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Waste-based fuels as part of sustainable mobility

Bence ZSOLDOS
Széchenyi University
Győr, Hungary
zsoldos.bence@ga.sze.hu

Abstract

The transition to sustainable energy systems necessitates innovative waste management and fuel production approaches. This study provides a comprehensive overview of waste-based fuels, emphasising their role in promoting circular economy principles and reducing environmental burdens. Various waste streams, including agricultural residues, sewage sludge, food waste, plastic waste, and end-of-life tyres, are examined for their potential to be converted into valuable energy carriers, such as biofuels, syngas, biogas, and fuel oils. The review synthesises findings from recent literature, highlighting thermochemical (e.g., pyrolysis, gasification) and biochemical (e.g., anaerobic digestion) conversion technologies. Key insights include the feasibility of integrating waste-derived fuels into existing combustion systems, the potential for emission reduction, and the ongoing economic and technological challenges. The concept of biorefineries is identified as a promising strategy for maximising resource efficiency and economic viability. The study concludes with a call for further research, particularly life cycle assessments (LCA), to evaluate these technologies' environmental and economic impacts. Based on the literature analysis, it can be concluded that waste-derived fuels can be used in existing internal combustion engines; however, further optimisation may be necessary. Moreover, there is great potential in converting waste into useful energy; however, further research is needed to develop these methods.

Keywords

waste-based fuels, circular economy, pyrolysis, anaerobic digestion, biorefinery, sustainability, alternative fuels

1. Introduction

Waste-based fuels are paramount for sustainability and environmental protection for several reasons. Human activity, both during production and consumption, generates significant waste. The development and application of waste-based fuels enables the utilisation of these materials, thereby reducing the amount of waste going to landfills (Torok, Torok, Heinitz, 2014).

One of the fundamental objectives of sustainability is to recycle and use materials generated as by-products or losses of original products (Németh, 2017). Fuels obtained from waste fit into the circular economy system along this principle. The recycling of materials, including the production of fuels from waste, generally involves less energy consumption than the extraction, transportation, and processing of raw materials. This reduces greenhouse gas emissions and reduces the environmental burden. The paper *Cognitive Sustainability* by Zöldy et al. (2022) aims to explore the concept of cognitive sustainability, likely focusing on how human cognition interacts with and influences sustainable practices and decision-making in various systems. The methodology probably involves theoretical frameworks and conceptual analysis within cognitive science and sustainability studies. Its achievement is potentially defining and structuring a new interdisciplinary area that bridges cognitive processes with environmental and societal well-being.

The increasing role of smart and cognitive tools is changing the landscape of mobility as well, and it provides a great opportunity to use these new technologies for more sustainable mobility solutions (Zöldy et al, 2022)

The essence of a circular economy is to keep resources in use for as long as possible, minimising waste generation and environmental impact. In contrast, the traditional, linear economy operates on the principle of "buy-use-dispose", which results in a huge amount of waste (Bera, 2025).

Waste-based fuels are a solution to this linear model. Instead of sending the waste to landfills or incinerators, where we often only relocate the problem, we produce fuel from waste. This way, waste is not an end product, but a new resource.

The financial aspects of the circular economy also deserve mention, with one source highlighting the importance of creating a transparent regulatory environment that facilitates the more efficient utilisation of waste and the development of related technologies. Developing and applying waste-based fuels is also key in this respect, as they can create economic

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incentives for waste management and alternative energy sources. In mobility, the role of state incentives is particularly important, as this can guide the operation of the market in a way that also considers environmental aspects (Szalmáné Csete et al, 2024). The Club of Rome's 1972 report, "The Limits to Growth", already drew attention to the unsustainability of unlimited growth, which forms the basis of today's circular economy and the demand for waste-based fuels (Bourguignon, 2016). The topic is also relevant from the perspective of rural development, as involving rural households in the circular economy, for example by utilising local waste for energy, can contribute to sustainable development. One study points out that rural households must also actively participate in implementing the circular economy, which may include the use or production of waste-based fuels.

2. Literature Review

The overview of the research is done in two steps. First, a quantitative overview was conducted on the SCOPUS database to determine the most published feedstocks and processing technologies. The second step is a deeper analysis of expert-selected papers.

A quantitative literature review was conducted to understand how different waste sources and hydrocarbon production methods are represented in academic publications. The assessment was based on the SCOPUS query of "TITLE-ABS-KEY(waste AND recycl* AND fuel) AND PUBYEAR > 2010 AND PUBYEAR < 2026", which yielded a total of 7531 documents containing the keywords "waste", "fuel" and keywords starting with the stem "recycle" in either their title, abstract, or the keywords assigned to the publication either by the authors or by the publisher. The query was limited to papers published after 2010 to favour more recent works. The resulting data was exported to an ASCII file and processed with a simple Python script, which compared the contents of the abstracts of each article with a list of predefined keyword tokens. Before counting how many papers deal with each of the methods and sources in question, an additional filtering step was introduced: papers that do not explicitly contain "fuel" or "energy" in their abstracts were discarded, resulting in 6659 entries. The number of papers dealing with different waste sources was determined by looking for the tokens "agricultural waste", "sludge", "food waste", "plastic waste", and "tyre".

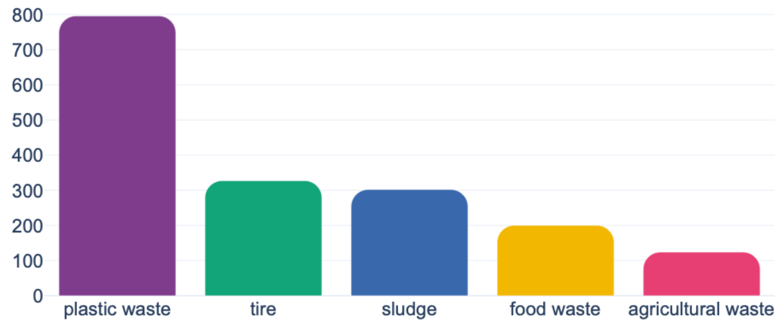

Figure 1 Count of papers by feedstock in the Scopus database from 2010 to 2025

For the number of papers dealing with selected production methods, the following tokens were used: "thermochemical", "biochemical", "biological", and "catalytic". The authors would like to acknowledge the simplicity of this method and its resulting limitations, as this approach cannot account for variations in wording, only exact matches. Therefore, the sum of papers in separate categories will not equal the number of papers involved in the analysis.

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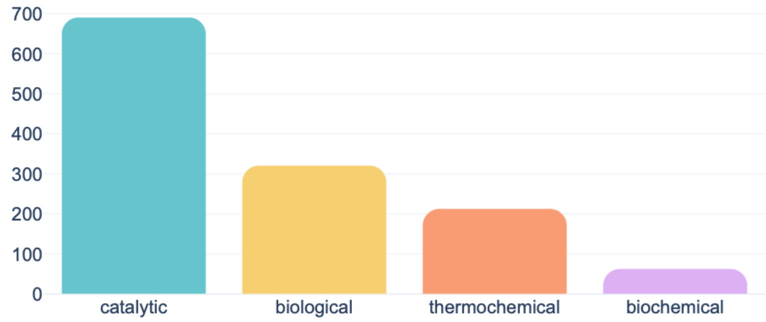

Figure 2: Count of papers by production process technology in the Scopus database from 2010 to 2025

More sophisticated approaches involving Large Language Models would lead to higher precision in categorising papers and determining the number of publications focusing on different methods and waste sources. Nevertheless, this simple method led to the realisation that most of the attention is focused on plastic waste as a source (Fig. 1), followed by end-of-life tyres, sludge, and food waste, whereas agricultural waste as a fuel or energy production source is less discussed. Regarding production methods, catalytic upgrading is the most popular technology (Fig. 2), followed by biological and thermochemical, with biochemical being of least interest in the scientific community. "

At the early stages of the renewable fuel research, waste, mostly agricultural waste, was handled as a potential feed for biofuels production. In the case of ethanol, byproduct-based fuel production could solve the problem of competing human feeding and biofuels production (Emőd et al., 2025).

Siwale et al. investigate the production of diesel fuel components (Siwale et al., 2013) using waste fatty acids and plastic fractions. The aim is to investigate the production of diesel fuel components using waste fatty acids and waste plastic fractions. The study likely employed catalytic co-hydrogenation processes. Demonstrated the feasibility of producing diesel fuel components from specific waste streams, showcasing a potential pathway for waste valorisation into liquid fuels.

Shanthi Sravan et al. review the potential of waste-derived fuels and chemicals within the bioeconomy framework (Shanthi Sravan et al., 2026), emphasising the biorefinery concept. The aim is to review the potential of waste-derived fuels and chemicals within the bioeconomy framework, emphasising the biorefinery concept. This comprehensive review article synthesises research on utilising waste biomass and other waste streams in biorefineries to produce both fuels and valuable chemicals, promoting a circular economy approach. Highlights the integrated approach of biorefineries, showing how waste can be a source for multiple valuable products, not just fuels, thereby maximising resource utilisation and economic benefits.

Colelli et al. examined the underlying assumptions, available technological solutions, and the challenges associated with producing alternative fuels from various waste streams (Colelli et al., 2026), particularly emphasising high-calorie waste fractions. The aim is to examine the underlying assumptions, available technological solutions, and the challenges of producing alternative fuels from various waste streams, particularly focusing on high-calorie waste fractions. This paper likely involves reviewing and analysing existing technologies and research related to waste-to-fuel conversion, identifying common assumptions and practical hurdles. Provides a practical overview of the real-world aspects of waste-based fuel production, offering insights into what works, what does not, and what needs to be overcome for wider adoption.

Misra et al. specifically address the pyrolysis process for converting plastic waste into fuel oil (Misra et al., 2025), detailing the resulting fuel's technological aspects and quality. The aim is to specifically address the pyrolysis process for converting plastic waste into fuel oil, detailing the resulting fuel's technological aspects and quality. This review likely analyses various pyrolysis techniques applied to different types of plastic waste, evaluating factors like temperature, residence time, and catalysts, and assessing the composition and properties of the produced fuel oil. It offers a focused look at plastic waste conversion, a significant waste stream, and demonstrates the potential of pyrolysis to yield usable fuel oil while outlining technological considerations.

Eleni et al. review the anaerobic digestion process for converting food waste into biogas (Eleni et al., 2025), a valuable renewable fuel. The aim is to review the anaerobic digestion process for converting food waste into biogas, a valuable

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renewable fuel. This review likely covers the biochemical pathways of anaerobic digestion, discusses key process parameters (like temperature, pH, C/N ratio), analyses factors affecting biogas yield, and identifies challenges and optimisation strategies. Provides a detailed understanding of biogas production from food waste, a major component of municipal solid waste, and highlights methods to improve the efficiency and stability of the digestion process.

Bayu et al. review the gasification of municipal solid waste (Bayu et al., 2025) to produce syngas, which can then be converted into various liquid or gaseous fuels. The aim is to review municipal solid waste (MSW) gasification to produce syngas, which can then be converted into various liquid or gaseous fuels. This review likely analyses different gasification technologies (e.g., fixed-bed, fluidised-bed, entrained-flow gasifiers) applied to MSW, evaluating their efficiency, syngas quality, and challenges related to feedstock variability and ash management. Demonstrates the potential of gasification as a versatile thermochemical conversion route for MSW, yielding syngas that can serve as a building block for a range of valuable fuels and chemicals.

Kosztyo, Nagy and Torok discuss the conversion of agricultural waste into biofuels (Kosztyo, Nagy, Torok, 2008), emphasising the sustainability aspects and the potential for these biofuels to substitute conventional fossil fuels. The aim is to discuss the conversion of agricultural waste into biofuels, emphasising the sustainability aspects and the potential for these biofuels to substitute conventional fossil fuels. This article likely reviews various conversion pathways for agricultural waste, such as fermentation for ethanol, transesterification for biodiesel, and thermochemical methods for biogas or bio-oil. Highlights the significant potential of agricultural waste as a sustainable source for biofuels, contributing to rural development and reducing reliance on fossil fuels.

Kondor and his peers presented their results in two papers (Kondor and Zöldy, 2020; Kondor et al.,2021) conducted ("Égésszimulációs vizsgálatok hulladékalapú tüzelőanyagok alkalmazásánál") combustion simulation investigations using waste-based fuels. The aim was to investigate the combustion characteristics of waste-based fuels through simulation. The methodology involved using computational fluid dynamics (CFD) or other combustion modelling software to simulate the burning process of fuels derived from waste materials. The achievement was to provide predictive insights into these fuels' combustion behaviour, efficiency, and potential emissions, aiding in their practical application. Kondor et al. (2021) aimed to experimentally evaluate a compression ignition engine's performance and emission characteristics when using fuel blends made from waste tyre pyrolysis oil and diesel. The methodology involved laboratory experiments running the engine on various blends, measuring parameters like power output, fuel consumption, and exhaust emissions (e.g., NO_x, CO, particulate matter). The achievement was to provide empirical data on the suitability of tyre pyrolysis fuel as a diesel blend, highlighting its performance and environmental impact, and assessing its potential as a viable alternative fuel.

3. Evaluation of the literature

The summary of the literature is presented in Table 1. The investigations show that a broad range of waste-based feedstock. The main aim of waste-based fuel research is to find diesel extenders, but in some cases, gasoline substitutes are also researched.

Table 1. An overview of the deep literature analysis, including the main findings

First Author et al.	Investigated Waste Types	Investigated Fuel Types	Main Findings
Kosztyo, Nagy and Torok. (2008)	Agricultural waste (e.g., crop residues, agricultural by-products)	Biofuels (e.g., bioethanol, biodiesel) will likely be produced through conversion pathways.	Highlighted the potential of agricultural waste as a sustainable source for biofuels, contributing to rural development and reducing reliance on fossil fuels.
Siwale et al. (2013)	Waste fatty acids, waste plastic fractions	Diesel fuel components	Demonstrated the feasibility of producing diesel fuel components from specific waste streams, showcasing a potential pathway for waste valorisation into liquid fuels.
Eleni et al. (2025)	Food waste	Biogas	Provided a detailed understanding of biogas production from food waste and highlighted methods to improve the efficiency and stability of the digestion process.
Bayu et al. (2025)	Municipal solid waste (MSW)	Syngas which can be converted into various liquid or gaseous fuels.	Demonstrated the potential of gasification as a versatile thermochemical conversion route for MSW, yielding syngas that can serve as a building block for a range of valuable fuels and chemicals.
Shanthi Sravan et al. (2026)	Various waste streams	Waste-derived fuels and renewable chemicals	Highlighted the integrated approach of biorefineries, showing how waste can be a source for multiple valuable products, not just fuels, maximising resource utilisation and economic benefits.
Colelli et al. (2026)	Various waste streams, particularly high-calorie fractions	Alternative fuels	Provided a practical overview of the real-world aspects of waste-based fuel production, offering insights into what works, what does not, and what needs to be overcome for wider adoption.

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Misra et al. (2025)	Plastic waste	Fuel oil	Offered a focused look at plastic waste conversion and demonstrated the potential of pyrolysis to yield usable fuel oil, outlining the technological considerations.
Kondor et al. (2021)	Waste-based tyre pyrolysis fuel	Diesel fuel blends	Provided experimental validation of waste-based tyre pyrolysis fuel as a viable alternative component for diesel engines, providing data on its impact on engine operation and environmental emissions.
Kondor & Zöldy (2020)	Waste-based fuels	N/A - Combustion modelling, focused on the behaviour of various waste-based fuels.	Generated insights into the combustion behaviour of waste-based fuels, predicting performance metrics and pollutant formation, which is crucial for designing efficient and clean combustion systems.

The technological readiness of the presented process is diverse, and the economic feasibility is very different. As the next step of this research, an LCA investigation is planned to involve economic and environmental aspects.

4. Conclusions

The presented research demonstrates that various waste streams, including agricultural waste, sewage sludge, food waste, plastic waste, and end-of-life tyres, can be effectively converted into valuable fuels and energy carriers. Key findings indicate that: Various thermochemical (pyrolysis, gasification) and biochemical (anaerobic digestion) processes are viable for transforming waste into biofuels, bio-oil, syngas, and biogas. These conversion methods offer significant potential for waste valorisation, turning problematic waste streams into valuable resources, thereby reducing landfill burden and promoting a circular economy. Waste-derived fuels, such as tyre pyrolysis oil blends, can be used in existing engines with acceptable performance and emission characteristics, although further optimisation may be required. Waste-derived fuels are positioned as a crucial component of sustainable energy systems, offering alternatives to fossil fuels. However, challenges related to process efficiency, economic viability, and scalability remain areas of active research and development. Biorefineries, which integrate the production of multiple products from waste, are highlighted as a promising strategy for maximising resource utilisation and economic benefits.

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