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Waste-based fuels as part of sustainable mobility

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Abstract
One of the main challenges for sustainable and new energy-based mobility is the development of alternative fuels, particularly those produced from waste. This paper aims to review the scientific literature on waste-based fuels and identify key technological, economic, and environmental trends. The paper presents a two-stage methodology: first, a quantitative analysis was conducted using the Scopus database. A qualitative evaluation of relevant studies follows it. The results of the analysis indicate that research primarily focuses on the pyrolysis of plastic waste and high-calorific fractions, as well as the biorefinery concept. In contrast, catalytic and thermochemical processes are the primary focus of the technological approaches. Waste-based fuels offer savings of up to 43% compared to fossil fuels and a favourable emissions profile; however, economic viability and regulatory frameworks remain significant challenges. The study concludes that widespread adoption requires an integrated approach that combines technological innovation, economic incentives, and life cycle assessments.

Keywords:
waste-based fuels; circular economy; biorefinery pyrolysis; sustainable mobility

1. Introduction

One of the greatest technological and societal challenges of the third millennium is the question of sustainable mobility. Since the global division of labour is one of the foundations of civilisation, people and goods move across countries and continents, which requires significant energy consumption and, in most cases, contributes to environmental pollution. The search for solutions has been ongoing for a long time, and economic instruments can significantly influence whether a particular technology is promoted or hindered. A good example of this is the European Union and electromobility, whose regulatory instruments have enabled the proliferation of electric cars (Zoldy et al., 2022). However, it is clear that electromobility, with its current technological solutions, cannot replace traditional mobility based on internal combustion engines. Another global trend present in all mobility sectors is data-driven transport, also known as cognitive mobility (Zoldy et al., 2024). Numerous complementary research projects have been initiated and are ongoing to develop sustainable mobility solutions. One research approach involves liquid fuels from waste. The use of waste fuels is of paramount importance for sustainability and environmental protection for several reasons. The development and application of waste fuels enable the utilisation of materials generated by human activities, thereby reducing the amount of waste that ends up in landfills (Torok et al., 2014).

The investigation of waste as a liquid fuel feedstock is closely linked to sustainability goals, specifically the recycling and utilisation of materials that arise as byproducts or losses in the original production process (Németh, 2021). Fuels produced from waste fulfil the requirements of the circular economy system, as recycling materials, including fuel production from waste, is generally less energy-intensive than the extraction, transportation, and processing of raw materials. This reduces greenhouse gas emissions and the overall environmental impact. Waste-based fuels can represent a solution for the transition from a linear to a circular value chain. Instead of simply

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disposing of waste in landfills or incinerators, which often only shifts the problem, waste is used to produce liquid fuel. Waste is thus not an end product, but a new resource.

The financial aspects of the circular economy also have a huge impact on use. One source highlights the importance of a transparent regulatory environment that promotes more efficient waste management and the development of corresponding technologies. The development and application of fuels from waste is also of central importance in this context, as it can create economic incentives for waste management and alternative energy sources. In the mobility sector, public funding programs play a particularly important role, as they can guide market development while taking environmental aspects into account (Szalmáné Csete et al., 2024). The Club of Rome's 1972 report, "The Limits to Growth" (Meadows et al., 1972), already warned about the unsustainability of unlimited growth, laying the foundation for today's circular economy and the demand for fuels derived from waste (Bourguignon, 2016).

This study aims to present and evaluate publications on the topic of fuel production from waste and to identify potential research directions through this analysis. A detailed evaluation and analysis follow the presentation of relevant studies.

2. Literature analysis

The overview of relevant sources was completed in two steps. First, a quantitative overview was conducted using the Scopus database. The focal points of the investigation were the feedstocks used and the processing technologies employed. In the second step, the selected papers were analysed more deeply.

The relevant sources were selected with the help of a 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 investigation was limited to papers published after 2010, with a focus on more recent works. The resulting data was exported to an ASCII file and processed using a simple Python script, which compared the contents of the article abstracts with a list of predefined keyword tokens. Prior to counting the number of papers that deal with each method and source in question, an additional filtering step was introduced: papers that did 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 "tire".

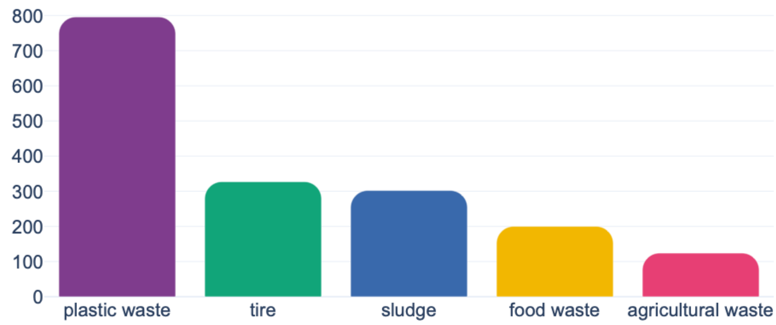

Figure 1. Count of papers by feedstock in the Scopus database from 2010 to 2025.

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 be equal to the total number of papers involved in the analysis.

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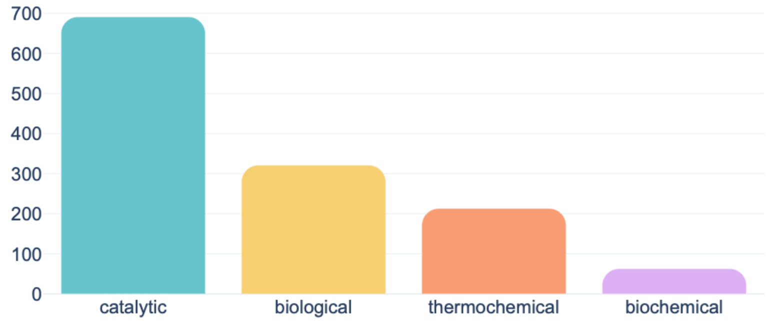

Figure 2. Count of papers by production process technology in the Scopus database from 2010 to 2025.

More sophisticated approaches involving Large Language Models would certainly 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 tires, sludge, and food waste, whereas agricultural waste as a source of fuel or energy production is less discussed. Regarding production methods, catalytic upgrading is the most popular technology (Fig. 2), followed by biological and thermochemical methods, with biochemical methods being of the least interest in the scientific community.

3. Literature review

To provide a deeper understanding of the technological, economic, and environmental dimensions of waste-based fuel research, this section critically examines selected studies that represent distinct milestones and thematic clusters within the broader literature. These papers were chosen because they introduced foundational concepts, proposed innovative technological pathways, or addressed practical challenges in scaling waste-derived fuels. The sequence of discussion follows a logical progression to illustrate the evolution of research on waste-based fuels. It begins with foundational studies that establish the broader context of sustainability and energy, highlighting the global imperative for clean, affordable, and reliable energy, as well as the conceptual frameworks that underpin the transition toward renewable sources. Building on this foundation, the review moves to early investigations into biomass and biofuel production, which introduced key technological pathways such as lignocellulosic conversion and ethanol synthesis, while addressing challenges related to cost and resource competition. The next stage focuses on integrated biorefinery concepts and circular economy approaches, emphasising strategies that maximise resource efficiency by producing not only fuels but also high-value chemicals from diverse waste streams. Following this, attention shifts to specific technological solutions, including thermocatalytic pyrolysis of plastics, hydrogenation of waste fractions, and the development of slurry fuels, each offering distinct advantages and facing unique technical and economic barriers. Finally, the section concludes with applied and experimental studies that validate these concepts through combustion simulations and engine performance tests, providing empirical evidence of feasibility and environmental benefits. This structured approach enables readers to trace the trajectory of research from theoretical foundations to practical applications, revealing both continuity and innovation in the pursuit of sustainable mobility.

Several studies provide a general overview of fuel production from waste. For example, Chu and Majumdar (2012) set the strategic context for why waste-based fuels are important. They argue that the world needs a "new industrial revolution" to achieve affordable, accessible, and sustainable energy, emphasising the urgency of decarbonising transportation fuels. The paper highlights biofuels – particularly those derived from lignocellulosic biomass and waste streams – as critical alternatives to petroleum-based fuels. It also frames the challenges of scalability, infrastructure, and life-cycle emissions, noting that advanced biofuels can reduce greenhouse gas emissions by over 60% compared to fossil fuels when properly managed. By situating biofuels within broader energy policy and technology pathways, this article provides a macro-level rationale for investing in waste-derived fuels as part of a diversified clean energy portfolio. In the 21st century, energy use must be sustainable. Solar energy, hydroelectric power, and the development of microorganisms for biofuel production are examples of

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alternative energy sources. This study situates these options within a broader context, linking the areas of energy transport and production, and provides an overview of the current energy landscape, as well as the lines of research and development that can lead to a sustainable and secure future.

Huber et al. (2006) conducted a comprehensive review to understand the technical feasibility of converting waste biomass into liquid fuels. It details the chemistry and engineering of major conversion routes – gasification to syngas, pyrolysis to bio-oil, hydrolysis to sugars, and upgrading processes such as hydrodeoxygenation and zeolite catalysis. The paper also analyses process thermal efficiencies, life-cycle considerations, and economic factors, making it clear that waste biomass is the only renewable source of organic carbon suitable for producing liquid fuels on a large scale. Importantly, it introduces the concept of integrated biorefineries and evaluates emerging catalytic strategies for improving yields and reducing costs. This work remains a key reference for researchers developing waste-based fuel technologies because it bridges fundamental chemistry with industrial process design and sustainability metrics. They examined methods and future possibilities for fuel production from biomass. Topics covered include the chemical composition and growth rate of biomass, gasification, synthesis gas utilisation, bio-oil production and refining, monomer production, sugar-to-fuel conversion, conversion of non-sugar monomers from lignocellulose, and triglyceride conversion, as well as ethical considerations.

In the early stages of renewable fuel research, agricultural waste was primarily considered a potential feedstock for biofuel production. In the case of ethanol, producing fuels from byproducts could resolve the competition between food supply and biofuel production (Emőd et al., 2005). Sun and Cheng (2002) also demonstrate that lignocellulosic biomass can be utilised for the production of ethanol, a promising alternative energy source due to the limited availability of oil reserves. The conversion process involves two main steps: the hydrolysis of cellulose to produce reducing sugars, and the subsequent fermentation of these sugars into ethanol. Costs are currently high, mainly due to the low hydrolysis yield and the associated expenses. Research focuses on removing lignin and hemicellulose, optimising the enzymes, and simultaneously saccharifying and fermenting to increase yield.

Shanthi Sravan et al. (in press) are investigating the potential of waste-derived fuels and chemicals in the context of bioeconomy, highlighting the concept of the biorefinery. This comprehensive review summarises research on the use of biomass waste and other waste streams in biorefineries for the production of both fuels and valuable chemicals, thus promoting a circular economy approach. It demonstrates how waste can be a source of more valuable products than simple fuels, thereby maximising resource utilisation and economic benefits.

Moving on to more specialised technologies, Misra et al. (2025) specifically address the pyrolysis process for converting plastic waste into fuel oil, describing in detail the technological aspects and the quality of the resulting fuel. This study analyses the various pyrolysis techniques applied to different types of plastic waste, evaluates factors such as temperature, residence time, and catalysts, and assesses the composition and properties of the resulting fuel oil. Polystyrene was found to be the most promising candidate for producing fuel oil through pyrolysis.

Another technology is described by Tóth, Holló, and Hancsók (2020). Their study demonstrates that waste fractions generated during the refining of vegetable oils and animal fats, as well as in paper production, can be converted into an alternative diesel fuel through several steps. In their research work, several waste fractions were hydrogenated with raw gas oil, and the reactions and product quality were investigated. The fuel produced under optimal conditions demonstrated better application performance compared to conventional diesel, thus offering a more environmentally friendly and lower-emission solution.

It is not only selectively collected waste that may serve as the basis for fuel production. According to a study by Vershinina, Shlegel, and Strizhak (2020), sewage sludge fuels derived from waste can have favourable energy properties (calorific value, ignition delay, and combustion temperature) and a low environmental impact (low CO_2, NO_x, and SO_x emissions). The mixtures were produced from wood, agricultural, and household waste, as well as wastewater, petrochemical waste, and heavy oil additives. The results indicate that the use of coal and oil can be reduced by up to 43% with such mixtures.

While the above-discussed articles introduced technologies to produce fuels from waste, other studies tested the properties of the resulting fuels. Kondor and colleagues presented their results on waste-based fuels in two studies

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(Kondor and Zoldy, 2020; Kondor et al., 2021). In the article "Combustion Simulation Studies with Waste-Based Fuels", the aim was to investigate the combustion properties of waste-based fuels using simulation. The methodology involved the use of CFD (Computational Fluid Dynamics) simulations or other combustion modelling software to simulate the combustion process of fuels derived from waste materials, focusing on the combustion behaviour, efficiency, and potential emissions of these fuels to support their practical application. As presented in the other study, Kondor et al. (2021) aimed to experimentally evaluate the performance and emission characteristics of a compression-ignition engine using fuel mixtures of waste tire pyrolysis oil and diesel. The methodology included engine bench tests, in which the engine was operated with different mixtures of pyrolysis oil and diesel. The results provided empirical data on the suitability of tyre pyrolysis oil as a diesel fuel additive, highlighting its performance and environmental compatibility, and assessing its potential as a viable alternative fuel.

4. Evaluation of the literature

A summary of the literature review is given in Table 1. Studies have shown that a wide range of waste-based raw materials exists. The main goal of research on waste-based fuels is the development of diesel fuel additives; however, in some cases, gasoline substitutes are also being investigated.

Table 1. Waste-derived fuels and bio-based alternatives – literature review

Authors and Year	Focus	Waste Stream / Feedstock	Technology / Approach	Key Findings
Sravan et al. (in press)	Biorefinery concept, circular economy	Mixed waste streams, biomass	Integrated biorefinery systems	Waste can be a source of multiple valuable products (fuels + chemicals), and resource maximisation.
Misra et al. (2025)	Pyrolysis of plastic waste for fuel oil production	Plastic waste	Pyrolysis (temperature, catalyst, residence time)	Fuel oil quality and composition, potential of pyrolysis
Chu & Majumdar (2012)	Future of sustainable energy	Renewable energy sources	Solar, hydro, biofuels	Sustainability framework, R&D directions
Huber et al. (2006)	Biomass-based transportation fuels	Biomass	Gasification, syngas utilisation, bio-oil, sugar conversion	Current methods and future possibilities
Sun & Cheng (2002)	Hydrolysis of lignocellulose for ethanol production	Lignocellulose	Hydrolysis + fermentation	High cost, yield issues, enzyme optimisation
Vershinina et al. (2020)	Waste-based slurry fuels	Wood, agricultural, and household waste	Wastewater + petrochemical additives	Up to 43% fossil fuel savings, favourable energy and environmental characteristics
Tóth et al. (2020)	Hydrogenation of waste fractions for diesel	Vegetable oil, animal fat, paper waste	Hydrogenation with raw gas oil	High-quality diesel, better performance, lower emissions

The studies in the table demonstrate that research on waste-derived fuels and bio-based alternatives is progressing in various directions and is increasingly aligning with the circular economy and sustainability paradigm. Three main focus points can be identified:

1. Integrated approach and the role of biorefineries – Sravan et al. emphasise the concept of the biorefinery, which produces not only fuels but also valuable chemicals from waste. This approach is essential for increasing economic feasibility and resource efficiency.

2. Technological diversity and challenges – Misra et al. point out that there is no overall solution to integrate waste streams based on their heterogeneity. Fuels with high caloric value and waste-based pyrolysis streams seem promising, but significant technological and economic challenges exist for industrial-scale applications. Catalysts, temperature parameters, and process optimisation are key factors.

3. Sustainability and environmental benefits – It has been clearly demonstrated that waste-based fuels can not only replace fossil fuels but also contribute to more favourable emission profiles.

5. Conclusions

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To summarise the study, research on waste-based fuels is a key area for sustainable mobility and energy transition. Based on the literature review, three main focus points can be identified. The first is the integrated biorefinery approach, in which waste is utilised not only as a fuel but also for the production of chemicals, thereby enhancing resource efficiency and economic benefits. The second focus point is the technological diversity and related challenges: pyrolysis, hydrogenation, and fermentation are promising technologies; however, heterogeneous waste streams and high investment costs may hinder their industrial-scale application. The third focus point concerns the sustainability benefits: waste-based fuels offer significant savings in fossil fuels and result in a more favourable emission profile, thereby contributing to the achievement of circular economy goals.

Research gaps in this field include the lack of economic viability, inadequate regulatory frameworks and the lack of life cycle assessments. Future research should take an integrated approach that combines technological innovation, economic incentives and quantification of environmental impacts. From a practical perspective, waste-based fuels have the potential not only to replace fossil fuels but also to contribute to waste reduction and energy security. However, their widespread adoption requires concerted efforts from industry, regulators and research institutions.

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