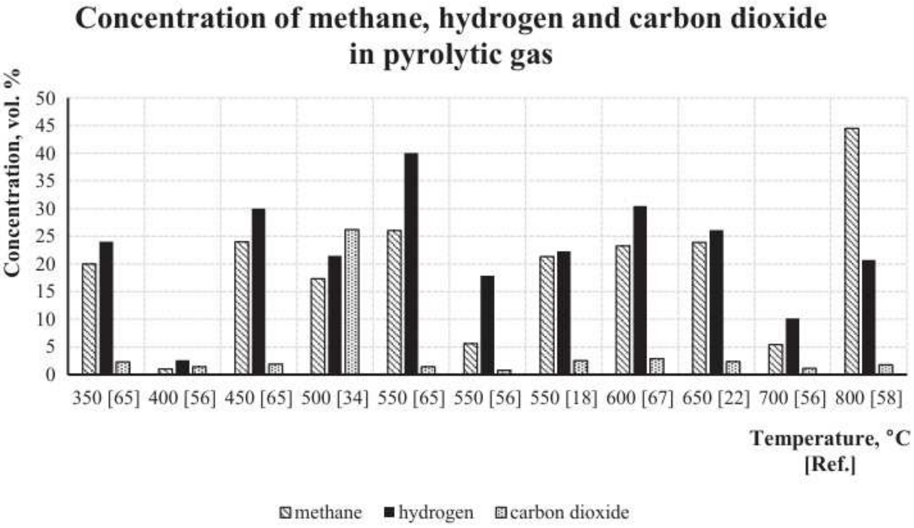


Figure 2.38: Concentration of methane,hydrogen and carbon dioxide in pyrolytic gas obtained in different conditions [6].

Table 2.14: Heating values of pyrolytic gas obtained in different conditions [6].

Temperature (°C)	**Details**	**Heating value (MJ/m^3)**
400	Fixed bed	11.97
600	Vacuum pyrolysis	17.30
450	Vacuum pyrolysis	19.80
550	Vacuum pyrolysis	20.50
500	Vacuum pyrolysis	20.70
550	Pilot plant	22.04
600	Pilot plant	23.98
500	Fixed bed	28.37
680	Pilot plant	29.03
900	Tire powder	34.90
800	Tire powder	38.10
600	Fixed bed	38.59
500	Test bench	40.50
700	Fixed bed	42.87
700	Tire powder	43.20
900	Fixed bed	57.50
550	Fixed bed	65.60
550	Pilot plant	68.70
700	Fixed bed	69.50
600	Fixed bed	73.80
500	Fixed bed	76.70
400	Fixed bed	81.60

A practical mitigation direction: mineral sorbents introduced in the process have been reported to reduce sulphur-related compounds in the produced gas. Even when such measures are used, gas handling must be designed as a chain that includes controlled combustion, monitoring, and (where needed) downstream purification units selected according to the specific pollutants observed for the chosen operating regime [6].

Solid-phase

The main solid residue from waste-tire pyrolysis is char (pyrolytic carbon black), a mesoporous material with an average heating value of about 30 MJ/kg. It is mainly composed of the reinforcing carbon black originally present in tires, together with inorganic compounds formed during pyrolysis; therefore, its properties depend on both the tire composition and the operating conditions [6].

Char typically has a high carbon content (up to 90 wt%) and contains sulphur (about 2 wt%), zinc (around 4 wt%), and other metals (e.g., Ca, Fe, Al). A key feature is its relatively high ash content compared with original carbon black (often > 5 wt% and up to ~ 20 wt%), arising from tire additives and deposited dirt; reported ash levels vary by reactor type and can be higher in fluidized beds due to entrained bed material. Char yields are commonly in the range of 35–55 wt%, although much higher values have been reported for catalytic pyrolysis under specific conditions [6].

From an application and economic perspective, the most widespread use of tire char is as a precursor for activated carbons. Because the raw char often has limited surface area (typically < 100 m^2/g), physical activation (CO_2 or steam at 800–1000 °C) or chemical activation (e.g., KOH at 600–800 °C) is used to substantially increase BET surface area and adsorption performance for pollutants such as phenols, dyes, metals, and pharmaceuticals [6].

Solid stream: char quality, ash burden, and upgrading as a control strategy. For the solid stream, the char fraction is not only a by-product but also a potential resource whose usefulness depends on quality. It explains that tire-derived char can have higher ash content than virgin carbon materials, and it links this ash burden to both Tire formulation and contamination such as dirt on waste Tires [6]. This creates a waste-management and logistics implication: upstream cleaning and feedstock quality control are not simply operational preferences, but mechanisms that improve solid-stream quality and reduce downstream handling burdens [6].

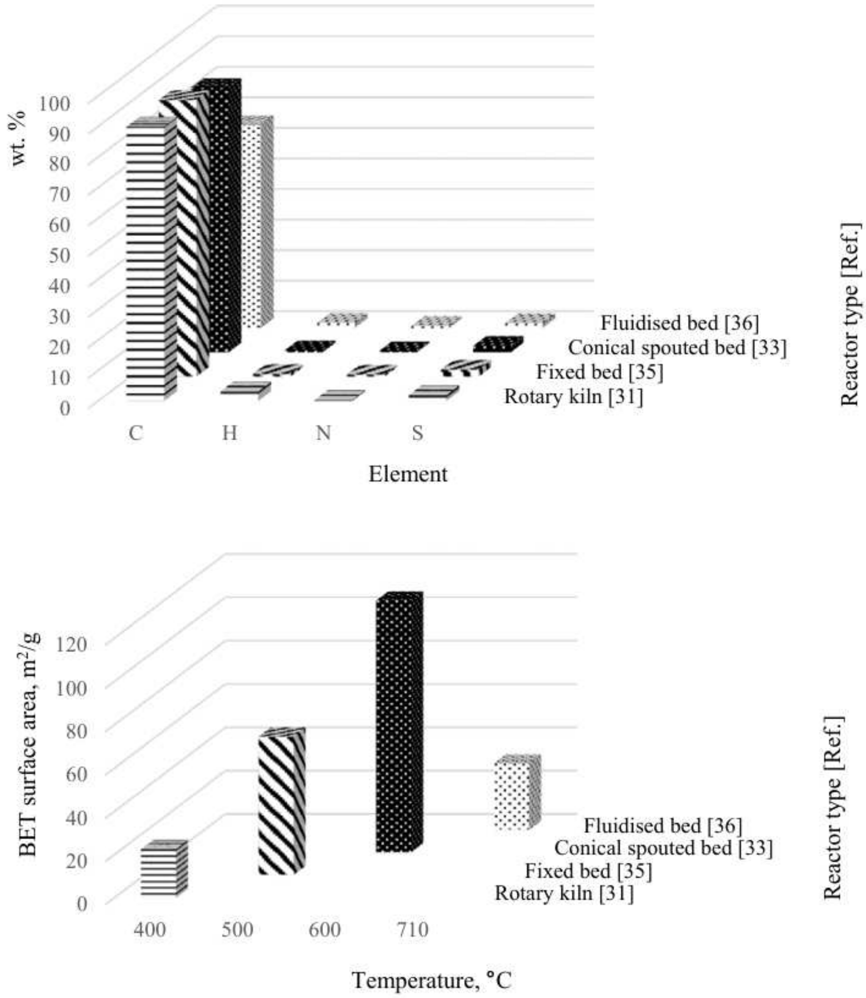


Figure 2.39: Characteristics and quality of char [6].

The review further frames upgrading as an innovation pathway: treated or activated forms of tire-derived char are discussed as higher-value products compared with untreated char, which supports a circular-economy logic in which a solid output of the process can be shifted from “residue” toward “functional material” [6]. In a system-design sense, this means that solid-stream management may include dedicated steps for separation, storage, and quality stabilization, and potentially an upgrading line that is matched to the intended end use [6].

Liquid-phase

For the liquid stream, the pyrolysis oil fraction can be energy-rich, but it can also be difficult to use directly as a fuel because of impurities and heavy fractions that reduce fuel suitability and stability [6]. The review therefore discusses conditioning and upgrading approaches, including distillation-type separation and further refining steps aimed at improving the oil quality for fuel use [6]. From a waste-management and innovation perspective, these upgrading steps are part of the solution because they reduce the risk that recovered liquids become difficult-to-market materials that require additional disposal routes [6].

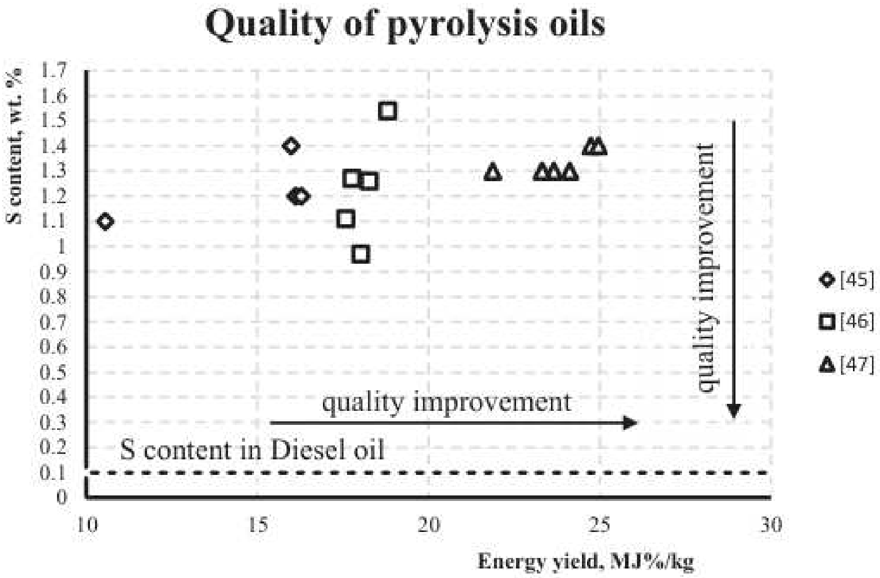


Figure 2.40: The quality of tire pyrolysis oil for use as a fuel: sulphur content and energy yield. [6].

System implication: innovation is the stream-treatment chain, not a single unit. Overall, the main innovation need is not only a better reactor, but an integrated chain for gaseous, solid, and liquid streams. The gas stream may enable internal energy recovery but can require emissions-managed combustion and purification; the solid stream can be upgraded to increase value and reduce disposal pressure; and the liquid stream often requires conditioning to become a usable product. There is a warning that flue-gas cleaning cost can dominate project feasibility reinforces that industrial implementation should treat downstream treatment capacity as a core part of plant design and investment planning [6].

2.7.9 Process-configuration innovation for multi-stream management in scrap-tire pyrolysis

A practical innovation pathway in tire-waste management is not only the selection of pyrolysis as a conversion route, but the engineering of a plant configuration that can reliably separate and handle the three main output streams (gas, liquid, solid) under controlled conditions. The seventh article develops a fixed-bed pyrolysis concept with an internally heated fire-tube reactor and emphasizes that product yields and quality depend on process parameters and on the specific characteristics of the system (reactor design, heat-transfer effectiveness, feed particle size, and vapor residence time) [10].

Integrated handling of gaseous, liquid, and solid streams

In the described experimental configuration, tire feed is introduced through a feeder into a fixed-bed reactor that is purged with nitrogen to remove air, enabling thermal decomposition under an inert atmosphere. The produced vapors are routed through two condenser stages to quench and recover a liquid fraction, which is collected as oil. The remaining uncondensed gases are treated as a separate stream and are directed to a controlled outlet (reported as flaring in the test configuration). The solid char is removed from the reactor chamber and collected separately (reported using a dedicated char collection bag) [10]. This system description is directly relevant to industrial feasibility because it demonstrates that "innovation" includes the downstream routing architecture that prevents uncontrolled releases while allowing each stream to be managed and evaluated independently.

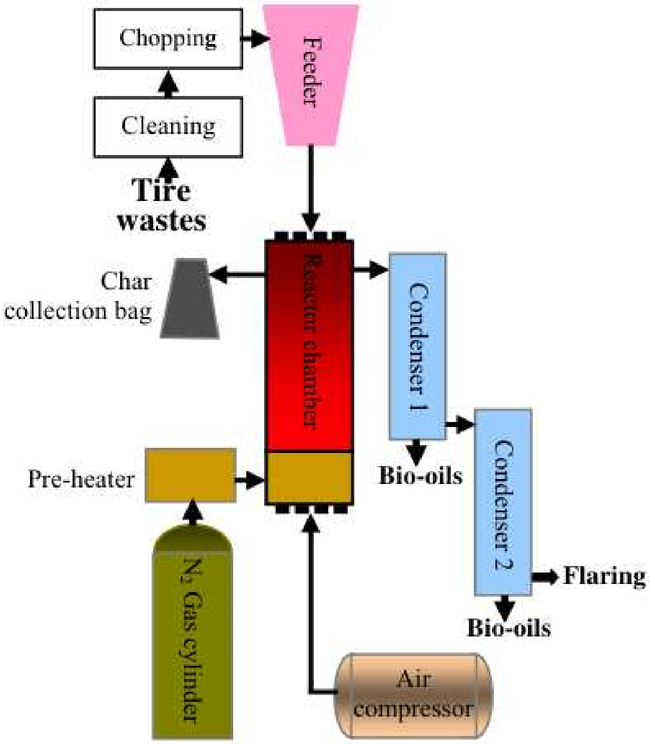


Figure 2.41: A fixed-bed fire-tube heating pyrolysis system [10].

Table 2.15: Proximate analysis, ultimate analysis, and gross calorific value (GCV) of the waste tire feedstock [10].

Category / Parameter	**Value**
Proximate analysis (wt%)	
Volatile matter	62.70
Fixed carbon	32.31
Ash	4.17
Moisture	0.82
GCV (MJ/kg)	33.30
Ultimate analysis (wt%)	
Carbon (C)	80.30
Hydrogen (H)	7.18
Nitrogen (N)	0.50
Sulfur (S)	1.19
Others (O + Ash)	10.83

Operating-condition optimization as an innovation lever

Optimizing operating conditions can shift the distribution among oil, gas, and char, and therefore changes both the potential revenue streams and the handling burdens. It reports an optimum region for maximizing liquid yield (linked to a specific temperature, feed size, and vapor residence time), and explains that at higher temperatures secondary cracking can reduce oil yields and increase gas formation, while char yields trend downward up to an intermediate point and then stabilize [10]. From a waste-management perspective, this matters because higher gas production can increase the importance of gas routing and safe combustion/handling, while higher char fractions increase requirements for solid handling, storage, and quality control.

Table 2.16: Effect of reactor temperature on product yields (wt%) [10].

Yield (wt%)	**375 °C**	**425 °C**	**475 °C**	**525 °C**	**575 °C**
Liquids	44 ± 2.5	48.5 ± 2	51 ± 1.5	47 ± 1.5	43 ± 2.1
Solid char	48.5 ± 1.5	43 ± 1.5	40.5 ± 2.8	40 ± 1.8	38 ± 1.8
Gases	7.5 ± 1.4	8 ± 2.6	8.5 ± 1.7	13 ± 2	19 ± 2.5

Table 2.17: Effect of feedstock size on product yields (wt%) [10].

Yield (wt%)	**2 cm^3**	**4 cm^3**	**8 cm^3**	**12 cm^3**
Liquids	48 ± 3	51 ± 1.5	49 ± 2.4	46 ± 1.8
Solid char	36 ± 2.6	40.5 ± 2.8	43 ± 1.8	47 ± 2.7
Gases	16 ± 1.3	8.5 ± 1.7	8 ± 1	7 ± 1.5

Table 2.18: Effect of vapour residence time on product yields (wt%) [10].

Yield (wt%)	**5 s**	**10 s**	**20 s**
Liquids	51 ± 1.5	48.5 ± 2.5	45 ± 2.7
Solid char	40.5 ± 2.8	38 ± 2	36 ± 1.6
Gases	8.5 ± 1.7	13.5 ± 1	19 ± 2

Liquid-stream issues: safety and upgrading needs

Beyond yield, liquid-stream management frequently requires additional treatment steps before market use. The recovered tire-derived liquids have favorable handling-related viscosity characteristics, but also a low flash point and an acidic nature, which introduces safety and materials-handling considerations in storage and transport. In addition, the article notes that sulphur content in the derived liquids can be high relative to environmental fuel requirements, and therefore lists preliminary treatments (e.g., separation/cleaning steps and desulphurization/hydrotreating-type upgrading) and blending strategies to improve usability as a fuel [10]. This directly supports the thesis framing that innovation can mean preventing "problem shifting": without conditioning, a recovered liquid product may become difficult to use and could create additional downstream waste-management burdens.

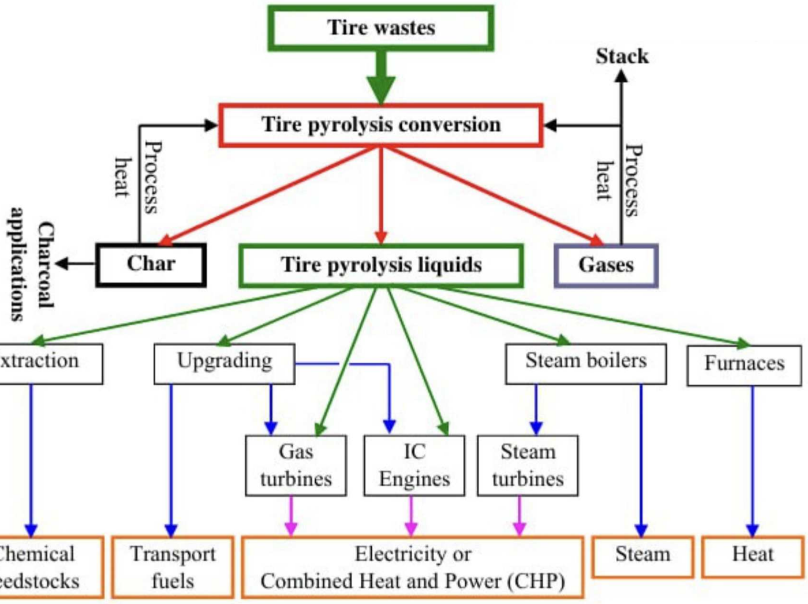


Figure 2.42: Tire pyrolysis conversion and applications of products [10].

System implication for waste management and innovation solutions

Overall,innovation is expressed in (i) reactor heating and controllability, (ii) explicit separation and routing of gas/liquid/solid streams, and (iii) recognition that downstream treatment (especially for the liquid stream) is often required for compliant and safe utilization [10].

2.8 Conclusion

The reviewed literature demonstrates that waste tires (WT) represent both an environmental challenge and a significant resource opportunity. As global motorization increases, the volume of end-of-life tires continues to grow, creating pressure on waste management systems and posing risks related to landfilling, uncontrolled storage, and pollutant release [2]. Despite these concerns, the high calorific value and carbon-rich composition of WT make them suitable candidates for energy recovery through thermal-chemical conversion processes [2]. Thermal-chemical technologies, including combustion, pyrolysis, and gasification, offer practical pathways to extract energy and generate valuable products from WT, transforming a disposal problem into a potential resource stream [2].

This section presents and discusses the findings from the combustion, pyrolysis-related insights, and gasification tests carried out with waste tires mixed with biomass. The purpose of the discussion is to highlight not only the thermal behaviour of tires but also the logistical implications for operating a tire-to-energy system. The results come from controlled laboratory and pilot-scale studies that measured emissions, power production, feeding behaviour, ash formation, and syngas composition [4].

These outcomes directly influence how an industrial plant must be designed, operated, and supplied with material. The study reviewed demonstrates that waste tires have strong potential for energy recovery through combustion, pyrolysis, and gasification. Their high energy content makes them an attractive supplement to biomass; however, the experimental results show that practical and logistical challenges significantly limit the proportion of tire material that can be used in real systems. The findings of the combustion, pyrolysis-related, and gasification analyses indicate that logistics and operational reliability are decisive factors in designing a tire-to-energy plant [4, 2].

Among the three thermal-chemical routes, combustion is technologically mature and capable of producing useful heat; however, it is limited by its emission profile and significant environmental impacts [2]. Pyrolysis emerges in the literature as a highly flexible and promising technology, capable of producing gas, oil, and char with diverse industrial applications [2, 3]. Gasification stands out for its ability to generate hydrogen-rich syngas, which aligns with global shifts toward cleaner energy systems [2]. Each technology offers unique advantages but also presents specific operational and environmental challenges that must be addressed for large-scale implementation [2].

Product applications from these processes are diverse and increasingly gaining attention. Pyrolysis oil can serve as an alternative fuel or chemical feedstock; syngas can be used for heat, power generation, or synthesis of fuels and chemicals; and char can be upgraded for environmental remediation, carbon capture, or advanced material production. These trends demonstrate an expanding market potential for WT-derived products. Nevertheless, product quality remains variable, and further improvements in upgrading technologies are necessary to meet industrial standards and regulatory requirements [2, 3].

Overall Conclusions and Logistics Implications

Across all thermal processes examined, several important conclusions can be drawn [4, 2]:

- Waste Tires are a high-energy, technically viable feedstock for thermal conversion systems.
- Operational stability decreases as tire percentages rise, making pre-treatment and reliable feed systems essential.
- Fused ash formation is a recurring problem in combustion and gasification, requiring enhanced ash-handling and cleaning logistics.
- Emission control becomes more challenging with high tire fractions, especially for sulfur emissions, requiring more advanced environmental management infrastructure.
- Gasification performs best at low to moderate tire shares (around 20%), balancing energy value and operational stability.
- Pyrolysis offers multiple product streams but introduces more complex logistics for storage, transport, and handling of outputs.

Despite the technological promise, several challenges hinder large-scale deployment. Major issues include feedstock heterogeneity, high energy requirements, complex pollutant emissions, tar formation in gasification, and the need for improved product purification. Additionally, economic barriers—such as fluctuating market prices, transportation costs, and competition with conventional fuels—limit commercial viability. These challenges underline the need for integrated solutions that combine technological innovation, effective logistics, policy support, and market development [2, 4].

Looking forward, the literature identifies multiple areas of growth. Advances in reactor design, catalyst development, and process optimization are expected to improve efficiency and reduce environmental impacts. Char upgrading and syngas utilization offer substantial pathways for value creation. Emerging techniques such as microwave pyrolysis and chemical looping gasification show potential for enhancing product quality and reducing contaminants. Furthermore, the increasing importance of circular economy strategies and low-carbon technologies is likely to strengthen the role of WT thermal-chemical processes in future waste management and energy systems [2, 3, 1].

The results show that a tire-to-energy system is feasible but must be designed with strong logistics planning. Fuel preparation, equipment selection, feeding reliability, ash management, and emission control all play central roles in determining long-term sustainability. For industrial applications, especially in contexts such as university research facilities or automation engineering laboratories, the most reliable performance will be achieved when tire percentages are carefully limited and supported by robust handling and pre-treatment infrastructure [4].

The literature concludes that thermal-chemical conversion provides a promising platform for transforming WT into useful energy and materials. To achieve sustainable large-scale implementation, continued research, technological innovation, and supportive policy frameworks will be necessary. Integrating these systems with efficient logistics, industrial automation, and resource recovery networks will be essential for fully realizing the environmental and economic benefits of WT-to-energy technologies [2, 3].

Chapter 3

Research Methodology

3.1 Research Design and Approach

This research adopts a qualitative case-study methodology to analyse waste tire-to-energy systems from a logistics and industrial automation perspective. The methodological focus is not on laboratory experimentation or chemical optimisation, but on understanding how real industrial actors organise material flows, manage operational constraints, and integrate pyrolysis and gasification technologies into existing waste and energy systems. This approach is particularly suitable for examining complex industrial processes where performance depends on coordination between logistics, automation, and market integration.

The methodology combines a systematic review of scientific literature with an analysis of publicly available industrial information. The literature review provides the theoretical and experimental background on waste tire conversion, while company-level data are used to contextualise these findings within real operational environments. This dual approach allows for the evaluation of how theoretical insights translate into industrial practice, especially in the Romanian context.

To strengthen methodological transparency and replicability in a secondary-data study, the overall research design follows well-established case-study logic (clear unit of analysis, explicit evidence chain, and triangulation across sources) and uses structured review and synthesis practices for the literature and documents [19, 20, 21, 22].

3.1.1 Case Study Selection and Rationale

Three companies were selected as case-study references due to their complementary roles within the waste tire–to–energy value chain in Romania. Gravita Europe represents an industrial operator directly involved in tire processing and pyrolysis-based recovery [23]. Geocycle Romania, part of the Holcim Group, represents an integrated waste management and co-processing actor with strong logistics capabilities and industrial linkages [24]. Beston Machinery represents the technology supply side, providing pyrolysis equipment and implementation support for industrial projects [25, 26].

The selection of these companies allows the analysis to cover the full system perspective, including feedstock sourcing and preparation, conversion technology deployment, and integration with industrial energy and material users. Together, they provide a representative framework for examining how logistics and automation shape the feasibility of waste tire conversion systems.

3.1.2 Gravita Europe as an Industrial Reference Case

Gravita Europe operates a tire recycling and pyrolysis-oriented facility in Romania and provides a practical example of industrial-scale waste tire conversion. According to published company information, Gravita describes a continuous process structure that includes tire collection, sorting, mechanical size reduction, pyrolysis treatment, and separation of recovered products [23]. This process structure highlights the importance of coordinated logistics flows, as continuous operation requires stable feedstock supply and consistent material preparation.

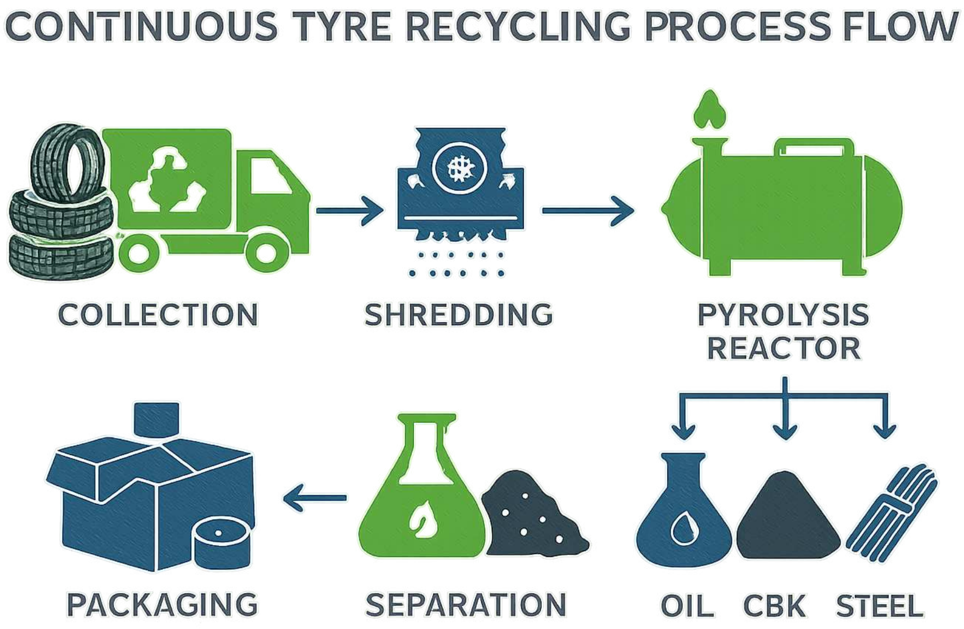


Figure 3.1: Continuous Tire Recycling Process Flow [23].

From a methodological standpoint, Gravita Europe is used to analyse how logistics decisions support continuous pyrolysis operation. The company's emphasis on feedstock preparation and controlled process flow reflects the literature findings regarding feeding stability and operational reliability [23]. The range of recovered outputs described by the company also illustrates the need for downstream logistics planning, including internal transport, storage capacity, and quality control [23].

The information published by Gravita Europe is therefore used as a reference for evaluating how industrial operators manage the transition from waste handling to energy and material recovery under real operating conditions [23].

3.1.3 Geocycle Romania and System Integration

Geocycle Romania operates as part of the Holcim Group's environmental services network and focuses on waste management and co-processing solutions for industrial users [24]. While Geocycle does not operate tire pyrolysis facilities directly, its activities provide insight into how waste-derived materials are integrated into large-scale industrial systems [24].

Methodologically, Geocycle Romania is used to examine logistics beyond the conversion plant boundary. The company's involvement in waste pre-processing, alternative fuel supply, and industrial co-processing demonstrates how stable logistics networks and established industrial demand can support waste-to-energy pathways [24]. This perspective is essential for understanding how tire-derived energy products can be absorbed into existing industrial operations.

Geocycle's role in landfill rehabilitation and industrial waste management further illustrates the importance of coordinated transport, staging, and regulatory compliance. These aspects inform the analysis of how tire-to-energy systems can be aligned with broader waste management and sustainability strategies at a regional level. [24]

3.1.4 Beston Machinery as a Technology Provider

Beston Machinery is analysed as a representative technology supplier for tire pyrolysis systems. According to company publications, Beston reports supplying pyrolysis plants to projects in Romania, including semi-continuous systems intended for industrial application [25, 26]. These projects demonstrate the practical deployment of conversion technology and the associated logistical and organisational requirements [25, 26].

Beston's role is used to assess how equipment design influences logistics and automation. The company's emphasis on modular plant design, continuous feeding options, and after-sales support reflects the need for technological solutions that accommodate material variability and operational constraints [25, 26]. The delivery and installation of equipment also highlight the importance of coordination between suppliers, operators, and local infrastructure [25, 26].

The information provided by Beston Machinery supports the evaluation of how technology suppliers shape the practical limits and opportunities of tire-to-energy systems through equipment design and implementation strategies [25, 26].

3.2 Analytical Framework

The analysis conducted in this thesis is based on a system-oriented framework that links logistics performance with operational stability. Information from the literature and company cases is synthesised to examine how feedstock preparation, storage capacity, feeding continuity, and product handling affect system feasibility [23, 24, 25]. Rather than comparing technologies on efficiency metrics alone, the framework evaluates how well different system components function together under realistic operating conditions.

This approach allows the identification of critical constraints and enabling factors that influence long-term operation. By focusing on logistics and automation, the framework provides a structured basis for assessing industrial tire-to-energy systems beyond theoretical potential.

Qualitative synthesis and coding of evidence

To make the synthesis step explicit (rather than implicit), the analysis was documented as a qualitative content-analysis procedure [27, 28]. Evidence extracted from literature and documents is grouped into operational categories aligned with the thesis scope, for example:

- **Upstream logistics:** collection structure, buffering/storage, transport constraints.
- **Pre-treatment and feeding:** size reduction, metal removal, feeding strategies, continuity risks.
- **Conversion stability:** operating constraints that link feed variability to process stability.

- **Downstream logistics:** storage and handling of oil/gas/char/steel/residues; offtake integration.
- **Compliance as capacity planning:** how emission limits and treatment stages create recurring logistics and operating burdens.

Within each category, repeated patterns are identified across sources: feeding stability is a binding constraint.

Early-stage screening, uncertainty, and sensitivity

Where the thesis uses simplified calculations (e.g., order-of-magnitude energy or capacity reasoning), the analysis reported the input ranges and the reason for selecting conservative midpoints, and then discuss how conclusions would change under reasonable parameter variation. This aligns with established sensitivity-analysis logic: conclusions should be tested against plausible uncertainty in key variables (yield ranges, calorific values, effective operating hours, transport distances, compliance operating expenditure (OPEX) [29].

Spatial/logistics siting as a multi-criteria problem

When discussing plant location options, the siting question was presented as a multi-criteria decision problem combining proximity to feedstock, access to transport corridors, proximity to industrial demand, and regulatory feasibility. Geographic information system (GIS)-based multi-criteria decision analysis is a standard approach to justify such siting arguments transparently (criteria definition, weighting rationale, sensitivity to weights) [30].

Staged design reasoning: screening calculations and system-chain representation. In design-oriented tire waste-to-energy research, a common analytical structure is to combine a simplified screening method with a more detailed system representation. A recent study on flue-gas composition and treatment potential presents two complementary methodologies for the design phase: a calculation-based approach that can be implemented in spreadsheet form for early estimates, and a process-simulation approach capable of representing treatment stages and estimating operational requirements for emissions control. This staged logic supports the analytical framework of the present thesis, where the aim is to connect controllable operating choices with downstream handling requirements and compliance constraints through transparent, system-level reasoning [5].

3.2.1 Methodological Limitations

The methodology is limited by the reliance on publicly available information, which may not capture all operational details of industrial facilities [23, 24, 25]. Quantitative performance data are often not disclosed by companies, restricting the analysis to qualitative assessment. Nevertheless, the use of multiple sources and cross-referencing with scientific literature helps mitigate this limitation.

Despite these constraints, the methodology provides a robust basis for evaluating waste tire-to-energy systems as integrated industrial processes, consistent with the objectives of this thesis.

3.3 Background of Companies

3.3.1 Gravita Europe

Gravita Europe presents itself as a Romania-based operator focused on converting end-of-life tires into raw materials and describes a processing capability of up to 18,000 metric tonnes of scrap tires per year [23]. The company describes a continuous tire recycling plant and a closed-loop approach aimed at maximizing recovery and minimizing emissions [23].

The company lists several outputs and product categories connected to tire processing, including tire pyrolysis oil (TPO), rubber crumb, and carbon-char/carbon-related materials [23]. The rubber crumb page describes production via mechanical recycling methods with separation of tire components and quality controls aimed at purity and uniformity [31].

For Romania presence, the website publishes a specific address in Județ Neamţ, 617188, Romania [23]. Regarding sourcing and logistics, the company describes collection and sorting practices for tires and includes Romania-focused guidance discussing documentation/traceability and pickup logistics for businesses [23].

Concerning rules and compliance, the company states that it adheres to EU environmental regulations and presents sustainability-oriented claims about monitoring or managing emissions and waste streams. For costs, the website uses qualitative language such as cost-effective and competitive rates, but it does not publish a numeric tariff schedule, gate fees, or EUR/ton pricing on the reviewed pages [23].

3.3.2 Geocycle Romania (Holcim)

Geocycle Romania describes itself as an environmental services provider integrated into Holcim Romania, offering services such as waste assessment, laboratory analysis/characterization, logistics/transport, and preparation of waste for co-processing in cement plants [24]. With respect to tires, Geocycle Romania states that every year it sends for co-processing thousands of tons of waste tires and frames this within a logistics and processing pathway connected to cement plants [24].

Also identifies locations associated with its service model, stating that in Aleșd and Câmpulung it offers pre-processing and co-processing solutions, and it refers to cement kilns in Câmpulung and Aleșd [24]. For the process definition and rules, Geocycle's published materials describe co-processing in cement kilns as a high-temperature process over extended time and frame it as aligned with standards and environmental permitting [24].

Geocycle also publishes acceptance and exclusion principles 9by its published materials, including examples of waste streams it may handle (including tires) and exclusions [24]. The Romania page also states that its laboratory is accredited by the Romanian Accreditation Association (RENAR) and lists a range of testing and analytical capabilities [24].

3.3.3 Beston Machinery

On the specific case page provided, Beston Machinery states that a BLJ-16 semi-continuous tire pyrolysis plant and a BZJ-10 waste oil distillation plant were shipped to Romania [25, 26]. The same page describes the intended chain as producing oil from waste tires/rubber via pyrolysis and then purifying or upgrading that oil through a distillation unit [25, 26]. The page also makes environmental and economic claims about the solution [25, 26].

Regarding costs, the Romania case page does not publish an equipment price or full cost breakdown [25, 26]. The page includes a contact flow that requests information such as the buyer's budget for machinery purchasing, which indicates that pricing is handled through inquiry rather than a published price list [25, 26].

In this thesis, these actors are positioned within the broader tire end-of-life value chain as different actor types based on their published descriptions. Gravita Europe describes an operational facility converting tires into material outputs such as oil and carbon-related products [23], Geocycle Romania describes waste management and co-processing of tires in cement kilns [24], and Beston describes supplying pyrolysis and oil distillation equipment and reports at least one shipment of such equipment to Romania [25, 26].

3.4 Cost and Benefit

This section synthesizes publicly available information relevant to converting end-of-life tires (ELT) into energy and energy-related products in Romania, with emphasis on (i) the size of the ELT stream, (ii) the Romanian and EU regulatory context for ELT management, (iii) existing Romanian treatment capacity and market demand (including cement co-processing), and (iv) an evidence-based reasoning framework for whether additional ELT-to-energy capacity is needed, where it could be located, and how costs may compare to energy outputs.

3.4.1 Romania ELT Market Demand and Available Feedstock

Tires placed on the Romanian market and ELT quantities

Romania's national waste management planning documents provide historical quantities of tires placed on the market and tires collected [32]. In the National Waste Management Plan (Planul Naţional de Gestionare a Deşeurilor, National Waste Management Plan(PNGD)), the reported quantities of tires placed on the market (tonnes) for 2011–2015 are 78,592 (2011), 74,702 (2012), 74,666 (2013), 80,135 (2014), and 77,060 (2015), while collected quantities (tonnes) are 56,556 (2011), 55,272 (2012), 61,381 (2013), 64,878 (2014), and 51,816 (2015) [32]. The same PNGD section states that the 2015 collected quantity was insufficient for meeting the collection obligation, indicating a remaining need of 9,832 tonnes for compliance and noting a reported collection rate of 67% for the referenced compliance calculation [32].

For a more recent market proxy, the Romanian Environmental Fund Administration (Administraţia Fondului pentru Mediu, the Environmental Fund Administration (AFM)) publishes totals of tires introduced to the Romanian market for fee and contribution administration. AFM reports a total of 102,201,063 kg of tires introduced to the national market for 01.01.2023–31.12.2023 [33]. This figure is not a direct measure of ELT generated in the same year (because tires remain in use for multiple years), but it is a useful indicator of the national scale of the tire flow that eventually becomes ELT.

3.4.2 Current demand channels for ELT management in Romania

Romania has a structurally important demand channel for the energetic use of ELT via cement kilns. The PNGD reports that roughly 80% of the collected ELT quantity is valorised through co-processing in cement plants and that the total co-processing capacity for waste tires across the seven cement plants is approximately 110,000 tonnes per year [32].

More broadly, the PNGD describes seven cement plants authorised for waste co-incineration in Romania and lists their operators and counties: CRH Romania (Braşov, Constanţa), HeidelbergCement Romania (Hunedoara, Dâmboviţa, Neamţ), and Holcim Romania (Bihor, Argeş) [32].

Geocycle Romania (a Holcim-related waste management and co-processing operator) publicly states that it directs waste tires to co-processing within the cement production process and describes dedicated storage, feeding, and automated co-processing equipment as well as logistics services for waste transport to the cement plants [24].

Taken together, these sources support the conclusion that Romania already has a large, operational, energy-recovery demand channel for ELT (cement co-processing), with capacities comparable to the order of magnitude of national tire flows reported in planning and administrative datasets [32, 33].

3.4.3 Regulatory and Compliance Framework Relevant to ELT-to Energy Projects

Romanian ELT-specific obligations

Romania's ELT management framework is anchored in Government Decision (HG) 170/2004 regarding waste tire management [34]. The PNGD references the HG 170/2004 mechanism and discusses collection obligations and compliance gaps in the analyzed period [32].

For project developers, the general waste regime (including permitting and authorisation requirements for waste treatment operators) is addressed under Emergency Ordinance (OUG) 92/2021 regarding the waste regime [35]. In addition, the Environmental Fund contribution mechanism relevant to shortfalls is reflected in AFM-published legislation and procedures, including Ordin 3173/2023 (as published by AFM) specifying a contribution of 2 lei/kg in the context of declared quantities and compliance administration for several waste streams including tires [36].

Emissions limits as design constraints for monitoring and treatment capacity. Literature on waste-to-energy incineration emphasises that regulatory requirements translate directly into design constraints, because permitted emission ranges determine both monitoring needs and the selection of treatment stages. A design-oriented study summarises applicable emissions targets for waste-to-energy plants in Europe and discusses how achieving these targets can require staged reduction solutions when a single technique is insufficient. In practical terms, compliance therefore becomes a capacity-planning problem: the plant must be designed and operated so that upstream process conditions and downstream treatment capability remain aligned under expected throughput variability [5].

3.4.4 EU context: landfill restrictions and the policy preference for recovery

At EU level, the Landfill Directive (1999/31/EC) includes restrictions that were implemented as bans on landfilling whole tires from 16 July 2003 and shredded tires from 16 July 2006, reinforcing the policy direction toward reuse, recycling, and recovery routes [37].

3.4.5 Existing Romanian Treatment Capacity Beyond Co-processing

Material recycling and thermal treatment referenced in national planning

The PNGD lists additional ELT treatment routes in Romania beyond co-processing, including mechanical recycling (rubber powder), retreading, and thermal degradation (pyrolysis-type operations classified as recovery operation R3 (recycling/reclamation of organic substances)in the cited document) [32]. It identifies named recyclers for rubber powder and mentions a thermal degradation operator (Power Oil Company S.R.L., Chişoda, Timiş) and states that, in total, 50 economic operators are registered as valorising waste tires [32].

3.4.6 Gravita Europe as a currently operating pyrolysis-based recycler in Romania

Gravita Europe publicly describes itself as operating a tire recycling facility in Romania with a processing capacity of up to 18,000 metric tonnes of scrap tires per year, producing outputs such as tire pyrolysis oil (TPO), recovered carbon black/carbon materials, and steel [23].

Independent industry reporting also describes an ambition to expand Romanian capacity from 18,000 to 45,000 tonnes over approximately two years [31].

3.4.7 Is one company enough for Romania's ELT-to-Energy needs?

If the objective is national ELT management through any compliant recovery route, then existing Romanian cement co-processing capacity (reported at about 110,000 tonnes/year for waste tires) already represents a large energy-recovery sink for ELT, and national planning documents indicate that co-processing is historically the dominant route for collected tires [32].

If the objective is instead to convert most Romanian ELT into pyrolysis-derived energy carriers (such as TPO and combustible pyrolysis gas) and material outputs (such as recovered carbon black), then a single 18,000 t/y facility cannot physically process the full national scale suggested by administrative and planning figures [23, 33]. Using AFM's 2023 tire introduction total (102,201 t) only as a scale proxy, 18,000 t/y corresponds to about 18% of that flow, and even a 45,000 t/y expansion would correspond to about 44% of that proxy flow [33, 31]. This reasoning does not assert that 2023 ELT generation equals 2023 introductions; it only shows that one facility at the published capacities is unlikely to represent national-scale coverage if pyrolysis were intended to dominate ELT treatment.

Therefore, one pyrolysis-based company is not sufficient to replace all other ELT recovery routes at national scale unless it expands substantially and/or unless additional plants are built. Conversely, one company can still be "enough" for a targeted regional project, a niche product strategy, or a partial diversion strategy away from cement kilns.

3.4.8 Where could a new ELT-to-Energy plant be located in Romania?

A defensible siting argument is developed using publicly documented Romanian infrastructure for ELT recovery and the logistics implications of heavy, bulky feedstock.

Romania's cement co-processing infrastructure is geographically distributed across counties including Braşov, Constanţa, Hunedoara, Dâmboviţa, Neamţ, Bihor, and Argeş, as reported in the PNGD [32]. Gravita Europe's published facility address is in Sat Izvoare, Comuna Dumbrava Roşie, Judeţ Neamţ, indicating an existing pyrolysis-based processing node in the North-East [23].

From these published facts, a reasonable thesis recommendation (as an analytical inference rather than a reported fact) is that a new ELT-to-energy plant would reduce transport costs and increase feedstock resilience if it is placed to complement the existing North-East node and to serve high-traffic corridors and industrial demand centres.

3.4.9 Costs, Energy Yields, and a Transparent Techno-Economic reasoning framework

Emissions compliance as a recurring cost and logistics driver. Beyond energy yield, waste-to-energy feasibility is shaped by the cost and operational burden of meeting emissions limits. Design literature notes that achieving required performance can demand multiple treatment stages and that some configurations introduce additional operational needs. From a logistics viewpoint, these requirements imply recurring costs and planning tasks, including supply of treatment inputs, residue handling, maintenance scheduling, and coordination between upstream operating conditions and downstream treatment capacity. Therefore, a transparent techno-economic reasoning framework should treat emissions control as a core subsystem rather than an add-on [5].

Evidence-based ranges for product yields and energy content

Peer-reviewed reviews report that waste tire pyrolysis typically yields oil, char, and gas in broad ranges, with one review summarising literature-reported ranges of approximately 30–65% oil, 25–45% char, and 5–20% gas (mass basis), depending on reactor type and operating conditions [2].

A technical study reports calorific values for tire pyrolysis oil and char, providing an empirical anchor for energy calculations. In that source, tire pyrolysis oil has reported higher heating value (HHV) / lower heating value (LHV) values of 49.5/46.7 MJ/kg, and solid char has HHV/LHV values of 34.7/33.7 MJ/kg [38].

3.4.10 A conservative illustrative energy calculation per tonne of tires

To translate the cited ranges into a single illustrative calculation (clearly labelled as an engineering estimate), consider a representative mid-point mass split of 45% oil and 35% char, with the remainder being gas and steel. This selection lies within published ranges and is used only to estimate order-of-magnitude energy content [2].

For one tonne (1,000 kg) of tires, the thermal energy embodied in the oil and char streams is estimated as

$$E_{\mathrm{th}} \approx (0.45 \cdot 1000 \cdot 46.7) + (0.35 \cdot 1000 \cdot 33.7) \text{ MJ} \approx 3.28 \times 10^4 \text{ MJ}. \tag{3.0}$$

This equals about 9.11 $\mathrm{MWh_{th}}$ per tonne (using 1 MWh = 3,600 MJ). The combustible gas stream could increase usable energy further, but it is omitted here to keep the estimate anchored tightly to the cited calorific values for oil and char [38].

Scaling this estimate to published Romanian plant capacities gives approximately 164,000 $\mathrm{MWh_{th}}$/year for an 18,000 t/y facility and approximately 410,000 $\mathrm{MWh_{th}}$/year for a 45,000 t/y facility, under the same illustrative assumptions [23, 31].

Public sources provide partial cost signals rather than a single Romanian benchmark. Industry reporting on Gravita's entry into Romania describes a transaction-scale investment on the order of Indian rupees (INR) 400 million (40 crore) for acquiring a Romanian ELT recycling plant (reported capacity around 17,000 t/y) [39]. This is a transaction-specific figure and should not be treated as a universal capital expenditure (CAPEX) benchmark, but it is a useful published reference point for order-of-magnitude discussion.

Independent academic work provides an additional lens on operating economics. One published economic analysis reports per-tonne economics for a mid-sized scrap tire pyrolysis plant and discusses processing costs and per-tonne value generation, which is used as a comparative benchmark when building Romanian scenarios (after adjusting for Romanian labour, utilities, compliance, and offtake pricing) [40].

To answer to whether costs are "worth the energy ultimately gained" should not rely on a single energy price. Instead, it should compute a break-even condition. If CAPEX is denoted by C, annual processed tonnage by Q, net sellable energy per tonne by e ($\mathrm{MWh_{th}/t}$), conversion efficiency to the sold energy form by η, and net realised selling price by p (currency/MWh), then the annual energy revenue is approximately $R \approx Q \cdot e \cdot \eta \cdot p$. A simple payback estimate is

$$\text{Payback (years)} \approx \frac{C}{R - \text{OPEX}} \tag{3.0}$$

where OPEX should include feedstock logistics, pre-processing, labour, maintenance, permitting, emissions control, and residue management under Romanian authorisation requirements [35, 5].

Because Romania already has an established ELT energy recovery pathway in cement kilns, the economic case for a new pyrolysis plant is typically stronger when revenue is not limited to “energy-only” sale, but also includes higher-value material recovery and, where applicable, gate fees or compliance-driven demand for non-cement recovery routes [32, 23]. The PNGD notes that Romania’s reliance on cement co-processing is high and that recycling capacities were identified as low in the referenced period, supporting an argument that additional capacity can be justified when it improves circularity outcomes beyond energy-only recovery [32].

3.4.11 Relationship Among Gravita Europe, Geocycle Romania, and Beston

Gravita Europe is a Romanian-based tire recycling operator that publishes a process converting ELT into products such as tire pyrolysis oil, recovered carbon materials, and steel, with a stated capacity of up to 18,000 t/y and a published facility location in Judeţ Neamţ [23].

Geocycle Romania publishes that it manages waste through co-processing in cement kilns and explicitly includes waste tires as a stream it directs to co-processing, describing logistics and automated feeding/co-processing equipment at the cement plants [24]. This positions Geocycle primarily as an alternative-fuels and recovery-services channel tied to cement production rather than a pyrolysis recycler.

Beston is a technology and equipment supplier that publishes case stories about shipping and installing pyrolysis plants to and in Romania, including tire pyrolysis equipment delivered to Romania [25, 26]. Beston is therefore not inherently an ELT manager, but a potential enabling supplier for Romanian operators that develop pyrolysis capacity.

The main relationship among the three entities, based on their published materials, is that Gravita and Geocycle represent two different ELT recovery pathways (pyrolysis-based recycling versus cement co-processing) [23, 24], while Beston is positioned as an upstream equipment supplier that can increase the number of Romanian pyrolysis operators (and therefore potentially intensify competition for ELT feedstock or expand national pyrolysis capacity) [25, 26].

Chapter 4

Conclusion

In this thesis, I investigated the conversion of end-of-life tires into energy and reusable materials through pyrolysis and gasification, adopting a perspective grounded in logistics and industrial automation. Rather than analysing chemical reactions or material compositions, the work focused on how waste tire-to-energy systems perform as industrial systems, where success depends on coordinated material flows, stable operation, and integration with existing industrial and logistics networks. The combined analysis of the several scientific articles and the selected industrial actors leads to a clear and consistent conclusion: the feasibility, sustainability, and long-term performance of tire-to-energy plants are determined primarily by logistics-driven operational reliability rather than by conversion technology alone.

Both pyrolysis and gasification are technically capable of converting waste tires into usable energy carriers and material outputs. Experimental and review studies demonstrate that tires can be thermochemically processed to generate combustible gases, liquid fuels, and solid carbon-rich residues. However, these same studies repeatedly show that technical feasibility does not automatically translate into industrial feasibility. Gasification systems, while capable of producing a combustible gas, are shown to operate within a narrow stability range when processing tire-derived material. Increasing the proportion of tires beyond certain limits leads to feeding interruptions, unstable operation, and accumulation inside the reactor, ultimately forcing shutdowns. These limitations are described in the literature not as chemical failures, but as mechanical and operational constraints linked to the physical behavior of the tire material.

Pyrolysis systems offer greater flexibility by producing multiple output streams and operating under more controlled conditions. However, this flexibility comes at the cost of stricter requirements for feedstock preparation, feeding stability, and downstream handling. The literature clearly indicates that pyrolysis systems are particularly sensitive to feedstock quality and contaminants, and that inconsistent feeding leads to fluctuations in output and reduced reliability. Across both technologies, the literature converges on a fundamental insight: the effective operating window of tire-to-energy systems is defined by logistics and automation constraints. Feeding systems, storage capacity, material preparation, and product handling determine whether a plant can operate continuously or must run intermittently at reduced capacity.

In addition, the automation part of the system constraint is not limited to mechanical feeding stable operation also depends on measurement and diagnostics. In industrial reactors, the most important internal variables are not always directly measurable in real time, so plants rely on robust monitoring architectures that combine indirect measurements (e.g., external temperatures), estimation based on known wall and lining characteristics, and redundant sensors to detect drift,blockages, or abnormal thermal behaviour early. This reinforces the central conclusion of the thesis: operational reliability is achieved through coordinated logistics and control design, not through the conversion reactor alone.

A major contribution of the reviewed studies is the recognition that waste tires behave very differently from conventional fuels. Their size, elasticity, and heterogeneous structure create challenges at every stage of the supply chain, from collection and transport to feeding and residue removal. The literature consistently shows that insufficient attention to these characteristics results in blockages, downtime, and increased manual intervention. Feedstock preparation emerges as a decisive factor. Mechanical size reduction and metal separation are not auxiliary operations, but enabling conditions for stable operation. When these steps are poorly designed or inconsistently applied, even well-designed reactors experience frequent operational problems. As a result, the literature suggests that system design should prioritise consistency and reliability over maximum throughput.

Equally important is downstream logistics. Pyrolysis produces multiple output streams, each requiring dedicated storage, safety systems, and distribution routes. In practice, downstream planning must also account for product usability: tire-derived liquids and solids can require conditioning (for example separation, blending, distillation, or desulphurisation-related upgrading)before they can be reliably marketed or used within industrial systems. Gasification concentrates value mainly into a gaseous stream, but introduces requirements for gas cleaning and residue handling that affect plant layout and operation. In both cases, downstream bottlenecks are shown to limit overall plant performance, even when conversion units function as intended.

Beyond energy yield, feasibility is also shaped by the operational burden of environmental compliance. Emissions limits and monitoring requirements translate into design and planning constraints: the treatment chain, residue handling, and maintenance schedule must be sized so that they remain adequate under expected feedstock variability and throughput fluctuations. From a logistics viewpoint, compliance therefore becomes a capacity-planning problem that links upstream operation to downstream cleaning and residue-management capability.

The sustainability-focused articles and the life cycle assessment study deepen the system-level conclusions by showing that environmental performance is tightly linked to operational and logistics decisions. The life cycle assessment of an industrial-scale fast pyrolysis plant demonstrates that tire-to-energy systems can provide environmental benefits compared to conventional disposal routes, particularly by avoiding landfilling and by substituting fossil-based fuels. However, the LCA results also make clear that these benefits depend strongly on how the process is operated and integrated. One of the most important findings is the positive impact of internal energy integration. When non-condensable gases produced during pyrolysis are reused on-site to supply process heat, the overall environmental performance improves compared to scenarios where external fuels are required. This result links sustainability directly to logistics and plant design, as internal energy loops reduce external fuel transport, storage, and associated emissions.

The literature further emphasizes that pre-treatment and logistics stages contribute to environmental impacts through energy use and transport emissions. Shredding, separation, storage, and transport are not environmentally neutral activities. Nevertheless, the studies show that these impacts can be offset when tire-derived energy and materials displace conventional fuels and virgin resources. This reinforces the importance of minimising transport distances, avoiding unnecessary handling steps, and stabilising operation to achieve positive life-cycle outcomes. From a broader sustainability perspective, the reviewed articles frame pyrolysis and gasification as technologies that support circular economy objectives by extending the value of waste tires beyond disposal. However, they also caution that poor system design can undermine these benefits. Unstable feeding, inefficient energy use, or accumulation of by-products increase energy consumption and emissions, reducing overall sustainability. Sustainability therefore emerges not as an inherent property of the technology, but as the result of integrated logistics, automation, and operational planning.

The literature and industrial evidence suggest that tire-to-energy plants have the greatest positive effect when they are embedded within existing industrial systems. Integration with energy-intensive industries reduces the need for extensive storage and long-distance transport, stabilises demand for recovered products, and improves overall system efficiency. Gravita Europe presents an industrial example of continuous tire processing and pyrolysis-based recovery, explicitly framing its activity around converting waste tires into reusable products rather than disposing of them. The company's emphasis on continuous operation, controlled feedstock preparation, and product recovery mirrors the operational priorities identified in the literature. Geocycle Romania, part of the Holcim Group, demonstrates how waste tires can be integrated into established industrial systems through co-processing, automated feeding, and organised logistics. This approach directly addresses the downstream challenges by providing stable demand, existing infrastructure, and regulated operating environments. Beston Machinery illustrates the availability of industrial-scale pyrolysis technology and its deployment in Romania.

In the Romanian context, the existence of a large cement co-processing pathway means that new pyrolysis or gasification capacity must justify itself through system advantages beyond "energy only", such as higher-value material recovery, stronger circularity outcomes, and reliable regional logistics performance. This also supports using a transparent techno-economic reasoning approach: viability should be assessed by linking achievable throughput and product yields to realised offtake prices, while explicitly accounting for recurring costs driven by logistics, pre-treatment, compliance, emissions control, and residue management. Under these conditions, plant integration with established industrial users reduces market risk and improves the probability of stable, economically viable operation.

The documented installation of tire pyrolysis units confirms that technology supply is no longer the primary barrier. Instead the decisive challenges lie in feedstock logistics, operational stability, and product integration.

Bringing together the reviewed literature and the industrial case context and the industrial case context, this thesis reaches a comprehensive conclusion. Pyrolysis and gasification offer viable pathways for converting waste tires into energy and materials, but their success depends on system-level integration rather than process chemistry. Logistics reliability, feeding stability, and the capacity of downstream handling, product conditioning, gas cleaning, and residue management define both operational performance and sustainability outcomes, particularly under variability and compliance requirements. In parallel, robust monitoring and control strategies are essential because key internal process states are not always directly measurable in industrial operation. When tire-conversion plants are designed as integrated industrial systems where logistics, automation, compliance capacity, energy integration, and product utilisation are coordinated—life cycle assessments indicate that meaningful environmental benefits can be achieved. In the Romanian context, where cement co-processing already provides a major recovery route, additional deployment is therefore strongest when it is integrated with existing industrial users and backed by credible offtake pathways. Under these conditions, waste tires are transformed from an environmental burden into a managed industrial resource that contributes to energy recovery, material reuse, and circular economy objectives.

References

[1] H Afash, B Ozarisoy, and H Altan. “Biofuel production using tire waste in fast pyrolysis: A life cycle assessment study”. In: *Sustainable Environment* 11.1 (2025), p. 2510728.

[2] Shoujun Wang et al. “From waste to energy: Comprehensive understanding of the thermal-chemical utilization techniques for waste tire recycling”. In: *Renewable and Sustainable Energy Reviews* 211 (2025), p. 115354.

[3] Hisham Afash et al. “Recycling of tire waste using pyrolysis: An environmental perspective”. In: *Sustainability* 15.19 (2023), p. 14178.

[4] Luís Carmo-Calado et al. “Co-combustion of waste tires and plastic-rubber wastes with biomass technical and environmental analysis”. In: *Sustainability* 12.3 (2020), p. 1036.

[5] Qahtan Thabit, Abdallah Nassour, and Michael Nelles. “Flue gas composition and treatment potential of a waste incineration plant”. In: *Applied sciences* 12.10 (2022), p. 5236.

[6] Dina Czajczyńska et al. “Use of pyrolytic gas from waste tire as a fuel: A review”. In: *Energy* 134 (2017), pp. 1121–1131.

[7] Francesco Lombardi et al. “Waste incineration in rotary kilns: a new simulation combustion tool to support design and technical change”. In: *Waste Management & Research* 31.7 (2013), pp. 739–750.

[8] NEUWAHL Frederik et al. *Best Available Techniques (BAT) Reference Document for Waste Incineration: Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control).* Tech. rep. Joint Research Centre, 2020.

[9] Dóra Mentes et al. “Investigation of gaseous and solid pollutants emitted from waste tire combustion at different temperatures”. In: *Waste Management* 149 (2022), pp. 302–312.

[10] M Rofiqul Islam et al. “Innovation in pyrolysis technology for management of scrap tire: a solution of energy and environment”. In: *International Journal of Environmental Science and Development* 1.1 (2010), p. 89.

[11] Frederik Neuwahl et al. “Best available techniques (BAT) reference document for waste incineration: industrial emissions directive 2010/75/EU (Integrated Pollution Prevention and Control)”. In: (2019).

[12] BEUMER Group GmbH & Co. KG. *Fully automated tyre transport system ensures continuous feed of waste tyres.* Plant report; published in ZKG issue 7–8/2019. ZKG International. 2019. URL: `https://www.zkg.de/en/artikel/zkg_Fully_automated_tyre_transport_system_ensures_continuous_feed_of_waste-3403313.html` (visited on 02/23/2026).

[13] Heidelberg Materials. *Alternative Fuels & Raw Materials (AFR) Policy.* May 2024. URL: `https://www.heidelbergmaterials.com/sites/default/files/2024-05/Heidelberg_Materials_AFR_Policy.pdf` (visited on 02/23/2026).

[14] Heidelberg Materials. *Glossary: Alternative fuels*. n.d. URL: `https://www.heidelbergmaterials.com/en/company/glossary` (visited on 02/23/2026).

[15] HeidelbergCement. *Alternative Fuels: Indispensable Resources for Sustainable Production*. n.d. URL: `https://www.heidelbergmaterials.com/sites/default/files/assets/document/74/27/heidelbergcement-factsheet-alternative-fuels.pdf` (visited on 02/23/2026).

[16] BEUMER Group. *System technology for alternative fuels for re-use in cement plants*. n.d. URL: `https://www.beumergroup.com/industry/cement/system-technology-for-alternative-fuels/` (visited on 02/23/2026).

[17] BEUMER Group. *BEUMER Systems for Solid Alternative Fuels: Conveying Technology*. Brochure (PDF). Also provided in the BEUMER download area; ident. no. 3003368-BE-200-V1-0.5-EN-0116-GB150589. 2017. URL: `https://www.beumergroup.com/app/uploads/2019/03/BEUMER-Systems-Solid-Alternative-Fuels.pdf` (visited on 02/23/2026).

[18] Alessandro Dal Pozzo, Sarah Capecci, and Valerio Cozzani. “Techno-economic impact of lower emission standards for waste-to-energy acid gas emissions”. In: *Waste Management* 166 (2023), pp. 305–314.

[19] Robert K. Yin. *Case Study Research and Applications: Design and Methods*. 6th ed. Los Angeles: SAGE Publications, 2018. ISBN: 9781506336169.

[20] Kathleen M Eisenhardt. “Building theories from case study research”. In: *Academy of management review* 14.4 (1989), pp. 532–550.

[21] Hannah Snyder. “Literature review as a research methodology: An overview and guidelines”. In: *Journal of business research* 104 (2019), pp. 333–339.

[22] David Tranfield, David Denyer, and Palminder Smart. “Towards a methodology for developing evidence-informed management knowledge by means of systematic review”. In: *British journal of management* 14.3 (2003), pp. 207–222.

[23] Gravita Europe SRL. *Gravita Europe*. Accessed: 2026-01-28. 2026. URL: `https://gravitaeurope.com/` (visited on 01/28/2026).

[24] Geocycle (Holcim Group). *Geocycle Romania*. Accessed: 2026-01-28. 2026. URL: `https://www.geocycle.com/romania` (visited on 01/28/2026).

[25] Beston Machinery. *Beston Machinery*. Accessed: 2026-01-28. 2026. URL: `https://bestonmachinery.com/` (visited on 01/28/2026).

[26] Beston Group. *BLJ-16 pyrolysis plant and BZJ-10 distillation machine shipped to Romania*. Case page accessed: 2026-01-28. 2019. URL: `https://bestongroup.com/project/blj-16-pyrolysis-plant-and-bzj-10-distillation-machine-shipped-to-romania/` (visited on 01/28/2026).

[27] Hsiu-Fang Hsieh and Sarah E Shannon. “Three approaches to qualitative content analysis”. In: *Qualitative health research* 15.9 (2005), pp. 1277–1288.

[28] Philipp Mayring. “Qualitative Content Analysis”. In: *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research* 1.2 (2000). Accessed: 2026-02-08, Art. 20. URL: `https://www.qualitative-research.net/index.php/fqs/article/view/1089`.

[29] Andrea Saltelli et al. *Global sensitivity analysis: the primer*. John Wiley & Sons, 2008.

[30] Jacek Malczewski. “GIS-based multicriteria decision analysis: a survey of the literature”. In: *International journal of geographical information science* 20.7 (2006), pp. 703–726.

[31] Tyre & Rubber Recycling. *Gravita Group expands into tyre recycling to build a full circular value chain.* Accessed: 2026-01-28. 2025. URL: `https://www.tyreandrubberrecycling.com/articles/granulation/gravita-group-expands-into-tyre-recycling-to-build-a-full-circular-value-chain/` (visited on 01/28/2026).

[32] Ministerul Mediului (Romania). *Planul Naţional de Gestionare a Deşeurilor (PNGD).* Tech. rep. Accessed: 2026-01-28. Ministerul Mediului, 2017. URL: `https://www.mmediu.ro/app/webroot/uploads/files/PNGD_vers5.pdf` (visited on 01/28/2026).

[33] Administraţia Fondului pentru Mediu (AFM). *Cantităţi totale de anvelope noi şi/sau uzate destinate reutilizării introduse pe piaţa naţională ın anul 2023.* AFM reporting page. 2023. URL: `https://afm.ro/main/venituri/2025/taxe_cantitati_deseuri_anvelope_introduse_piata_nationala_2023.pdf` (visited on 01/28/2026).

[34] Guvernul României. *Hotărârea Guvernului nr. 170/2004 privind gestionarea anvelopelor uzate.* Accessed: 2026-01-28. 2004. URL: `https://legislatie.just.ro/Public/DetaliiDocument/49879` (visited on 01/28/2026).

[35] Guvernul României. *Ordonanţa de urgenţă nr. 92/2021 privind regimul deşeurilor.* Accessed: 2026-01-28. 2021. URL: `https://legislatie.just.ro/Public/DetaliiDocument/248080` (visited on 01/28/2026).

[36] Ministerul Mediului, Apelor şi Pădurilor (Romania). *Ordin nr. 3173/2023 (contribuţii/obligaţii pentru anumite fluxuri, inclusiv anvelope).* Accessed: 2026-01-28. 2023. URL: `https://legislatie.just.ro/Public/DetaliiDocument/277946` (visited on 01/28/2026).

[37] European Union. *Council Directive 1999/31/EC on the landfill of waste.* Accessed: 2026-01-28. 1999. URL: `https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:31999L0031` (visited on 01/28/2026).

[38] Elena Cristina Rada et al. “Energy recovery from tyres waste through thermal option”. In: *UPB Scientific Bulletin, Series D: Mechanical Engineering* 74.4 (2012), pp. 201–210. URL: `https://www.researchgate.net/publication/235424640_Energy_recovery_from_tyres_waste_through_thermal_option` (visited on 01/28/2026).

[39] Business Standard. *Gravita to acquire a 17,000 MTPA waste tyre plant in Romania.* Last updated: Sep 11, 2024 (Capital Market news feed on Business Standard). Accessed: 2026-01-28. Sept. 2024. URL: `https://www.business-standard.com/markets/capital-market-news/gravita-to-acquire-a-17-000-mtpa-waste-tyre-plant-in-romania-124091100667_1.html` (visited on 01/28/2026).

[40] Fatma Pinar Goksal. “An economic analysis of scrap tire pyrolysis, potential and new opportunities”. In: *Heliyon* 8.11 (2022), e11669. DOI: `10.1016/j.heliyon.2022.e11669`.