processes

MDPI

Review

Comprehensive Assessment of Thermochemical Processes for Sustainable Waste Management and Resource Recovery

Halil Durak

Vocational School of Health Services, Yuzuncu Yil University, 65080 Van, Turkey; halildurak@yyu.edu.tr

Abstract: Thermochemical techniques have emerged as promising and sustainable approaches for converting diverse waste materials into valuable products, including chemicals and fuels. This study critically assesses the strengths and limitations of various thermochemical processes, focusing on their potential for large-scale implementation and commercial viability. The investigation encompasses a comprehensive examination of processes such as pyrolysis, gasification, and liquefaction, aiming to compare them based on crucial parameters including energy efficiency, product yield, product quality, and environmental impact. Through this comparative analysis, the study aims to identify the most suitable thermochemical treatment for specific waste materials, thereby facilitating the development of sustainable and economically feasible waste management strategies. By providing valuable insights into the selection and optimization of thermochemical processes, this research contributes to the advancement of waste-to-value technologies and supports the transition towards a circular economy.

Keywords: biomass; environmental impact; industrial waste; municipal solid waste; plastic waste; sustainable waste management; thermochemical process

check for updates

Citation: Durak, H. Comprehensive Assessment of Thermochemical Processes for Sustainable Waste Management and Resource Recovery. *Processes* **2023**, *11*, 2092. https://doi.org/10.3390/pr11072092

Academic Editor: Ángeles Blanco

Received: 7 June 2023
Revised: 7 July 2023
Accepted: 11 July 2023
Published: 13 July 2023

1. Introduction

Thermochemical processes offer innovative and promising approaches for transforming waste into valuable materials and chemicals. These processes utilize high temperatures and chemical reactions to convert various types of waste into useful products, thereby reducing waste volumes, mitigating environmental impacts, and promoting resource recovery. Let us explore some of the key thermochemical processes: hydrothermal liquefaction, hydrothermal carbonization, pyrolysis, and gasification [1,2].

1.1. Hydrothermal Liquefaction: Parameters and Applications

Hydrothermal liquefaction (HTL) is a thermochemical process that converts wet biomass or organic waste into a liquid bio-oil under high temperature and pressure conditions in the presence of water. It offers a promising pathway for efficiently utilizing wet and low-value biomass resources, such as algae, sewage sludge, and agricultural residues, by converting them into a valuable energy-dense product [3]. HTL utilizes high temperature, high pressure, and water to convert biomass or organic waste feedstock, which usually contains significant moisture content. The process involves subjecting the feedstock to temperatures of 250–400 °C (482–752 °F) and pressures of 10–25 megapascals (MPa). Under these conditions, the complex organic compounds present in the feedstock undergo thermal decomposition and chemical reactions, resulting in the production of a liquid bio-oil [3]. Figure 1 shows the schematic representation of the HTL process.

Parameters:

The working conditions in HTL are critical for achieving optimal product yields and qualities. The key parameters include temperature, pressure, reaction time, and feedstock characteristics. Higher temperatures and longer reaction times typically result in higher bio-oil yields. However, the reaction conditions need to be carefully controlled to prevent excessive degradation and the formation of unwanted byproducts. The presence of water in the reaction medium is crucial as it acts as a solvent, enhancing the thermal conversion and promoting the liquefaction process [4].

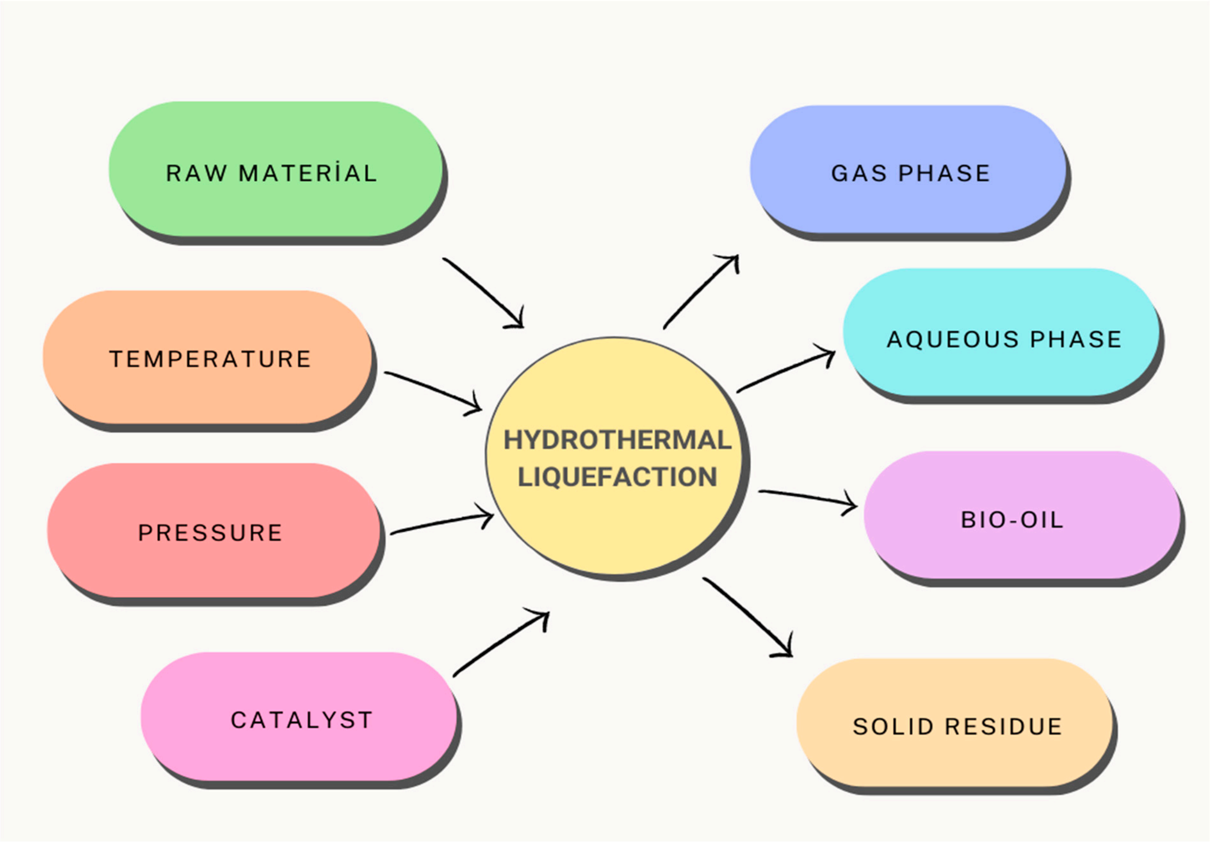

Figure 1. Schematic representation of the HTL process.

Purposes of Hydrothermal Liquefaction:

Biofuel Production: One of the primary purposes of HTL is the production of bio-oil, which serves as a renewable and energy-dense liquid fuel. The produced bio-oil can be used as a drop-in replacement for fossil fuels in existing combustion systems, such as power plants, boilers, and engines. It offers the advantage of reducing greenhouse gas emissions and dependence on finite fossil fuel resources [5].

Chemical Feedstock: HTL can also generate valuable chemical feedstocks from biomass. The bio-oil obtained from the process contains a range of organic compounds that can be further refined and upgraded into various chemicals, such as platform chemicals, solvents, and specialty chemicals. These chemicals have applications in industries such as plastics, pharmaceuticals, and agriculture [5].

Waste Valorization: HTL process enables the valorization of wet biomass and organic waste materials that are typically challenging to utilize efficiently. By converting these waste streams into bio-oil, the process offers an opportunity to reduce waste volumes, minimize environmental pollution, and create economic value from resources that would otherwise be discarded or underutilized [5].

Resource Efficiency and Sustainability: HTL contributes to resource efficiency and sustainability by utilizing biomass resources that do not compete with food production, such as algae and agricultural residues. It provides an alternative route for biomass utilization, complementing other conventional processes like anaerobic digestion and pyrolysis.

By converting wet biomass into a liquid product, the process also offers advantages in terms of transport, storage, and handling compared to solid biomass [5,6].

In summary, HTL offers a versatile and promising thermochemical process for converting wet biomass and organic waste into a valuable liquid bio-oil. With its potential applications in biofuel production, chemical feedstocks, waste valorization, and resource efficiency, HTL plays a significant role in sustainable waste management and the development of a more environmentally friendly and resource-conscious society.

1.2. Hydrothermal Carbonisation: Parameters and Applications

Hydrothermal carbonization (HTC) is an innovative thermochemical process that converts wet biomass or organic waste into hydrochar or biocarbon through high-temperature and high-pressure reactions in the presence of water. This process mimics the natural coal formation process, but on a much shorter timescale, typically ranging from a few minutes to a few hours. HTC offers several advantages, including its ability to handle wet feedstocks, its versatility in accepting a wide range of biomass and waste materials, and its production of a carbon-rich solid product with various applications [7]. HTC involves complex interactions among biomass feedstock, water, and heat. The process applies elevated temperatures (180–250 °C) and pressures (10–25 bar) to the biomass, leading to a series of chemical reactions such as hydrolysis, dehydration, decarboxylation, and polymerization. These reactions culminate in the formation of hydrochar, a carbon-rich solid with high fixed carbon content, enhanced energy density, and improved stability. Water serves as both a reactant and a solvent, facilitating the reactions, maintaining desired temperature and pressure conditions, and providing a source of hydrogen. Overall, HTC offers promising prospects as an alternative to fossil fuels and other carbonaceous materials [7]. Figure 2 shows the schematic representation of the HTC process.

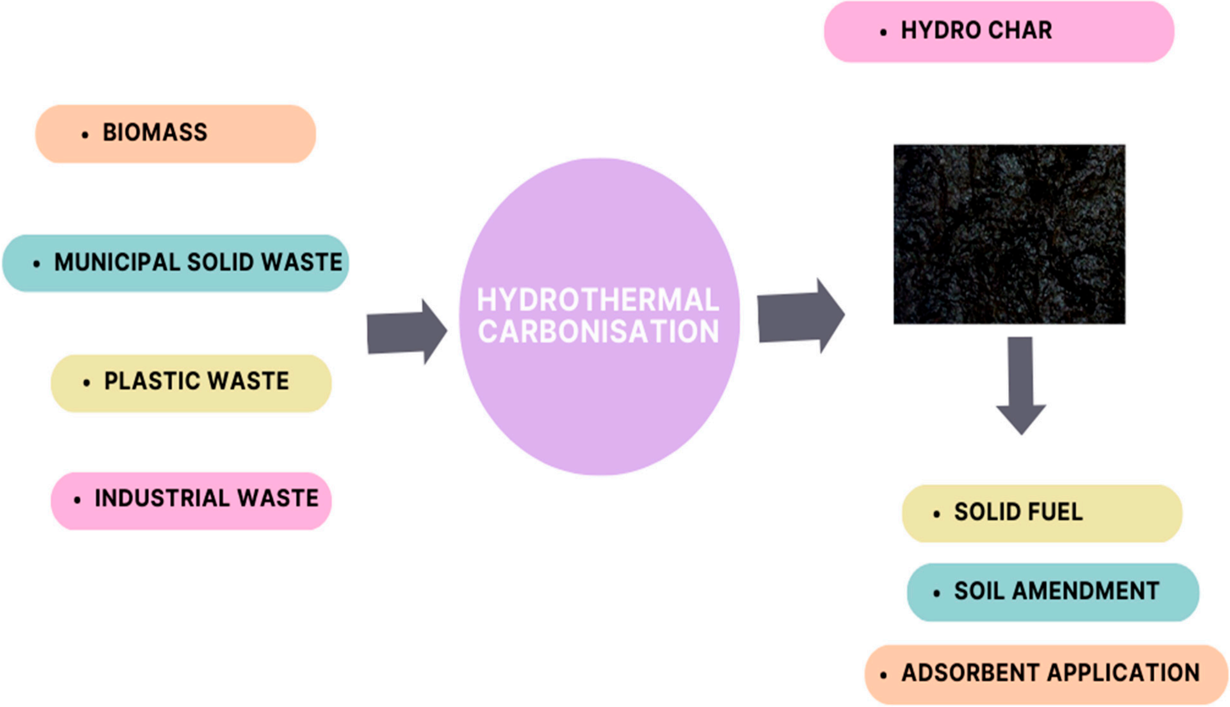

Figure 2. Schematic representation of the HTC process.

Parameters:

The working conditions in HTC are carefully controlled to ensure efficient carbonization and product quality. The key parameters include the following:

Temperature: The temperature is typically maintained in the range of 180 to 250 °C. Higher temperatures can lead to increased carbonization rates but may also result in the formation of undesired byproducts.

Pressure: The pressure is controlled within the range of 10 to 25 bar. Higher pressures enhance the solubility of organic compounds in water, promoting their reactions and the formation of hydrochar.

Reaction Time: The duration of the reaction varies depending on the feedstock and desired hydrochar properties but typically ranges from a few minutes to several hours.

Purposes and Applications:

The hydrochar produced through HTC has various purposes and applications, including the following:

Renewable Energy Source: Hydrochar can be used as a renewable energy source due to its high carbon content and energy density. It can be combusted to generate heat or used as a solid fuel in biomass power plants.

Soil Amendment: Hydrochar has beneficial properties as a soil amendment. It can improve soil structure, water retention, and nutrient holding capacity. It also promotes microbial activity and carbon sequestration in the soil, contributing to sustainable agriculture and land management practices.

Carbon Sequestration: Hydrochar has the potential to sequester carbon, contributing to the reduction in greenhouse gas emissions. When applied to soil, it can serve as a long-term carbon sink by storing carbon for extended periods.

Chemical Feedstock: Hydrochar can be further processed to extract valuable chemicals and compounds, such as activated carbon, bio-based polymers, and specialty chemicals. These compounds have applications in various industries, including water treatment, energy storage, and manufacturing [8].

In summary, HTC is a thermochemical process that converts wet biomass and organic waste into hydrochar through high-temperature and high-pressure reactions in the presence of water. It offers a versatile and environmentally friendly approach to waste management, providing opportunities for renewable energy production, soil improvement, carbon sequestration, and the production of value-added chemicals and materials.

1.3. Pyrolysis: Parameters and Applications

Pyrolysis is a thermochemical process that converts organic materials, such as biomass and waste, into biochar, bio-oil, and syngas in the absence of oxygen. This process is based on the principle of thermal decomposition, where the organic material is subjected to high temperatures in a controlled environment, leading to the breakdown of complex organic compounds into simpler molecules. Let us delve into the detailed information about the pyrolysis process, including its basic principles, working conditions, and purposes [9]. Pyrolysis comprises three key stages: drying, pyrolysis, and char activation. In the drying stage, moderate heat is applied to remove moisture from the feedstock. Pyrolysis occurs at higher temperatures (400–800 °C), causing rapid heating of the organic material in the absence of oxygen. This thermal degradation breaks down complex compounds into smaller molecules, resulting in the formation of biochar, bio-oil, and syngas. The final stage, char activation, involves enhancing the properties of biochar for specific applications, such as adsorption or soil amendment [9]. Figure 3 shows the schematic representation of the pyrolysis process.

Parameters:

Several factors influence the pyrolysis process, including temperature, heating rate, residence time, and feedstock characteristics. The temperature range in pyrolysis can vary depending on the desired product composition and process objectives. Slow pyrolysis, characterized by lower heating rates and longer residence times, typically operates at temperatures below 500 °C, favoring the production of higher amounts of biochar. Fast pyrolysis, on the other hand, employs higher heating rates and shorter residence times at temperatures ranging from 500 to 800 °C, resulting in a higher yield of bio-oil. The working conditions of the pyrolysis process are carefully controlled to optimize the production of desired products. The absence of oxygen during the process prevents complete combustion and ensures the formation of biochar and bio-oil rather than ash or gas combustion byproducts. The feedstock size and composition also play a crucial role in the efficiency and product yields of pyrolysis. Factors such as feedstock moisture content, particle size, and feedstock composition (e.g., lignocellulosic biomass, agricultural waste, or plastic waste) can significantly impact the process performance [9].

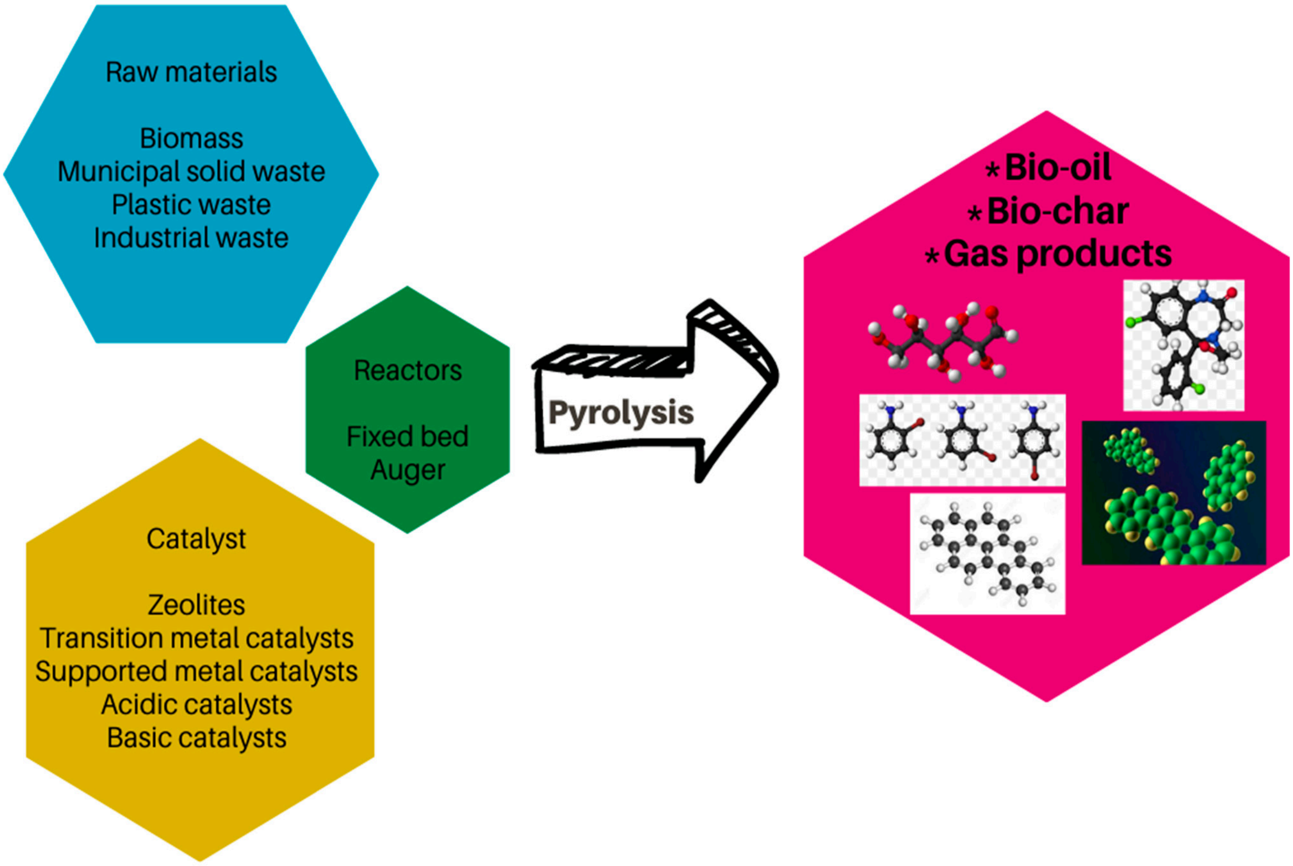

Figure 3. Schematic representation of the pyrolysis process stages.

Purposes and Applications:

The pyrolysis process serves various purposes and finds applications in several sectors:

Energy Production: Bio-oil and syngas produced during pyrolysis can be used as renewable energy sources. Bio-oil can be refined and upgraded to produce transportation fuels, while syngas can be utilized for electricity and heat generation through combustion or gasification processes.

Waste Management: Pyrolysis offers an effective solution for waste management, enabling the conversion of organic waste, such as agricultural residues, wood waste, and municipal solid waste, into valuable products. It helps reduce waste volumes and mitigate environmental pollution associated with improper disposal.

Carbon Sequestration and Soil Amendment: Biochar produced from pyrolysis has a high carbon content and can be used as a soil amendment to improve soil fertility, water retention, and nutrient cycling. Biochar acts as a carbon sink, contributing to carbon sequestration and mitigating climate change.

Chemical and Material Production: Bio-oil obtained from pyrolysis can serve as a feedstock for the production of various chemicals, such as platform chemicals, specialty chemicals, and bioplastics. The syngas produced can also be further processed into chemicals and fuels through catalytic reactions.

Environmental Remediation: The porous nature of biochar makes it an effective adsorbent.

1.4. Gasification: Parameters and Applications

Gasification is a thermochemical process that converts carbonaceous materials, such as biomass, coal, or waste, into a synthesis gas (syngas) consisting mainly of hydrogen (H_2), carbon monoxide (CO), and other trace gases. This process occurs under high temperatures and in the presence of a controlled amount of oxygen or steam. Gasification is a versatile and efficient method that offers several advantages over traditional combustion or incineration processes [10]. Gasification involves four primary chemical reactions: drying, pyrolysis, combustion, and reduction. These reactions take place in distinct zones within the gasifier. Drying: In the drying zone, the feedstock is heated to remove moisture, typically at temperatures of 100–200 °C, preparing it for further decomposition. Pyrolysis: In the pyrolysis zone, the dried feedstock undergoes thermal decomposition at higher temperatures (300–800 °C) without oxygen, releasing volatile organic compounds (VOCs) such as tars, oils, and gases. Combustion: The combustion zone introduces a controlled amount of oxygen to react with carbonaceous material, partially oxidizing it and generating the heat required for the gasification process.

Reduction: In the reduction zone, remaining carbonaceous material reacts with steam or carbon dioxide (CO_2) through water–gas shift or carbon–gas shift reactions, respectively. This yields syngas enriched with hydrogen and carbon monoxide. These reactions collectively enable the conversion of feedstock into syngas during gasification [10]. Figure 4 shows the gasification process stages and the products obtained.

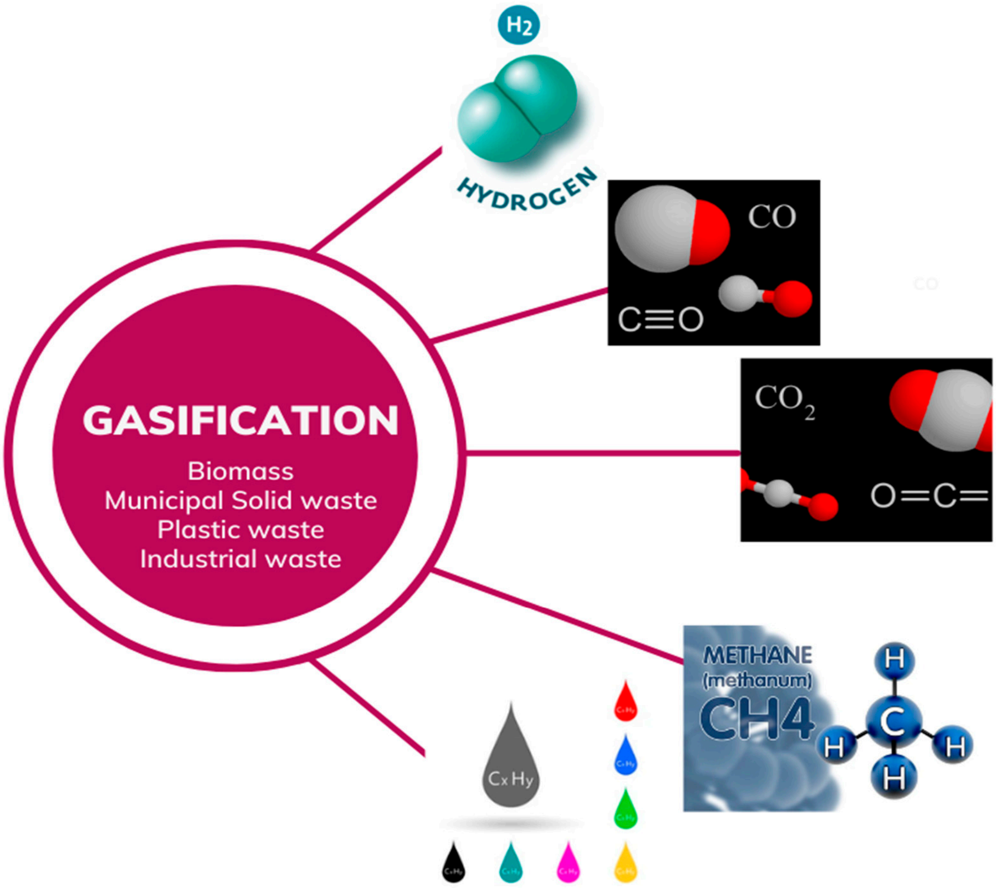

Figure 4. Schematic representation of the gasification process and products stages.

Parameters:

Working Conditions: The gasification process operates under specific conditions to optimize syngas production and control byproducts. The key parameters include temperature, pressure, and residence time. Typically, gasification takes place at temperatures ranging from 700 to 1300 °C, depending on the feedstock and desired syngas composition. The pressure within the gasifier can vary, with most systems operating at near atmospheric pressure or slightly elevated pressures. The residence time, or the duration that the feedstock remains within the gasifier, is carefully controlled to ensure efficient conversion and sufficient reaction time [11].

Purposes and Applications:

Gasification serves several purposes and offers diverse applications:

Syngas Production: The primary purpose of gasification is to generate syngas, a versatile fuel gas mixture. Syngas, consisting of hydrogen and carbon monoxide, can be utilized in various applications, including power generation, heating, and industrial processes.

Chemicals and Fuels: The syngas produced from gasification can serve as a valuable feedstock for the production of chemicals and transportation fuels through further processing, such as catalytic reactions and synthesis.

Waste Management: Gasification provides an efficient and environmentally friendly method for waste management. It enables the conversion of various waste materials, such as municipal solid waste and biomass residues, into syngas, reducing the volume of waste and minimizing environmental impacts.

Renewable Energy: Gasification contributes to renewable energy production by utilizing biomass or other renewable feedstocks. It offers a pathway for sustainable energy generation while reducing reliance on fossil fuels.

Carbon Capture and Storage: Gasification can be integrated with carbon capture and storage (CCS) technologies, enabling the capture and sequestration of carbon dioxide emissions produced during the gasification process. This integration contributes to reducing greenhouse gas emissions and mitigating climate change.

Chemical Synthesis: Syngas serves as a valuable feedstock for the production of various chemicals and fuels. Through additional catalytic reactions, syngas can be converted into methanol, ammonia, synthetic natural gas (SNG), and other hydrocarbon-based products.

Hydrogen Production: Syngas contains a significant amount of hydrogen, which can be separated and used for hydrogen production, a critical component in various industries, such as fuel cells and chemical processes [10,11].

Gasification has proven to be a versatile and efficient process with diverse applications across energy, chemicals, and waste management sectors. With further advancements in technology and research, gasification holds significant potential in promoting sustainable development. Gasification is a thermochemical process that converts carbonaceous materials, such as biomass, coal, or waste, into a syngas through a series of controlled reactions. It operates at high temperatures, typically between 700 and 1200 °C, and in the presence of a controlled amount of oxygen or steam. The gasification process involves several key steps, including drying, pyrolysis, combustion, and reduction. Gasification offers several advantages over traditional combustion processes. It enables the utilization of a wide range of carbonaceous feedstocks, including biomass, coal, and waste materials, providing an opportunity to convert these resources into useful energy and chemicals.

The purpose of the study is to critically assess and compare various thermochemical processes, including HTL, HTC, pyrolysis, and gasification, for the conversion of biomass and waste materials into valuable products. This study aims to evaluate the strengths and limitations of these processes, considering parameters such as energy efficiency, product yield, product quality, and environmental impact. The goal is to identify the most suitable thermochemical treatment method for specific waste materials, with a focus on large-scale implementation and commercial viability. By providing valuable insights into the selection and optimization of thermochemical processes, the study aims to contribute to the advancement of waste-to-value technologies and support the transition towards a circular economy. The overall purpose is to develop sustainable and economically feasible waste management strategies that maximize resource utilization, minimize environmental impact, and promote the shift towards renewable energy sources.

This research presents a unique and innovative approach to the field of waste management, bringing forth several key innovations that significantly advance the current state of knowledge in this critical area.

Novelty in Comprehensive Examination: One of the key innovations of this study lies in its comprehensive examination of various thermochemical techniques, including HTL, HTC, pyrolysis, and gasification. While previous reviews often focused on specific aspects or a limited set of processes, this research encompasses all these techniques, providing a holistic perspective that is unprecedented in the field.

Comprehensive Analysis of Crucial Parameters: In addition to the holistic examination, this research introduces a comprehensive analysis of crucial parameters, such as energy efficiency, product yield, product quality, and environmental impact. By evaluating and comparing these parameters across different thermochemical processes, valuable insights into their performance and potential are offered, thereby enhancing decision-making and facilitating the adoption of waste-to-value technologies.

Comparative Assessment for Identifying Strengths and Limitations: This article stands out by conducting a rigorous comparative assessment among the thermochemical processes examined. This innovation allows for the identification of the unique strengths and limitations of each technique, paving the way for informed decision-making and targeted improvements. By understanding the distinct advantages and challenges associated with each process, researchers and practitioners can better tailor their approaches to maximize efficiency and effectiveness.

Addressing Research Gaps: This study explicitly aims to fill existing research gaps in the field of waste management. Through detailed analysis and evaluation, areas where further investigation is needed are uncovered and a foundation for future studies to build upon is provided. By addressing these research gaps, a more comprehensive understanding of thermochemical processes is fostered and contributions to the advancement of waste management technologies are made.

Support for the Transition to a Circular Economy: This research emphasizes the significance of my work in supporting the transition towards a circular economy. By effectively transforming waste materials into valuable products, my findings have the potential to minimize environmental impacts and promote resource efficiency. This innovation aligns with the global efforts towards sustainable development and offers practical solutions to address the challenges posed by waste management.

By incorporating these additional details, this article not only presents a unique and innovative approach to thermochemical processes for waste management but also showcases the specific innovations that my research has brought and will continue to contribute to the field. I believe that our work will inspire further advancements and serve for future research and practical applications in sustainable waste management practices. It holds significant importance as a valuable resource for future research endeavors and practical applications in this domain.

2. Waste Materials and General Classification

Thermochemical conversion is a process that uses heat and chemicals to transform waste materials into useful products. This technology has become increasingly important in recent years as the world has become more aware of the need to reduce waste and create a more sustainable future. There are several waste materials that can be converted into new products using thermochemical conversion methods [12,13]. In this article, we will discuss five of the most common waste materials that can be transformed through thermochemical conversion.

2.1. Biomass

Biomass refers to any organic matter derived from plants, animals, and microorganisms that can be utilized as a source of renewable energy or various valuable products. It encompasses a wide range of materials, including dedicated energy crops, agricultural residues, forestry residues, algae, organic waste, and byproducts from industrial and municipal activities. The utilization of biomass as an energy resource offers several advantages, including its renewability, carbon neutrality, and potential to reduce greenhouse gas emissions compared to fossil fuels [14]. The classification of biomass can be based on its origin, composition, and purpose of utilization. One commonly used classification scheme categorizes biomass into three main types: energy crops, agricultural and forestry residues, and organic waste. Energy crops are specifically cultivated for their high biomass yield and energy content. These crops include perennial grasses (such as switchgrass and miscanthus), short-rotation woody crops (such as willow and poplar), and dedicated energy crops (such as sugarcane and corn). Energy crops provide a sustainable feedstock for bioenergy production, and their cultivation can contribute to rural development and land reclamation. Agricultural and forestry residues encompass the organic byproducts generated from agricultural and forestry activities. Agricultural residues include crop residues (such as corn stover, wheat straw, and rice husks) and animal manure. Forestry residues comprise branches, bark, sawdust, and other woody biomass generated during logging and timber processing. These residues are often abundant and readily available, making them valuable for bioenergy production, as well as applications in the pulp and paper industry and the production of bio-based chemicals. Organic waste consists of various organic materials derived from municipal, industrial, and commercial sources. This category includes food waste, yard waste, sewage sludge, and other organic byproducts generated from food processing, agriculture, and wastewater treatment. The effective management and utilization of organic waste are crucial for waste reduction, resource recovery, and environmental sustainability [14]. Organic waste can be converted into biogas through anaerobic digestion, used as a feedstock for composting, or processed through technologies like HTC to produce bioenergy and value-added products. Another classification approach involves categorizing biomass based on its composition and characteristics. Biomass can be classified as lignocellulosic biomass (e.g., woody materials and agricultural residues), herbaceous biomass (e.g., grasses and energy crops), algal biomass (e.g., microalgae and macroalgae), and animal biomass (e.g., manure and animal byproducts). Each biomass type possesses unique characteristics and requires specific conversion technologies and processes for efficient utilization [14].

Biomass is one of the most common waste materials that can be converted into new products through thermochemical conversion. Biomass refers to any organic matter that comes from plants or animals. This includes wood, agricultural waste, and other plant matter. Thermochemical conversion can transform biomass into biofuels, such as ethanol and biodiesel, and biochar, which is a form of charcoal that can be used as a soil amendment [15,16].

2.2. Municipal Solid Waste (MSW)

MSW refers to the waste generated by households, commercial establishments, institutions, and other non-industrial sources within a defined municipal area. It encompasses a wide range of materials, including but not limited to paper, plastics, glass, metals, textiles, organic waste, and miscellaneous items. MSW is distinct from industrial waste, construction and demolition debris, and hazardous waste, which are typically managed separately due to their unique characteristics and disposal requirements. The classification of MSW plays a crucial role in waste management planning, as it helps in identifying the composition, characteristics, and potential environmental impacts of the waste stream [17]. MSW can be classified based on various parameters, including its physical state, source, and potential for recycling or recovery. One common classification is based on the physical state of the waste, which distinguishes between solid waste, liquid waste, and gaseous waste. Solid waste, the most common form of MSW, includes materials such as household garbage, packaging waste, and discarded items. Liquid waste refers to waste that is predominantly in a liquid state, such as wastewater and sewage sludge, while gaseous waste comprises gases emitted during waste decomposition, such as methane from landfills. Another classification criterion for MSW is based on its source or origin. This classification helps in understanding the waste generation patterns and designing appropriate waste management strategies. Sources of MSW can include residential households, commercial establishments (e.g., offices, restaurants, and retail stores), institutional facilities (e.g., schools, hospitals, and government buildings), and public spaces (e.g., parks and streets) [18]. Each source may have unique waste characteristics and quantities, necessitating tailored approaches for waste collection, treatment, and disposal. Furthermore, MSW classification can also consider the potential for recycling and recovery. This classification helps identify materials that can be diverted from landfill disposal and utilized for resource conservation and energy recovery. Common categories based on recycling potential include paper and cardboard, plastics, glass, metals, and organic waste. Recycling and recovery efforts for these materials can involve processes such as sorting, separation, composting, anaerobic digestion, and recycling technologies, thereby reducing the environmental burden of waste disposal and conserving valuable resources [17,18].

MSW is another waste material that can be transformed through thermochemical conversion. MSW is the waste that is generated by households and businesses, such as food scraps, paper, and plastic. MSW can be processed through pyrolysis, gasification, or combustion to produce electricity, heat, and other valuable products like metals and chemicals [19,20].

2.3. Plastic Waste

Plastic waste refers to any discarded or abandoned plastic material that has reached the end of its useful life and is no longer required for its original purpose. Plastic waste has become a significant environmental concern due to its persistence in the environment and detrimental effects on ecosystems, wildlife, and human health. Understanding the classification of plastic waste is crucial for effective waste management strategies and the development of sustainable solutions. Plastic waste can be classified based on various criteria, including its source, composition, and physical form. Firstly, plastic waste can originate from different sectors, such as household, commercial, industrial, and medical sources. Household plastic waste primarily consists of packaging materials, single-use plastics, and consumer goods. Commercial plastic waste includes plastics used in retail, offices, and hospitality industries. Industrial plastic waste comprises plastics generated during manufacturing processes, such as packaging, machinery components, and construction materials. Medical plastic waste encompasses various plastics used in healthcare facilities, including syringes, medical packaging, and laboratory equipment.

Another classification criterion for plastic waste is based on its composition and polymer type [21]. Plastics are composed of different polymers, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET), among others [21]. Each polymer type exhibits distinct properties, recycling capabilities, and environmental impacts. Categorizing plastic waste based on polymer composition is essential for efficient sorting, recycling, and recovery processes. Furthermore, plastic waste can be classified according to its physical form or shape. This includes categories such as packaging waste, film and sheet waste, foam waste, rigid plastic waste, and microplastics. Packaging waste encompasses various plastic materials used for product packaging, such as bottles, containers, and wraps. Film and sheet waste refer to thin plastic materials used in applications like bags, plastic film, and protective covers. Foam waste includes expanded polystyrene (EPS) foam commonly used for packaging and insulation. Rigid plastic waste includes larger plastic items like crates, buckets, and furniture. Lastly, microplastics are tiny plastic particles measuring less than 5 millimeters in size and can be found in various forms, including microbeads, fragments, and fibers.

The classification of plastic waste serves as a foundation for effective waste management strategies. It enables the development of targeted recycling and recovery processes tailored to different plastic types and forms. Moreover, proper classification facilitates the implementation of policies and regulations to reduce plastic waste generation, promote recycling initiatives, and encourage the use of more sustainable alternatives [22].

Plastic waste is a significant environmental problem, but it can be transformed through thermochemical conversion. Pyrolysis and gasification technologies can convert plastic waste into fuel, chemicals, and other products. These technologies break down the plastic into its chemical components, which can then be used to create new products [23,24].

2.4. Industrial Waste

Industrial waste refers to the byproducts generated from industrial processes, manufacturing operations, and commercial activities. It comprises a wide range of materials, substances, and pollutants that are discarded or discharged during production, construction, or maintenance activities. These wastes can pose significant environmental and health risks if not managed and treated properly. Understanding the definition and classification of industrial waste is essential for developing effective waste management strategies and ensuring sustainable industrial practices. The definition of industrial waste encompasses various types of solid, liquid, and gaseous materials generated by industrial activities. Solid industrial waste includes materials such as scrap metals, packaging materials, construction debris, and manufacturing residues. Liquid industrial waste refers to wastewater, chemical solutions, and contaminated liquids produced during industrial processes. Gaseous industrial waste includes emissions and exhaust gases released from combustion processes, chemical reactions, and volatile organic compounds (VOCs) generated by industrial operations. The classification of industrial waste is based on its physical state, chemical composition, and potential environmental impact. One common classification of industrial waste is based on its hazardousness [25]. Hazardous waste consists of materials that exhibit characteristics such as toxicity, flammability, corrosiveness, or reactivity. These wastes pose significant risks to human health and the environment and require special handling, treatment, and disposal methods to prevent contamination and potential harm. Non-hazardous industrial waste, on the other hand, does not exhibit these hazardous characteristics and can be managed through conventional waste management practices. Another classification criterion for industrial waste is its origin or sector-specific categorization. Industrial waste can be categorized based on the industry or sector from which it originates, such as manufacturing, construction, mining, chemical production, or electronic waste. This classification helps in identifying specific waste streams, understanding the nature of the waste, and tailoring waste management approaches accordingly. Each industry may generate unique waste types that require specialized treatment or recycling methods to minimize environmental impact and resource depletion. Industrial waste can also be classified based on its recyclability or potential for resource recovery. Some industrial wastes, such as certain metals, plastics, or organic materials, can be recycled or repurposed to reduce the demand for virgin resources and minimize waste generation. Other waste streams, such as certain chemicals or hazardous materials, may require specific treatment technologies for safe disposal or neutralization to prevent environmental contamination. Thermochemical conversion can also be used to process industrial waste, such as sludge, waste oils, and hazardous wastes, turning them into useful products. For example, waste oils can be converted into biofuels through pyrolysis or gasification, while hazardous waste can be treated and transformed into non-hazardous products [26–28].

Coal and other Fossil Fuels: While not necessarily a "waste" material, fossil fuels can be processed through various thermochemical conversion methods to produce electricity and other products. These methods include combustion, gasification, and liquefaction. While fossil fuels are not renewable resources, using thermochemical conversion can help to reduce their environmental impact. In conclusion, thermochemical conversion is a promising technology that can help to reduce waste and create a more sustainable future.

By transforming waste materials into new products, we can reduce our reliance on finite resources and reduce the environmental impact of waste. The waste materials discussed in this article are just a few examples of the many materials that can be transformed through thermochemical conversion. As technology advances, it is likely that we will discover new and innovative ways to use this technology to transform waste into valuable resources.

The global economy has been experiencing significant growth due to the increasing demand for energy, chemicals, and commodities [29]. The chemical sector, for instance, has seen a surge in the consumption of intermediate products, polymer-based materials, and integrated derivatives. However, this growth has come at a cost, as non-renewable fossil fuels and their derivatives, which provide nearly 100% of the energy required for the transportation sector and 80–86% of the energy needed for the global economy, are unsustainable due to their associated environmental degradation, high prices, and pollution [30,31].

The use of fossil fuels, especially in vehicles, has been linked to three primary challenges, namely environmental destruction, climate change, and health risks arising from carbon dioxide pollution. In 2018, the United States Environmental Protection Agency reported that 6677 gigatons of greenhouse gases were released into the environment, with the transportation sector contributing 28%; electricity production, 27%; industrial activities, 22%; commercial and domestic use, 12%; and agriculture, 10% [29]. Carbon dioxide, the most dangerous greenhouse gas, is responsible for around 30% of the effects of global warming [32,33].

Several methods for removing carbon dioxide from the atmosphere exist, and they can be classified as conventional, negative emission, and radiative forcing geoengineering methods. Additionally, researchers have developed preoxyfuel and postcombustion systems that can be used for carbon dioxide capture, representing a significant breakthrough. However, these technologies are still in the early stages of research and cannot be used commercially or on a large scale [34,35]. The scientific community is constantly searching for renewable energy resources in a biological form and possible techniques for converting them into liquid biofuels with sustainable performance, such as bio-oil, biodiesel, bioethanol, and biohydrogen. Bio-oil, in particular, has been identified as a viable substitute for liquid fossil fuels. Nevertheless, further research is necessary to determine the long-term sustainability and environmental impact of using biofuels as a viable alternative to fossil fuels [36,37].

3. Waste Production Problem and Sustainability

The issue of waste generation has emerged as a critical challenge in today's society, necessitating a comprehensive understanding of its magnitude and the urgent need for sustainable waste management practices. With the increasing population, urbanization, and industrialization, the volume of waste generated has reached unprecedented levels, resulting in severe environmental, health, and socioeconomic consequences. This academic analysis aims to delve into the problem of waste generation and highlight the imperative for adopting sustainable waste management practices. By exploring the diverse sources and types of waste, assessing the environmental and social impacts, and emphasizing the importance of sustainable waste management, this article aims to contribute to the discourse surrounding waste reduction and resource conservation. Waste generation encompasses a wide range of materials and byproducts produced by households, industries, and commercial activities. MSW, comprising domestic and commercial waste, is a significant contributor to the overall waste stream. Industrial waste, originating from manufacturing processes, construction activities, and agricultural practices, adds to the environmental burden. Additionally, hazardous waste, including toxic chemicals, pharmaceuticals, and electronic waste (e-waste), poses unique challenges due to its potential for environmental contamination and health hazards. The environmental impacts of unchecked waste generation are profound. Improper waste disposal and inadequate waste management infrastructure lead to the pollution of air, water bodies, and soil. Landfills, commonly used as waste disposal sites, emit greenhouse gases, contributing to climate change. Moreover, the leaching of hazardous substances from landfills contaminates groundwater and surface water sources, posing risks to ecosystems and human health. The accumulation of plastic waste in oceans has garnered significant attention due to its detrimental effects on marine life and ecosystems. The problem of waste generation extends beyond environmental concerns, impacting society and the economy. Inadequate waste management practices disproportionately affect marginalized communities, as they often bear the brunt of living in proximity to landfills and waste disposal sites [38]. The health risks associated with exposure to pollutants from waste can lead to respiratory problems, infectious diseases, and other adverse health effects. Furthermore, the economic costs of waste management, including collection, transportation, and disposal, place a burden on local governments and taxpayers. To mitigate the challenges posed by waste generation, sustainable waste management practices are imperative. Such practices encompass a holistic approach that prioritizes waste reduction, recycling, resource recovery, and the adoption of environmentally sound disposal methods. Waste reduction strategies focus on minimizing waste generation at the source through public awareness campaigns, product design improvements, and sustainable consumption patterns [38]. Recycling programs enable the recovery of valuable materials from waste streams, reducing the demand for virgin resources and minimizing energy consumption. Resource recovery processes, such as composting and anaerobic digestion, convert organic waste into useful products like fertilizer and biogas. Additionally, the implementation of advanced waste-to-energy technologies allows for the generation of renewable energy from waste. The problem of waste generation poses significant environmental, social, and economic challenges, demanding urgent action to transition towards sustainable waste management practices. By recognizing the diverse sources and types of waste, understanding their environmental impacts, and advocating for waste reduction, recycling, and resource recovery, societies can move towards a more sustainable and circular waste management paradigm [39]. Embracing sustainable waste management practices is crucial for safeguarding the environment, protecting human health, and ensuring the efficient use of resources for future generations.

3.1. Biomass

Woody biomass is currently the most important source of renewable energy in the world and is a significant contributor to global primary energy consumption. In 2010, the global use of woody biomass for energy was approximately 3.8 Gm^3/year (30 EJ/year), with 1.9 Gm^3/year (16 EJ/year) used for household fuelwood and 1.9 Gm^3/year (14 EJ/year) used for large-scale industrial purposes [40,41]. Despite its widespread use, current consumption of woody biomass is still below the existing resource potential and there is ample surplus land that could be utilized for energy crop plantations. Estimates of available woody biomass resources in 2050 range from 100 to 400 EJ/year, which could cover 10–40% of the world's primary energy consumption in 2050 if all these resources were used for energy production. This highlights the significant potential for woody biomass as a renewable energy source and the need for increased investment and research in this area to fully harness its potential [42–44]. Table 1 shows the studies in which the biomass raw material was converted by different thermochemical processes.

Table 1. Investigation of thermochemical conversion methods applied to biomass wastes in terms of raw materials, conversion parameters, and product types.

Conversion Process	Feed Stock	Reaction Parameters	Catalyst	HHV	Ref.
Hydrothermal Liquefaction (HTL)	*Ammi visnaga*	250–325 °C, 0–45 min	Cu, W, Fe metal powders	30.30 MJ/kg	[45]
	Prosopis farcta	250–350 °C, 0 min	H_3BO_3, $Na_2B_4O_7 \cdot 10H_2O$, NaOH	19.75–30.02 MJ/kg	[46]
	Datura stramonium L.	250–380 °C, 3.91–23.23 Mpa, 15 min	Colemanite and borax	-	[47]
	Birchwood sawdust	300 °C, 30 min	KOH, $FeSO_4 \cdot 7H_2O$, K_2CO_3, MgO, synthetic hydrotalcite, colemanite	26.0–31.3 MJ/kg	[48]
	Soybean oil, potato starch, microcrystalline cellulose	320 °C, 30 min	KH_2PO_4, K_2HPO_4, K_3PO_4	13.40–36 MJ/kg	[49]
	Macroalgae (*Enteromorpha prolifera*)	230–310 °C, 20–100 min	Sulfuric acid and acetic acid	24.5–32.00 MJ/kg	[50]
	Microalgae and cyanobacteria	350 °C, 250 bar	Na_2CO_3 and formic acid	32.3–37.1 MJ/kg	[51]
	Wheat straw	350, 400 °C, 18–35 Mpa, 15 min	K_2CO_3	16.53–35.97 MJ/kg	[52]
	Beech wood	250–350 °C, 0 min	Calcium borate mineral and colemanite	23.81–27.53 MJ/kg	[53]
	Lignin	250–310 °C	MCM-41, Ni-Al/MCM-41	25.4–36.6 MJ/kg	[54]
Hydrothermal Carbonization (HTC)	Coconut fiber and dead eucalyptus leaves	150–375 °C, 30 min	-	18.4–30.6 MJ/kg	[55]
	Miscanthus	190–260 °C	-	18.5–25.9 MJ/kg	[56]
	Cellulose, lignin, D-xylose, wood meal	225–265 °C	-	24–30 MJ/kg	[57]
	Corn stalk and Tamarix ramosissima	250 °C, 580 psi, 4 h	-	28.4–29.2 MJ/kg	[58]
	Bark mulch and sugar beet pulp	200, 250 °C, 3–20 h	-	-	[59]
	Water hyacinth	240 °C, 30 min–24 h	-	16.83–20.63 MJ/kg	[60]
	Giant bamboo, coffee wood, eucalyptus, and coffee parchment	180–240 °C, 3 h	-	24.6–29.2 MJ/kg	[61]
	Pinewood and poplar wood	180–240 °C	-		[62]
	Glucose, cellulose, chitin, chitosan, wood chips	200 °C, 6 h	-	13.29–25.45 MJ/kg	[63]
	Sorghum bagasse	250 °C,	-	26.4–31.9 MJ/kg	[64]

Table 1. *Cont.*

Conversion Process	**Feed Stock**	**Reaction Parameters**	**Catalyst**	**HHV**	**Ref.**
Pyrolysis	Pruning residues	400–600 °C	-	23.45–30.53 MJ/kg	[65]
	Martynia annua L. Seeds	650 °C, 3 h	-	-	[66]
	Black cumin seed	300–500 °C,	$Ca(OH)_2$, Al_2O_3, $SnCl_4·5H_2O$	32.44–36.19 MJ/kg	[67]
	Anchusea Azurea	350–550 °C	$Ca(OH)_2$, Na_2CO_3, $ZnCl_2$, Al_2O_3	17.43–24.18 MJ/kg	[68]
	Verbascum thapsus L.	400–550 °C	Al_2O_3, ZnO	-	[69]
	Wild mustard (*Sinapis arvensis*)	350–550 °C	H_2SO_4, HCI, NaOH, KOH,	12.35–28.06 MJ/kg	[70]
	Corn leaf waste	300–450 °C	-	24.4–26.1 MJ/kg	[71]
	Agricultural residue	400–700 °C	-	21.84–26.64 MJ/kg	[72]
	Wheat straw	340 °C, 1.6 h	Ru/C, $NiCu/Al_2O_3$	35.1–37.5 MJ/kg	[73]
	Cassava residues	450–500 °C	Volcanic rock	18.4–19.8 MJ/kg	[74]
Gasification	Oat straw	300–600 °C	-	-	[75]
	Corn straw	500–800 °C	-	-	[76]
	Cellulose, hemicellulose (xylan), lignin	500–800 °C	Ni/Al_2O_3	-	[77]
	Radiata pine	850 °C	MgO-Titanomagnetite	-	[78]
	Cellulose, hemicellulose, lignin, straw, pine	1000 °C	Dolomite and Na_2CO_3	-	[79]
	Wood (eucalyptus), lignin, shells of almond and hazelnut, lignin	600–1000 °C	-	-	[80]
	Cellulose, hemicellulose, lignin	500–800 °C	Ni-Ca-Al	-	[81]
	Wood chips, wood pellets, grass pellets	650–800 °C	-	-	[82]
	Sorghum, cotton gin trash	730–800 °C	-	-	[83]
	Sawdust, pelletized sawdust	750 °C	-	-	[84]

1. Hydrothermal Liquefaction (HTL): Different feedstocks and reaction parameters are used for HTL process. The higher heating values (HHVs) vary depending on different catalysts and reaction conditions used. HTL process enables the production of hydrocarbons with high HHVs for various feedstocks. Particularly, feedstocks such as ammi visnaga and birchwood sawdust may be suitable for obtaining high HHVs. In summary:
    - It offers suitable HHVs for various feedstocks;
    - The availability of feedstocks can vary widely;
    - Catalyst costs and process conditions should be economically evaluated.
2. Hydrothermal Carbonization (HTC): The HTC process is used for the carbonization of various biomasses. HHVs of the hydrocarbon obtained through HTC process vary for different biomasses. The HTC process provides medium HHVs, especially for feedstocks like coconut fiber and dead eucalyptus leaves. This method allows carbonization under low temperature and pressure conditions.
    - It provides medium HHVs;
    - It can be suitable for various biomass sources;
    - Energy costs are generally low due to low process temperatures and pressures.
3. Pyrolysis: The pyrolysis process is carried out using different feedstocks and temperature ranges. The use of different catalysts and reaction conditions affects the HHVs of pyrolysis products. Pyrolysis enables the production of products with high HHVs from feedstocks like pruning residues. Pyrolysis, conducted at high temperatures, results in the thermal decomposition of biomass into gas, liquid, and solid products.
    - It offers high HHVs and yields energy-intensive products;
    - Biomass sources generally have widespread accessibility;
    - The high temperature requirement of the pyrolysis process can increase energy costs.
4. Gasification: The gasification process is performed using various feedstocks and temperature ranges. The catalysts and gasification conditions used affect the HHVs of gasification products. Gasification process provides gas production with varying HHVs for different feedstocks. Especially, feedstocks like sawdust and pelletized sawdust can yield high-energy gas through gasification.
    - It offers varying HHVs for different gasification sources;
    - It has a wide range of biomass sources;
    - High temperature and pressure requirements can affect energy costs.

By analyzing the data, we can make some inferences to determine the most suitable method for biomass conversion, considering economic and availability factors. HHVs indicate the efficiency of conversion methods in terms of energy content. Higher HHVs indicate the production of products with higher energy density.

Economic factors:

- The cost and availability of feedstocks affect the conversion processes;
- Locally available and low-cost feedstocks may be economically preferred.

Availability factors:

- The availability of biomass sources can vary regionally and seasonally;
- Available resources in the region where the conversion processes will be used should be taken into account.

In conclusion, when selecting biomass conversion processes, it is important to consider both HHVs and the economic and availability factors of the feedstock. The appropriate process selection is a significant decision in terms of energy efficiency, economic sustainability, and utilization of local resources.

3.2. Municipal Solid Waste (MSW)

Solid waste and wastewater management are critical challenges facing communities worldwide. According to estimates, the world generates between 1.7–1.9 billion metric tons of MSW each year, with organic materials, such as paper, plastics, wood, and food waste, being the largest component [85]. In the United States alone, approximately 254 million tons of MSW were generated in 2013, with only 34% being recycled [86]. Improper management of MSW can lead to the contamination of soil, water, and air, contributing significantly to greenhouse gas emissions. It can also result in uncaptured potential economic values. In 2013, 134.3 million tons of MSW went to landfills, and only 32.7 million tons were combusted for energy recovery. This presents a significant opportunity for the recovery of energy from MSW [85]. The United States Environmental Protection Agency (EPA) estimated that in 2008, 74% of the US population was served by about 14,748 centralized municipal wastewater (MWW) treatment facilities or publicly owned treatment works (POTWs). Assuming an average daily volume of 300 liters per capita, the annual volume of US MWW is over 24 trillion liters [87]. The treatment of this wastewater is also energy-intensive, with a 2013 report by the Electric Power Research Institute, Inc. (EPRI) estimating that 2% of total US electricity use went towards moving and treating water and wastewater [88]. Furthermore, treatment of this water in POTWs generates over 8 million tons (dry weight) of sludge or biosolids, which require about one-third of the total electricity use by a wastewater treatment system. Approximately 55% of the total biosolids are applied to agricultural land, with the remainder either incinerated/processed for energy recovery, composted, or landfilled. In 2000, energy-related emissions from POTW operations resulted in total emissions of 15.5 million tons CO_2^- equivalents, an acidification potential of 145,000 tons SO_2^- equivalents, and eutrophication potential of 4000 tons PO_4^{3-} equivalents [85,88]. The degradation of biosolids also emits large amounts of CH_4 and N_2O, which contribute to global warming [89]. Given these challenges, effective solid waste and wastewater management strategies are crucial. The recovery of energy from MSW and the use of biosolids in agriculture present significant opportunities for reducing greenhouse gas emissions, capturing economic values, and improving the overall sustainability of these systems. Further research and development are needed to optimize these strategies and overcome the challenges facing solid waste and wastewater management [85]. Table 2 shows the studies in which the MSW were converted by different thermochemical processes.

Table 2. Investigation of thermochemical conversion methods applied to municipal solid waste (MSW) in terms of raw materials, conversion parameters, and product types.

Conversion Process	**Feed Stock**	**Reaction Parameters**	**Catalyst**	**HHV**	**Ref.**
Hydrothermal Liquefaction (HTL)	Biopulp	350–400 °C	K_2CO_3	37.4–40.7 MJ/kg	[90]
	Biogenic waste	200 °C, 100 bar	-	-	[91]
	Food waste	300–350 °C, 0, 30, 60 min	K_2CO_3	25.12 MJ/kg	[92]
	Food waste	280–380 °C, 10–60 min	-	32.71 MJ/kg	[93]
	Food waste	300 °C, 1 h	Na_2CO_3, $CeZrO_x$	24.20–35.60 MJ/kg	[94]
	Fruit and agricultural wastes	220 °C,	-	21.72 MJ/kg	[95]
	Spirulina algae, swine manure, and digested anaerobic sludge	300 °C, 10–12 Mpa, 30 min	-	32.0–34.7 MJ/kg	[96]
	Sewage sludge and Chlorella vulgaris	325 °C, 30 min	$NiMo/Al_2O_3$, $CoMo/Al_2O_3$, activated carbon felt	38.19 MJ/kg	[97]
	Watermelon peel	130 °C, 6 min	-	18.86 MJ/kg	[98]
	Garbage	250–340 °C–18 Mpa, 10, 30, 120 min	-	36 MJ/kg	[99]
Hydrothermal Carbonization (HTC)	Municipal mixed waste	200–220 °C, 1, 4, 8 h	-	13.5–18.5 MJ/kg	[100]
	Mixed municipal solid waste	180–220 °C, 1, 4, 8 h	-	18.46 MJ/kg	[101]
	Sewage sludge	250 °C, 8–10 Mpa, 15 min	-	15.82 MJ/kg	[102]
	Municipal solid waste pulp	200–300 °C, 30–120 min	-	15.8–21.0 MJ/kg	[103]
	Sewage sludge	180–280 °C, 60 min	-	10.11–31.50 MJ/kg	[104]
	Sewage sludge	200–300 °C, 30, 60, 120 min	-	18.2–21.5 MJ/kg	[105]
	Sewage sludge	140–200 °C, 30–240 min	-	16.66–18.65 MJ/kg	[106]
	Sewage sludge	160–240 °C, 60 min	-	9.82–11.57 MJ/kg	[107]
	Chicken manure	180–300 °C, 30–180 min	-	15.5 MJ/kg	[108]
	Anaerobically digested sludge	180–250 °C, 30 min	-	16.5–22.4 MJ/kg	[109]

Table 2. *Cont.*

Conversion Process	Feed Stock	Reaction Parameters	Catalyst	HHV	Ref.
Pyrolysis	Municipal solid waste	450–550 °C	-	20 MJ/Nm^3	[110]
	Mixture of plastic, paper, textile, and other organic wastes	500–600 °C	Y-zeolite, β-zeolite, FCC equilibrium, HZSM-5	18.41–50.69 MJ/kg	[111]
	Mixture of plastic, paper, textile, and other organic wastes	500–600 °C	Y-zeolite, b-zeolite, equilibrium FCC, MoO_3, Ni-Mo-catalyst, HZSM-5, $Al(OH)_3$	-	[112]
	Mixture of biomass, plastic, paper, and cardboard	450–550 °C	-	27.5–32.1 MJ/kg	[113]
	Municipal plastic wastes	450 °C	Commercial Y-zeolite and natural zeolite	-	[114]
	Municipal solid waste plastics, biomass, paper, rubber and textile	400 °C, 60 min	Natural activated zeolite	-	[115]
	Corrugated cardboard	350–450 °C	-	18–21.7 MJ/kg	[116]
	Organic fraction of municipal solid waste	500–800 °C	-	17.77–26.97 MJ/kg	[117]
	Municipal solid waste	500–700 °C	-	10.2–27.0 MJ/kg	[118]
	Rural solid waste and Chlorella vulgaris	500 °C	CaO, MgO, HZSM-5	20.13–22.39 MJ/kg	[119]
Gasification	Kitchen garbage, paper, cloth and fiber, plastics, residue	500–600 °C	-	-	[120]
	Kitchen garbage, textile, wood, and plastic, glass, ferrous materials	200–750 °C	Zeolite and calcined dolomite	-	[121]
	Kitchen waste, paper, textile, wood, plastic	750–900 °C	Calcined dolomite	-	[122]
	Plastics, paper, other organic wastes (wood, thin foil, vegetable garbage, etc.), textile/synthetic fibres, metal	500–600 °C	-	-	[111]
	Plastics, rubber, wood, cloth	700 °C	-	-	[123]
	MSW	750–950 °C	Dolomite	-	[124]
	MSW	600–1200 °C	-	9.31–15.45 MJ/kg	[125]
	Sewage sludge (SS)	700–890 °C	-	-	[126]
	MSW	800 °C	-	-	[127]
	Municipal waste and wood chips	800–1000 °C	-	23.93 MJ kg	[128]

Based on the data provided, we can make the following inferences about the recycling methods for domestic solid waste:

1. Hydrothermal Liquefaction (HTL):
    - Feedstocks, such as biopulp, biogenic waste, food waste, fruit and agricultural wastes, and sewage sludge, can be effectively converted using HTL;
    - Catalysts, such as K_2CO_3, Na_2CO_3, and CeZrOx, are used in the HTL process;
    - HHVs range from 18.86 MJ/kg to 38.19 MJ/kg for the mentioned feedstocks.
2. Hydrothermal Carbonization (HTC):
    - Municipal mixed waste, mixed municipal solid waste, sewage sludge, municipal solid waste pulp, and chicken manure are suitable feedstocks for HTC;
    - HTC is typically conducted at temperatures ranging from 140 °C to 300 °C;
    - The HHVs for the mentioned feedstocks range from 10.11 MJ/kg to 21.5 MJ/kg.
3. Pyrolysis:
    - MSW is a mixture of plastic, paper, textile, and other organic wastes; biomass; plastic; paper; cardboard; and the organic fraction of MSW that can be converted through pyrolysis;
    - Pyrolysis temperatures typically range from 350 °C to 600 °C;
    - The HHVs for the mentioned feedstocks range from 17.77 MJ/kg to 50.69 MJ/kg.
4. Gasification:
    - Kitchen garbage, paper, cloth and fiber, plastics, and other organic wastes can be subjected to gasification;
    - Gasification temperatures can range from 200 °C to 1200 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate gasification method.

The selection of the recycling method for domestic solid waste depends on various factors such as the composition of the waste, availability of feedstocks, energy requirements, and economic considerations. Further evaluation is needed to determine the most suitable method based on the specific context and objectives of the recycling process.

3.3. Plastic Waste

In recent decades, there has been a significant increase in the demand for plastic, with production reaching 460 million tons in 2019, which is double the amount produced in 2000. This is because plastic is versatile, cheap, lightweight, and durable, making it the preferred material for many products. However, plastics are often designed for endurance rather than recyclability, which makes it difficult to manage them at the end of their life [21]. As a result, plastic waste has accumulated in the environment, becoming a global problem. For example, in the United States, 12.2% of MSW in 2018 was made of plastics, with 75% of this being sent to landfills. Recycling rates are still relatively low, with only a little over 8% of plastics being recycled. In the European Union, 35% of plastics are collected for recycling, with most of it being burned for energy recovery, and the rest sent to landfills. Unfortunately, only a small percentage of this collected plastic is recycled at the highest level possible, with process losses and downcycling further reducing the actual global recycling flow [129–131].

This mismanagement of plastic waste is a threat to the environment and human health. In 2019, an estimated 22 million tons of plastic leaked into the environment, and by 2050, plastic production and incineration could release 2.8 gigatons of CO_2 per year [132,133]. Plastic pollution in the ocean is also a significant problem, with over 123 million tons of plastics leaking into the ocean from 1950 to 2015, leading to the death of 1 million sea birds and 100,000 sea animals annually. Studies have even found plastic particles in the fecal samples of people who consume seafood, indicating that plastic pollution is already affecting human health [134,135].

One of the causes of these problems is the considerable use of virgin fossil resources in plastic production, which is accelerating the depletion of petroleum resources. The current linear flow of the plastics value chain (produce–use–discard) exacerbates these negative impacts. To address this, the European Commission has introduced a circular economy action plan to encourage a more sustainable value chain and ensure that postconsumer waste is kept in the loop for as long as possible [136]. To achieve this goal, new technological solutions are needed, such as recycling strategies that improve the techno-economic feasibility of recycled plastics or lead to improved value/properties of new plastics (defined as "upcycling"). However, current recycling technology mainly transforms plastic waste into lower-value products (downcycling) or, at best, into the same level, which limits the feasibility of these strategies [137]. Table 3 shows the studies in which the plastic waste material was converted by different thermochemical processes.

Based on the data provided, we can make the following inferences about the recycling methods for plastic waste:

1. Hydrothermal Liquefaction (HTL):
    - Various types of plastics, such as PET, PC, polyamide 6 (PA6), polyurethane (PU), PE, PP, and PS, can be converted using HTL;
    - Reaction temperatures for HTL range from 100 °C to 450 °C;
    - Catalysts, such as NaOH, KOH, Na_2CO_3, and diaminotoluene (TDA), are used in the HTL process;
    - The HHVs for the mentioned plastics range from 17.43 MJ/kg to 49 MJ/kg.
2. Hydrothermal Carbonization (HTC):
    - Plastic waste, PVC waste, PVC, and various plastic mixtures can be subjected to HTC;
    - HTC is typically conducted at temperatures ranging from 180 °C to 300 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate HTC method.
3. Pyrolysis:
    - Plastic waste, such as HDPE, LDPE, IPP, PS, ABS, PP, and PVC can be effectively converted through pyrolysis;
    - Pyrolysis temperatures typically range from 290 °C to 730 °C;
    - Catalysts used in pyrolysis include HZSM-5, PZSM-5, Ziegler-Natta (Z-N), Ni/h-ZSM-5, and activated carbon;
    - The HHVs for the mentioned plastics range from 36.3 MJ/kg to 44.2 MJ/kg.
4. Gasification:
    - PE, PP, and other plastic mixtures can undergo gasification;
    - Gasification temperatures can range from 500 °C to 900 °C;
    - Various catalysts, such as $NiO/\gamma\text{-}Al_2O_3$, dolomite, olivine, and $Ca(OH)_2$ can be used in the gasification process;
    - The availability and economy of raw materials should be considered when choosing the appropriate gasification method.

The selection of the recycling method for plastic waste depends on the specific type of plastic, its composition, availability of feedstocks, energy requirements, and economic considerations. Further evaluation is needed to determine the most suitable method based on the specific context and objectives of the recycling process.

Table 3. Investigation of thermochemical conversion methods applied to plastic in terms of raw materials, conversion parameters, and product types.

Conversion Process	Feed Stock	Reaction Parameters	Catalyst	HHV	Ref.
Hydrothermal Liquefaction (HTL)	PET (polyethylene terephthalate)	100–250 °C, 120–200 °C, 300–420 °C	NaOH and KOH	-	[138–140]
	Polycarbonate (PC)	230, 430 °C, 130–300 °C, 400 °C	Na_2CO_3	-	[141–144]
	Polyamide 6 (PA6)	300–400 °C, 35 Mpa	-	-	[145]
	Polyurethane (PU)	150–350 °C	Diaminotoluene (TDA)	-	[146]
	Polyethylene (PE)	400–450 °C	-	-	[147]
	Polyproplyene	380–500 °C	-	48–49 MJ/kg	[148]
	Polyolefin	450 °C, 45–60 min, 23 Mpa	-	-	[149]
	Polyethylene (LDPE, PE) and Polyethylene	380–450 °C, 30–240 min 425–450 °C, 30–180 min	Acetic acid	-	[150,151]
	Polystyrene High impact polystyrene (HIPS)	380–420 °C, 0–60 min 350–550 °C, 5–60 min	-	-	[152,153]
	Synthetic polymers	350 °C, 20 min	KOH	-	[154]
Hydrothermal Carbonization (HTC)	Marine plastic debris	200–300 °C 3 h	-	-	[155]
	PVC waste	200–260 °C, 60 min	-	17.43–36.87 MJ/kg	[156]
	Poly(vinyl chloride) (PVC)	180–260 °C, 15 h	-	-	[157]
	Waste plastic	250–350 °C, 1 h	-	-	[158]
	Polyvinyl chloride–corncob	260 °C, 60 min	-	17.80–32.83 MJ/kg	[159]
	Polyvinyl chloride (PVC) and pinewood sawdust	280 °C, 1 h	-	18.3–30.89 MJ/kg	[160]
	PVC-containing medical wastes	210 °C, 30 min	-	24.18–30.52 MJ/kg	[161]
	Corn stover–polyurethane mixture	200–260 °C, 30 min	-	16.8–34.1 MJ/kg	[162]
	Poly(vinyl chloride) (PVC)	180–260 °C	-	-	[157]
	Cotton textile waste (CTW) and polyvinyl chloride waste (PVCW)	240–270 °C, 2 h	HCl	20.07–30.65 MJ/kg	[163]

Table 3. *Cont.*

Conversion Process	Feed Stock	Reaction Parameters	Catalyst	HHV	Ref.
Pyrolysis	HDPE, LDPE, IPP, PS, ABS, PE	420–480 °C	HZSM-5 and PZSM-5	-	[164]
	PP, HDPE, LDPE	500–730 °C	Ziegler-Natta (Z-N): $TiCl_4/MgCl_2$	-	[165]
	LDPE and PP	310–400 °C	Ni/h-ZSM-5, Ni/h-Beta) (Ni/Al-MCM-41, Ni/Al-SBA-15)	-	[166]
	Polymer wastes (LDPE/HDPE/PP/PS)	290–420 °C	USY, MOR, ASA, ZSM-5, MCM-41	-	[167]
	Waste plastics	430–571 °C	Activated carbon	-	[168]
	Mixed plastics and hard-burnt lime	600–700 °C	CaO, $Ca(OH)_2$, $CaCO_3$	-	[169]
	Mixed plastics	300–500 °C	AL-PILC	36.3–42.9 MJ/kg	[170]
	ABS/PC and PCB	500 °C	Y-Zeolite (YZ), ZSM-5, biochar (BC), electronic waste char (EWC), iron oxide loaded YZ (Fe/YZ), Fe/ZSM-5, Fe/BC, Fe/EWC	-	[171]
	Waste polyethylene and polypropylene Mixture	500 °C 600 °C	ZSM-5, AL-MCM-41, AL-SBA-15 H_3PO_4, activated carbon	-	[172,173]
	Municipal plastic waste Plastics wastes (PS, PE, PP, PET)	700 °C 450 °C	Me/Ni/ZSM-5 Modified natural zeolite	- 41.7–44.2 MJ/kg	[174,175]
Gasification	Waste polyethylene (PE) PE	700–900 °C 850 °C, 3 h	$NiO/\gamma\text{-}Al_2O_3$ -	-	[176,177]
	Polyethylene (PE) and polypropylene (PP)	900 °C	-	-	[178]
	Mixed plastic wastes (mainly polyolefins)	700 °C, 3 h	Olivine	-	[179]
	Recycled plastic (from packaging)	750 °C, 2 h	-	18.40–42.69 MJ/kg	[180]
	Mixture of waste polyolefins	700 °C	-	-	[181]
	Polypropylene waste	750–850 °C	Dolomite and olivine	-	[182]
	Waste plastic mixture	800 °C	-	13.44 MJ/kg	[183,184]
	Waste polyolefins	750 °C	-	-	[185]
	Waste plastic mixture Plastic wastes	500–900 °C, 500–750 °C	-	10 MJ/(Nm^3)	[186,187]
	Virgin PE	350 °C	$Ca(OH)_2$ and Ni(OH)	-	[188]

3.4. Industrial Waste

The OSW, or organic solid waste, has a lot of potential as a fuel in the future, and it's important to conserve energy by making good use of it. Organic solid waste is the waste that comes from people's daily lives and production processes [189]. It's mainly divided into two types: lignocellulosic waste (like agricultural and yard waste) and nonlignocellulosic waste (like sludge, manure, and food waste digestate). Food waste digestate is a big source of OSW in urban areas, and it could be used to create renewable energy. Biomass waste is a great source of renewable energy that is sustainable and does not pollute the environment [190,191]. There are many ways to treat OSW, but there are also some problems. Common methods include pyrolysis, bioconversion, torrefaction, and HTC. OSW is typically low quality and has high moisture content, so it needs to be dried and treated before being processed [192]. This takes extra energy and money. Wet biomass is best suited for the HTC process, while other biomass with low moisture content does not require as much energy. Biotransformation processes (like anaerobic digestion and fermentation) require less energy but take longer to complete [193]. Food waste and sewage sludge can be dangerous because they can contain pathogens, heavy metals, and other harmful substances that can harm the environment and human health. HTC technology is more economically efficient and uses water in the OSW as a reaction medium, which reduces the energy needed for drying and pretreatment. OSW can be converted into high-carbon products through the water-based reaction process and the generation of spontaneous pressure [194].

There are large amounts of biomass available in natural areas and as waste from human industrial activities. According to the World Bioenergy Association, the total global biomass resources on land and in water are about 1.8 trillion tons and 4 billion tons, respectively. This biomass has the potential to produce more than 80 times the world's annual energy consumption [195,196]. Table 4 shows the studies in which the industrial waste was converted by different thermochemical processes.

1. Hydrothermal Liquefaction (HTL):
    - Various types of domestic solid waste, such as food waste, tobacco-processing waste, oil palm fruit press fiber, shrimp shells, and olive oil waste, can be converted using HTL;
    - Reaction temperatures for HTL range from 90 °C to 350 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate HTL method.
2. Hydrothermal Carbonization (HTC):
    - Domestic solid waste, such as food waste, crude oil sludge, oily sludge, olive mill wastewater, and various agro-industrial wastes, can be subjected to HTC;
    - HTC is typically conducted at temperatures ranging from 150 °C to 275 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate HTC method.
3. Pyrolysis:
    - Domestic solid waste, such as olive oil industry waste, industrial wastes, tire industry wastes, and various agricultural and industrial wastes, can be effectively converted through pyrolysis;
    - Pyrolysis temperatures typically range from 300 °C to 700 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate pyrolysis method.
4. Gasification:
    - Domestic solid waste, such as palm kernel shell–oil sludge mixtures, bagasse residue, olive pomace, oily sludge, waste tires, and various industrial and municipal sludges, can undergo gasification;
    - Gasification temperatures can range from 400 °C to 1000 °C;
    - The availability and economy of raw materials should be considered when choosing the appropriate gasification method.

Table 4. Investigation of thermochemical conversion methods applied to industrial waste in terms of raw materials, conversion parameters, and product types.

Conversion Process	**Feed Stock**	**Reaction Parameters**	**Catalyst**	**HHV**	**Ref.**
Hydrothermal Liquefaction (HTL)	Lactose, maltose, lysine	250–350 °C, 20 min	-	-	[197]
	Montepulciano grape pomace, Cabernet Sauvignon grape pomace, sugar beet tailings, extracted grain	330–350 °C	-	-	[198]
	Tobacco-processing waste	280–340 °C	-	26.1–31.9 MJ/kg	[199]
	Food waste	240–295 °C	-	40.2 MJ/kg	[200]
	Food wastes (meat, chesee, fruit)	300 °C	-	-	[201]
	Food wastes	200–600 °C	-	35 MJ/kg	[202]
	Olive oil waste and hazel nutshell	180 °C, 4 h	-	-	[203]
	Oil palm fruit press fiber	210–337 °C	$ZnCl_2$, Na_2CO_3, NaOH	-	[204]
	Shrimp shells (seafood-processing waste)	90–250 °C, 5–60 min	-	-	[205]
	Oil mill wastewater (OMWW)	240–300 °C	-	38 MJ/kg	[206]
Hydrothermal Carbonization (HTC)	Food waste	225–275 °C, 24 h	-	-	[207]
	Crude oil sludge	150–250 °C	-	-	[208]
	Oily sludge	150–250 °C, 0.5–4 h	-	18.1–26.7 MJ/kg	[209]
	Olive Mill Wastewater	180–250 °C, 35–55 bar, 2–8 h	-	-	[210]
	Agro-industrial waste (Grape marc)	180–250 °C, 1, 3, 8 h	-	19.8–24.1 MJ/kg	[211]
	Moist agro-industrial waste (olive mill, canned artichoke, orange wastes)	200–250 °C, 2, 4, 8–24 h	-	25.09–33.21 MJ/kg	[212]
	Apple industry waste	180–230 °C, 2–4 h	-	30 MJ/kg	[213]
	Pharmaceutical biowastes	240 °C	-	24–25 MJ/kg	[214]
	Waste textile and waste wood	240 °C, 90 min	-	18.04–26.94 MJ/kg	[215]
	Antibiotic mycelial dreg	160–220 °C, 30 min	-	16.7–24.4 MJ/kg	[216]

Table 4. *Cont.*

Conversion Process	Feed Stock	Reaction Parameters	Catalyst	HHV	Ref.
Pyrolysis	Olive oil industry waste	300–500 °C	-	21.01–31.26 MJ/kg	[26]
	Olive mill	400–600 °C	-	25.74–29.78 MJ/kg	[217]
	Industrial wastes (olive and hazelnut bagasse)	500 °C	Activated alumina and sodium feldspar	31.80–35.74 MJ/kg	[218]
	Heavy shale oil–polyethylene waste	450 °C	Al-Co-Mo and Akzo Nobel (Mo + S)	-	[219]
	Tire industry wastes	300–600 °C	-	29.67–37.31 MJ/kg	[220]
	Industrial waste (lignin)	300–700 °C	-	29.19–31.62 MJ/kg	[221]
	Industrial alliaceous plant wastes	350–700 °C	-	-	[222]
	Industrial wastes (herb residue)	350–550 °C	ZSM-5, Al-SBA-15, alumina	18.66–25.94 MJ/kg	[223]
	Agricultural and industrial wastes	300–700 °C	-	-	[224]
	Industrial waste	400–700 °C, 300–700 °C, 1–2 h	-	32–37.91 MJ/kg	[225,226]
Gasification	Palm kernel shell–oil sludge mixture	400–1000 °C	-	18.18–42.27 MJ/kg	[227]
	Baggase residue organic solid wastes, corn stalk (CS), poplar sawdust (PS)	700–900 °C	-	-	[228]
	Olive pomace	700–900 °C	-	-	[229]
	Oily sludge and chicken manure	700–800 °C	-	-	[230]
	Waste tires	1000 °C	-	-	[231]
	Waste tyre	850–1000 °C	-	-	[232]
	Industrial wastewater sludge	600–800 °C	-	4.84–5.11 MJ/Nm^3	[233]
	Sewage and textile sludge	850 °C	-	-	[234]
	Olive industry wastes	850 °C	-	2.83–3.98 MJ/kg	[235]
	Municipal sewage sludge	600–850 °C	-	4.8–5.4 MJ/kg	[236]

The selection of the recycling method for domestic solid waste depends on the specific waste composition, availability of feedstocks, energy requirements, and economic considerations. It is important to assess the characteristics of the waste and the desired end products to determine the most suitable recycling method. Further evaluation and analysis are necessary to determine the optimal approach based on the specific context and objectives of the waste management process.

In evaluating the economic and availability factors for the recycling methods of wastes, the following considerations can be made:

Economic Factors:

Cost of raw materials: The availability and affordability of the feedstock or waste material play a significant role in determining the economic viability of the recycling method. Waste materials that are abundant and readily accessible are generally more economically favorable.

Energy requirements: The energy inputs required for the recycling process, such as heating or catalyst activation, can impact the overall cost. Methods that operate at lower temperatures or utilize energy-efficient processes may be more economically attractive.

Conversion efficiency: The efficiency of the recycling method in converting waste materials into valuable products is important. Higher conversion efficiencies can lead to higher yields of usable products, increasing the economic potential of the process.

Market demand: The market demand for the end products obtained from the recycling process is a crucial factor. If there is a strong demand and market value for the recycled products, it can enhance the economic feasibility of the recycling method.

Infrastructure and operational costs: The required infrastructure, equipment, and operational costs associated with the recycling method should be considered. Methods that can be integrated into existing waste management systems or utilize readily available equipment may be more cost-effective.

Availability Factors:

Feedstock availability: The abundance and availability of the waste materials or feedstock in the specific region or locality are important factors. Methods that can utilize a wide range of waste materials or have access to a consistent supply of feedstock are advantageous.

Geographic considerations: The geographical location and proximity to waste sources can impact the availability and logistics of waste collection and transportation. Methods that can efficiently utilize locally available waste materials may offer logistical advantages.

Regulatory framework: The regulatory environment and waste management policies in place can influence the availability of waste materials for recycling. Compliance with regulations and permits may be necessary for certain recycling methods.

Waste management infrastructure: The presence of waste management infrastructure, such as recycling facilities or waste treatment plants, can affect the availability and feasibility of specific recycling methods. Access to suitable facilities can streamline the recycling process.

It is important to assess both economic and availability factors when selecting a recycling method for domestic solid waste. A comprehensive analysis considering these factors can help determine the most suitable and sustainable recycling approach that aligns with the specific goals, resources, and constraints of the given context.

4. General Situation and Forecasts in the World

Fossil fuels, such as coal, oil, and natural gas, still dominate the global energy supply, accounting for about 81% of the total primary energy supply. Renewable energy technologies, like solar, wind, water, biomass, and geothermal, make up only 14.1% of the primary energy supply. In 2019, 56.9 EJ of domestic biomass supply was used, with 85% coming from solid biomass, like wood pellets and wood chips. Liquid biofuels, municipal and industrial waste, and biogas made up the rest [196].

Agriculture is a key area for increasing bioenergy potential in the future. There is a great opportunity to grow crops that can be used for food and fuel. Energy can also be produced from municipal and industrial waste. In 2019, 655 TWh of electricity was produced worldwide from biomass, with solid biomass sources accounting for 68% and municipal and industrial waste accounting for 17%. Asia produced 39% of bioenergy, followed by Europe with 35%. In total, power plants produced about 428 TWh of bioenergy, and 1.17 EJ of heat was produced from biomass [196]. European countries like Poland, Denmark, and Sweden are leaders in the production of heat from biomass. Poland plans to have 80% of its total energy come from renewable sources, with 75% of biomass energy coming from agricultural biomass. Austria, Sweden, and Finland also use a significant amount of biomass energy [237]. The United States only uses biomass for about 3% of its total energy demand. Globally, energy production is estimated at around 27,000 TWh/year, with waste heat recovery estimated at around 300 TWh/year [238].

Global energy consumption decreased by 4% in 2020 due to the COVID-19 pandemic but has since increased by 5.5% in 2021. Despite this increase in renewable energy consumption, fossil fuels like coal and oil continue to dominate the global energy supply [239].

China is the largest consumer of primary energy in the world, consuming around 158 EJ in 2021. The United States and India follow with around 93 EJ and 34 EJ, respectively. Renewable energy consumption is projected to increase and could reach around 247 EJ by 2050 [240].

Waste generation is a growing environmental concern that has significant economic and social impacts globally. The increase in population, urbanization, and industrialization has led to the generation of huge amounts of waste, posing a threat to the environment and human health. In addition, the disposal of waste in landfills contributes to the emission of greenhouse gases, which further exacerbates the problem of climate change. To address this challenge, sustainable waste management practices have become a critical area of focus. Sustainable waste management aims to reduce the amount of waste generated, maximize the reuse and recycling of waste, and minimize the impact of waste on the environment [241]. Thermochemical processes have emerged as a promising approach to sustainable waste management, as they can convert waste into valuable materials and chemicals. Thermochemical processes involve the use of heat to break down waste into its constituent components. One of the key advantages of thermochemical processes is that they can reduce the amount of waste sent to landfills, which helps to mitigate the environmental impacts of waste disposal. In addition, these processes can recover valuable materials and chemicals from waste, which can be sold or reused. Thermochemical processes can also reduce the demand for fossil fuels by producing renewable energy from waste. However, there are also challenges associated with thermochemical processes. One major challenge is the cost of implementing these processes, as they require significant investment in infrastructure and equipment. In addition, the efficiency of these processes can be affected by the type and composition of the waste being processed. Sustainable waste management practices are essential for mitigating the environmental impact of waste generation. Thermochemical processes offer a promising approach to transforming waste into valuable materials and chemicals, and reducing the amount of waste sent to landfills. While there are challenges associated with implementing these processes, their potential benefits make them an important area of focus for future research and development.

With similar studies in the literature, promising expectations are formed for sustainable waste management in the future. These studies highlight the utilization of renewable resources and waste materials for various applications, which can contribute to mitigating environmental challenges and promoting sustainable practices. Some of these studies are related to the utilization of biorenewable nanocomposites [242], alternative fuel sources from waste materials [243], and remediation of antibiotics and antibiotic-resistant bacteria [244].

Overall, these studies demonstrate the potential for sustainable waste management in the future. By harnessing renewable resources, transforming waste materials into valuable products, and implementing effective remediation methods, we can address environmental challenges and promote a more sustainable approach to waste management. However, it is important to continue research and development in these areas to further optimize and implement these sustainable practices on a larger scale.

Thermochemical processes, such as HTL, HTC, pyrolysis, and gasification, are commonly used for treating biomass, MSW, plastic waste and industrial waste. These processes aim to convert these feedstocks into liquid, solid, and gaseous products with various applications. To evaluate and compare these products, it is essential to consider their life cycle assessment (LCA) characteristics [245].

Life cycle assessment is a comprehensive methodology that analyzes the environmental impacts of a product or process throughout its entire life cycle, from raw material extraction to end-of-life disposal. It takes into account factors like resource depletion, energy consumption, greenhouse gas emissions, waste generation, and toxicity [246]. Conducting an LCA allows for the assessment and comparison of the sustainability and environmental performance of different products. In the context of HTL, HTC, pyrolysis, and gasification processes, conducting an LCA analysis provides valuable insights into the environmental implications of these technologies. LCA helps identify potential environmental hotspots, evaluate process energy efficiency, and assess overall environmental sustainability of the products obtained [247].

For example, in the case of HTL, LCA analysis evaluates the environmental impacts associated with converting biomass, MSW, plastic waste and industrial waste into liquid fuels. It assesses parameters such as energy consumption, carbon emissions, water usage, and waste generation throughout the entire life cycle of the process. Comparing the LCA results of different feedstocks and process configurations enables the identification of the most environmentally favorable options [248]. Similarly, in the case of HTC, pyrolysis, and gasification processes, LCA analysis provides insights into the environmental performance of the solid and gaseous products obtained. It assesses factors like carbon sequestration potential, greenhouse gas emissions, pollutant emissions, and resource utilization efficiency. This information guides decision-making processes, facilitating the selection of sustainable and environmentally friendly options. Considering the LCA characteristics of the products obtained, it is important to evaluate their potential environmental impacts and compare them to alternative products or processes. Comprehensive LCA analysis quantifies and understands the environmental benefits and drawbacks of different thermochemical processes. This knowledge informs policymakers, researchers, and industry stakeholders, aiding them in making informed decisions regarding the utilization of biomass, MSW, plastic waste, and industrial waste for energy production and resource recovery [246,249].

In conclusion, evaluating the environmental performance and sustainability of HTL, HTC, pyrolysis, and gasification processes through LCA analysis is crucial. Such analyses provide valuable insights into the environmental impacts and help identify the most sustainable options for utilizing biomass and various waste materials.

However, in general, thermochemical processes such as HTL, HTC, pyrolysis, and gasification have the potential to be environmentally friendly and have positive LCA characteristics compared to traditional waste disposal methods or fossil fuel-based processes. These thermochemical processes offer opportunities for resource recovery, energy production, and waste management.

To determine which method is more environmentally friendly or better in terms of LCA, a comparative LCA analysis should be conducted for each specific case, considering the specific feedstock, process conditions, and desired products. This analysis should assess a range of environmental factors such as energy consumption, carbon emissions, water usage, waste generation, pollutant emissions, and resource utilization efficiency. Therefore, it is recommended to conduct a comprehensive and site-specific LCA analysis for each thermochemical method and the desired products, taking into account the specific circumstances and environmental priorities. This analysis will provide a robust basis for evaluating the environmental performance and making informed decisions regarding the selection of thermochemical methods for biomass and waste treatment.

5. Conclusions

Thermochemical processes, including HTL, HTC, pyrolysis, and gasification, have shown potential as sustainable waste management solutions. These processes convert various feedstocks into valuable products, such as high-energy hydrocarbons and gases. However, the selection of an appropriate method depends on factors such as waste composition, feedstock availability, energy requirements, and economic considerations.

Economic factors, including feedstock cost and availability, should be carefully evaluated for each conversion process. Local and low-cost feedstocks are preferable to ensure feasibility and sustainability. Additionally, regional and seasonal variations in biomass sources should be considered to ensure a consistent feedstock supply. The HHV is an important parameter to assess the energy content and efficiency of conversion methods. However, HHVs vary based on feedstocks, catalysts, and reaction conditions.

Renewable energy sources, including biomass, have a relatively small share compared to fossil fuels in global energy consumption. Nevertheless, there is an increasing trend in renewable energy consumption, with biomass playing a significant role in power generation and heat production. The agricultural sector has great potential for bioenergy production, and utilizing municipal and industrial waste can contribute to sustainable energy production. Thermochemical processes offer advantages by converting waste into valuable materials while reducing the need for landfill disposal. However, challenges such as implementation costs and process efficiency need to be addressed for widespread adoption.

By embracing thermochemical processes and integrating them into comprehensive waste management systems, societies can reduce their environmental impact, conserve resources, and contribute to a more sustainable future.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The author declares no conflict of interest.

References

1. Seo, M.W.; Lee, S.H.; Nam, H.; Lee, D.; Tokmurzin, D.; Wang, S.; Park, Y.-K. Recent Advances of Thermochemical Conversion Processes for Biorefinery. *Bioresour. Technol.* **2022**, *343*, 126109. [CrossRef]
2. Raza, M.; Inayat, A.; Abu-Jdayil, B. Crude Glycerol as a Potential Feedstock for Future Energy via Thermochemical Conversion Processes: A Review. *Sustainability* **2021**, *13*, 12813. [CrossRef]
3. Tews, I.J.; Garcia-Perez, M. Advanced Oxidative Techniques for the Treatment of Aqueous Liquid Effluents from Biomass Thermochemical Conversion Processes: A Review. *Energy Fuels* **2022**, *36*, 60–79. [CrossRef]
4. Genel, S.; Durak, H.; Durak, E.D.; Güneş, H.; Genel, Y. Hydrothermal Liquefaction of Biomass with Molybdenum, Aluminum, Cobalt Metal Powder Catalysts and Evaluation of Wastewater by Fungus Cultivation. *Renew Energy* **2023**, *203*, 20–32. [CrossRef]
5. Mathanker, A.; Das, S.; Pudasainee, D.; Khan, M.; Kumar, A.; Gupta, R. A Review of Hydrothermal Liquefaction of Biomass for Biofuels Production with a Special Focus on the Effect of Process Parameters, Co-Solvents, and Extraction Solvents. *Energies* **2021**, *14*, 4916. [CrossRef]
6. Venkatachalam, C.D.; Ravichandran, S.R.; Sengottian, M. Lignocellulosic and Algal Biomass for Bio-Crude Production Using Hydrothermal Liquefaction: Conversion Techniques, Mechanism and Process Conditions: A Review. *Environ. Eng. Res.* **2021**, *27*, 200555. [CrossRef]
7. Shen, Y. A Review on Hydrothermal Carbonization of Biomass and Plastic Wastes to Energy Products. *Biomass Bioenergy* **2020**, *134*, 105479. [CrossRef]
8. Bardhan, M.; Novera, T.M.; Tabassum, M.; Islam, M.A.; Islam, M.A.; Hameed, B.H. Co-Hydrothermal Carbonization of Different Feedstocks to Hydrochar as Potential Energy for the Future World: A Review. *J. Clean Prod.* **2021**, *298*, 126734. [CrossRef]
9. Li, Q.; Faramarzi, A.; Zhang, S.; Wang, Y.; Hu, X.; Gholizadeh, M. Progress in Catalytic Pyrolysis of Municipal Solid Waste. *Energy Convers. Manag.* **2020**, *226*, 113525. [CrossRef]
10. Du, Y.; Ju, T.; Meng, Y.; Lan, T.; Han, S.; Jiang, J. A Review on Municipal Solid Waste Pyrolysis of Different Composition for Gas Production. *Fuel Process. Technol.* **2021**, *224*, 107026. [CrossRef]
11. Zaccariello, L.; Montagnaro, F. Fluidised Bed Gasification of Biomasses and Wastes to Produce Hydrogen-Rich Syn-Gas—A Review. *J. Chem. Technol. Biotechnol.* **2023**, *98*, 1878–1887. [CrossRef]

12. Okolie, J.A.; Epelle, E.I.; Tabat, M.E.; Orivri, U.; Amenaghawon, A.N.; Okoye, P.U.; Gunes, B. Waste Biomass Valorization for the Production of Biofuels and Value-Added Products: A Comprehensive Review of Thermochemical, Biological and Integrated Processes. *Process Saf. Environ. Prot.* **2022**, *159*, 323–344. [CrossRef]
13. Jha, S.; Nanda, S.; Acharya, B.; Dalai, A.K. A Review of Thermochemical Conversion of Waste Biomass to Biofuels. *Energies* **2022**, *15*, 6352. [CrossRef]
14. Sánchez, J.; Curt, M.D.; Robert, N.; Fernández, J. Chapter Two—Biomass Resources. In *The Role of Bioenergy in the Bioeconomy*; Lago, C., Caldés, N., Lechón, Y., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 25–111; ISBN 978-0-12-813056-8.
15. Lim, C.H.; Lam, H.L. Biomass Supply Chain Optimisation via Novel Biomass Element Life Cycle Analysis (BELCA). *Appl. Energy* **2016**, *161*, 733–745. [CrossRef]
16. Pan, H. Synthesis of Polymers from Organic Solvent Liquefied Biomass: A Review. *Renew. Sustain. Energy Rev.* **2011**, *15*, 3454–3463. [CrossRef]
17. Lu, J.-S.; Chang, Y.; Poon, C.-S.; Lee, D.-J. Slow Pyrolysis of Municipal Solid Waste (MSW): A Review. *Bioresour. Technol.* **2020**, *312*, 123615. [CrossRef]
18. Ashani, P.N.; Shafiei, M.; Karimi, K. Biobutanol Production from Municipal Solid Waste: Technical and Economic Analysis. *Bioresour. Technol.* **2020**, *308*, 123267. [CrossRef] [PubMed]
19. Arena, U. Process and Technological Aspects of Municipal Solid Waste Gasification. A Review. *Waste Manag.* **2012**, *32*, 625–639. [CrossRef]
20. Nanda, S.; Berruti, F. A Technical Review of Bioenergy and Resource Recovery from Municipal Solid Waste. *J. Hazard Mater.* **2021**, *403*, 123970. [CrossRef]
21. Lomwongsopon, P.; Varrone, C. Critical Review on the Progress of Plastic Bioupcycling Technology as a Potential Solution for Sustainable Plastic Waste Management. *Polymers* **2022**, *14*, 4996. [CrossRef]
22. Alam, S.S.; Husain Khan, A.; Khan, N.A. Plastic Waste Management via Thermochemical Conversion of Plastics into Fuel: A Review. *Energy Sources Part A Recovery Util. Environ. Eff.* **2022**, *44*, 1–20. [CrossRef]
23. Prajapati, R.; Kohli, K.; Maity, S.K.; Sharma, B.K. Potential Chemicals from Plastic Wastes. *Molecules* **2021**, *26*, 3175. [CrossRef]
24. Yansaneh, O.Y.; Zein, S.H. Latest Advances in Waste Plastic Pyrolytic Catalysis. *Processes* **2022**, *10*, 683. [CrossRef]
25. Viganó, J.; Machado, A.P.d.F.; Martínez, J. Sub- and Supercritical Fluid Technology Applied to Food Waste Processing. *J. Supercrit. Fluids* **2015**, *96*, 272–286. [CrossRef]
26. Nunes, L.J.R.; Loureiro, L.M.E.F.; Sá, L.C.R.; Silva, H.F.C. Thermochemical Conversion of Olive Oil Industry Waste: Circular Economy through Energy Recovery. *Recycling* **2020**, *5*, 12. [CrossRef]
27. Nunes, L.J.R.; Loureiro, L.M.E.F.; Sá, L.C.R.; Silva, H.F.C. Sugarcane Industry Waste Recovery: A Case Study Using Thermochemical Conversion Technologies to Increase Sustainability. *Appl. Sci.* **2020**, *10*, 6481. [CrossRef]
28. Rodríguez-Sánchez, S.; Ruiz, B.; Martínez-Blanco, D.; Sánchez-Arenillas, M.; Diez, M.A.; Suárez-Ruiz, I.; Marco, J.F.; Blanco, J.; Fuente, E. Sustainable Thermochemical Single-Step Process to Obtain Magnetic Activated Carbons from Chestnut Industrial Wastes. *ACS Sustain. Chem. Eng.* **2019**, *7*, 17293–17305. [CrossRef]
29. Ali Qamar, O.; Jamil, F.; Hussain, M.; Al-Muhtaseb, A.H.; Inayat, A.; Waris, A.; Akhter, P.; Park, Y.-K. Feasibility-to-Applications of Value-Added Products from Biomass: Current Trends, Challenges, and Prospects. *Chem. Eng. J.* **2023**, *454*, 140240. [CrossRef]
30. Sajid, M.; Farooq, U.; Bary, G.; Azim, M.M.; Zhao, X. Sustainable Production of Levulinic Acid and Its Derivatives for Fuel Additives and Chemicals: Progress, Challenges, and Prospects. *Green Chem.* **2021**, *23*, 9198–9238. [CrossRef]
31. Wu, L.; Wei, W.; Chen, Z.; Chen, X.; Ni, B.-J. Long-Chain Alcohol Production in Open Culture Anaerobic Fermentation. *Chem. Eng. J.* **2023**, *452*, 139225. [CrossRef]
32. Chai, W.S.; Bao, Y.; Jin, P.; Tang, G.; Zhou, L. A Review on Ammonia, Ammonia-Hydrogen and Ammonia-Methane Fuels. *Renew. Sustain. Energy Rev.* **2021**, *147*, 111254. [CrossRef]
33. Žula, M.; Grilc, M.; Likozar, B. Hydrocracking, Hydrogenation and Hydro-Deoxygenation of Fatty Acids, Esters and Glycerides: Mechanisms, Kinetics and Transport Phenomena. *Chem. Eng. J.* **2022**, *444*, 136564. [CrossRef]
34. Fawzy, S.; Osman, A.I.; Doran, J.; Rooney, D.W. Strategies for Mitigation of Climate Change: A Review. *Environ. Chem. Lett.* **2020**, *18*, 2069–2094. [CrossRef]
35. Osman, A.I.; Hefny, M.; Abdel Maksoud, M.I.A.; Elgarahy, A.M.; Rooney, D.W. Recent Advances in Carbon Capture Storage and Utilisation Technologies: A Review. *Environ. Chem. Lett.* **2021**, *19*, 797–849. [CrossRef]
36. Kwon, G.; Cho, D.-W.; Kwon, E.E.; Rinklebe, J.; Wang, H.; Song, H. Beneficial Use of Fe-Impregnated Bentonite as a Catalyst for Pyrolysis of Grass Cut into Syngas, Bio-Oil and Biochar. *Chem. Eng. J.* **2022**, *448*, 137502. [CrossRef]
37. Leng, L.; Zhang, W.; Peng, H.; Li, H.; Jiang, S.; Huang, H. Nitrogen in Bio-Oil Produced from Hydrothermal Liquefaction of Biomass: A Review. *Chem. Eng. J.* **2020**, *401*, 126030. [CrossRef]
38. Ferronato, N.; Torretta, V. Waste Mismanagement in Developing Countries: A Review of Global Issues. *Int. J. Environ. Res. Public Health* **2019**, *16*, 1060. [CrossRef]
39. Siddiqua, A.; Hahladakis, J.N.; Al-Attiya, W.A.K.A. An Overview of the Environmental Pollution and Health Effects Associated with Waste Landfilling and Open Dumping. *Environ. Sci. Pollut. Res.* **2022**, *29*, 58514–58536. [CrossRef]
40. Lauri, P.; Havlík, P.; Kindermann, G.; Forsell, N.; Böttcher, H.; Obersteiner, M. Woody Biomass Energy Potential in 2050. *Energy Policy* **2014**, *66*, 19–31. [CrossRef]
41. IEA. *International Energy Association Database*; IEA: Paris, France, 2013.

42. Berndes, G.; Hoogwijk, M.; van den Broek, R. The Contribution of Biomass in the Future Global Energy Supply: A Review of 17 Studies. *Biomass Bioenergy* **2003**, *25*, 1–28. [CrossRef]
43. Van Vuuren, D.P.; Bellevrat, E.; Kitous, A.; Isaac, M. Bio-Energy Use and Low Stabilization Scenarios. *Energy J.* **2010**, *31*, 193–221. [CrossRef]
44. Offermann, R.; Seidenberger, T.; Thrän, D.; Kaltschmitt, M.; Zinoviev, S.; Miertus, S. Assessment of Global Bioenergy Potentials. *Mitig. Adapt. Strateg. Glob Chang.* **2011**, *16*, 103–115. [CrossRef]
45. Durak, H.; Genel, S.; Durak, E.D.; Özçimen, D.; Koçer, A.T. Hydrothermal Liquefaction Process of Ammi Visnaga and a New Approach for Recycling of the Waste Process Water: Cultivation of Algae and Fungi. *Biomass Convers. Biorefin.* **2022**, 1–17. [CrossRef]
46. Çolak, U.; Durak, H.; Genel, S. Hydrothermal Liquefaction of Syrian Mesquite (Prosopis Farcta): Effects of Operating Parameters on Product Yields and Characterization by Different Analysis Methods. *J. Supercrit. Fluids* **2018**, *140*, 53–61. [CrossRef]
47. Aysu, T.; Durak, H. Bio-Oil Production via Catalytic Supercritical Liquefaction of Syrian Mesquite (Prosopis Farcta). *J. Supercrit. Fluids* **2016**, *109*, 26–34. [CrossRef]
48. Nazari, L.; Yuan, Z.; Souzanchi, S.; Ray, M.B.; Xu, C. (Charles) Hydrothermal Liquefaction of Woody Biomass in Hot-Compressed Water: Catalyst Screening and Comprehensive Characterization of Bio-Crude Oils. *Fuel* **2015**, *162*, 74–83. [CrossRef]
49. Ding, X.; Mahadevan Subramanya, S.; Fang, T.; Guo, Y.; Savage, P.E. Effects of Potassium Phosphates on Hydrothermal Liquefaction of Triglyceride, Protein, and Polysaccharide. *Energy Fuels* **2020**, *34*, 15313–15321. [CrossRef]
50. Yang, W.; Li, X.; Liu, S.; Feng, L. Direct Hydrothermal Liquefaction of Undried Macroalgae Enteromorpha Prolifera Using Acid Catalysts. *Energy Convers. Manag.* **2014**, *87*, 938–945. [CrossRef]
51. Biller, P.; Riley, R.; Ross, A.B. Catalytic Hydrothermal Processing of Microalgae: Decomposition and Upgrading of Lipids. *Bioresour. Technol.* **2011**, *102*, 4841–4848. [CrossRef] [PubMed]
52. Seehar, T.H.; Toor, S.S.; Shah, A.A.; Pedersen, T.H.; Rosendahl, L.A. Biocrude Production from Wheat Straw at Sub and Supercritical Hydrothermal Liquefaction. *Energies* **2020**, *13*, 3114. [CrossRef]
53. Tekin, K.; Karagöz, S.; Bektaş, S. Hydrothermal Liquefaction of Beech Wood Using a Natural Calcium Borate Mineral. *J. Supercrit. Fluids* **2012**, *72*, 134–139. [CrossRef]
54. Feng, L.; Li, X.; Wang, Z.; Liu, B. Catalytic Hydrothermal Liquefaction of Lignin for Production of Aromatic Hydrocarbon over Metal Supported Mesoporous Catalyst. *Bioresour. Technol.* **2021**, *323*, 124569. [CrossRef] [PubMed]
55. Liu, Z.; Quek, A.; Kent Hoekman, S.; Balasubramanian, R. Production of Solid Biochar Fuel from Waste Biomass by Hydrothermal Carbonization. *Fuel* **2013**, *103*, 943–949. [CrossRef]
56. Kambo, H.S.; Dutta, A. Strength, Storage, and Combustion Characteristics of Densified Lignocellulosic Biomass Produced via Torrefaction and Hydrothermal Carbonization. *Appl. Energy* **2014**, *135*, 182–191. [CrossRef]
57. Kang, S.; Li, X.; Fan, J.; Chang, J. Characterization of Hydrochars Produced by Hydrothermal Carbonization of Lignin, Cellulose, d-Xylose, and Wood Meal. *Ind. Eng. Chem. Res.* **2012**, *51*, 9023–9031. [CrossRef]
58. Xiao, L.-P.; Shi, Z.-J.; Xu, F.; Sun, R.-C. Hydrothermal Carbonization of Lignocellulosic Biomass. *Bioresour. Technol.* **2012**, *118*, 619–623. [CrossRef]
59. Cao, X.; Ro, K.S.; Libra, J.A.; Kammann, C.I.; Lima, I.; Berge, N.; Li, L.; Li, Y.; Chen, N.; Yang, J.; et al. Effects of Biomass Types and Carbonization Conditions on the Chemical Characteristics of Hydrochars. *J. Agric. Food Chem.* **2013**, *61*, 9401–9411. [CrossRef]
60. Gao, Y.; Wang, X.; Wang, J.; Li, X.; Cheng, J.; Yang, H.; Chen, H. Effect of Residence Time on Chemical and Structural Properties of Hydrochar Obtained by Hydrothermal Carbonization of Water Hyacinth. *Energy* **2013**, *58*, 376–383. [CrossRef]
61. Mendoza Martinez, C.L.; Sermyagina, E.; Saari, J.; Silva de Jesus, M.; Cardoso, M.; Matheus de Almeida, G.; Vakkilainen, E. Hydrothermal Carbonization of Lignocellulosic Agro-Forest Based Biomass Residues. *Biomass Bioenergy* **2021**, *147*, 106004. [CrossRef]
62. He, Q.; Cheng, C.; Raheem, A.; Ding, L.; Shiung Lam, S.; Yu, G. Effect of Hydrothermal Carbonization on Woody Biomass: From Structure to Reactivity. *Fuel* **2022**, *330*, 125586. [CrossRef]
63. Simsir, H.; Eltugral, N.; Karagoz, S. Hydrothermal Carbonization for the Preparation of Hydrochars from Glucose, Cellulose, Chitin, Chitosan and Wood Chips via Low-Temperature and Their Characterization. *Bioresour. Technol.* **2017**, *246*, 82–87. [CrossRef] [PubMed]
64. Yoshimoto, S.; Luthfi, N.; Nakano, K.; Fukushima, T.; Takisawa, K. Effects of Potassium on Hydrothermal Carbonization of Sorghum Bagasse. *Bioresour. Bioprocess* **2023**, *10*, 24. [CrossRef]
65. Kazimierski, P.; Hercel, P.; Suchocki, T.; Smoliński, J.; Pladzyk, A.; Kardaś, D.; Łuczak, J.; Januszewicz, K. Pyrolysis of Pruning Residues from Various Types of Orchards and Pretreatment for Energetic Use of Biochar. *Materials* **2021**, *14*, 2969. [CrossRef] [PubMed]
66. Kumar, R.S.; Sivakumar, S.; Joshuva, A.; Deenadayalan, G.; Vishnuvardhan, R. Bio-Fuel Production from *Martynia Annua* L. Seeds Using Slow Pyrolysis Reactor and Its Effects on Diesel Engine Performance, Combustion and Emission Characteristics. *Energy* **2021**, *217*, 119327. [CrossRef]
67. Durak, H.; Genel, S.; Tunç, M. Pyrolysis of Black Cumin Seed: Significance of Catalyst and Temperature Product Yields and Chromatographic Characterization. *J. Liq. Chromatogr. Relat. Technol.* **2019**, *42*, 331–350. [CrossRef]

68. Aysu, T.; Durak, H.; Güner, S.; Bengü, A.Ş.; Esim, N. Bio-Oil Production via Catalytic Pyrolysis of Anchusa Azurea: Effects of Operating Conditions on Product Yields and Chromatographic Characterization. *Bioresour. Technol.* **2016**, *205*, 7–14. [CrossRef] [PubMed]
69. Aysu, T.; Durak, H. Pyrolysis of Giant Mullein (*Verbascum Thapsus* L.) in a Fixed-Bed Reactor: Effects of Pyrolysis Parameters on Product Yields and Character. *Energy Sources Part A Recovery Util. Environ. Eff.* **2016**, *38*, 661–669. [CrossRef]
70. Alayont, Ş.; Kayan, D.B.; Durak, H.; Alayont, E.K.; Genel, S. The Role of Acidic, Alkaline and Hydrothermal Pretreatment on Pyrolysis of Wild Mustard (Sinapis Arvensis) on the Properties of Bio-Oil and Bio-Char. *Bioresour. Technol. Rep.* **2022**, *17*, 100980. [CrossRef]
71. Amer, M.W.; Aljariri Alhesan, J.S.; Ibrahim, S.; Qussay, G.; Marshall, M.; Al-Ayed, O.S. Potential Use of Corn Leaf Waste for Biofuel Production in Jordan (Physio-Chemical Study). *Energy* **2021**, *214*, 118863. [CrossRef]
72. Kakku, S.; Naidu, S.; Bhatt, M.; Chakinala, A.G.; Joshi, J.; Gautam, S.; Mohanty, K.; Kataria, G.; Sharma, A. Pyrolytic Conversion of Agricultural Residue Using Continuous Auger Reactor for Resource Recovery. *J. Anal. Appl. Pyrolysis* **2023**, *171*, 105951. [CrossRef]
73. Boscagli, C.; Raffelt, K.; Grunwaldt, J.-D. Reactivity of Platform Molecules in Pyrolysis Oil and in Water during Hydrotreatment over Nickel and Ruthenium Catalysts. *Biomass Bioenergy* **2017**, *106*, 63–73. [CrossRef]
74. Rueangsan, K.; Heman, A.; Kraisoda, P.; Tasarod, H.; Duanguppama, K.; Trisupakitti, S.; Morris, J. Bio-Oil Production via Fast Pyrolysis of Cassava Residues Combined with Ethanol and Volcanic Rock in a Free-Fall Reactor. *Cogent Eng.* **2023**, *10*, 2156054. [CrossRef]
75. Mlonka-Mędrala, A.; Evangelopoulos, P.; Sieradzka, M.; Zajemska, M.; Magdziarz, A. Pyrolysis of Agricultural Waste Biomass towards Production of Gas Fuel and High-Quality Char: Experimental and Numerical Investigations. *Fuel* **2021**, *296*, 120611. [CrossRef]
76. Sun, H.; Feng, D.; Sun, S.; Zhao, Y.; Zhang, L.; Chang, G.; Guo, Q.; Wu, J.; Qin, Y. Thermal Evolution of Gas-Liquid-Solid Products and Migration Regulation of C/H/O Elements during Biomass Pyrolysis. *J. Anal. Appl. Pyrolysis* **2021**, *156*, 105128. [CrossRef]
77. Jaffar, M.M.; Nahil, M.A.; Williams, P.T. Pyrolysis-Catalytic Hydrogenation of Cellulose-Hemicellulose-Lignin and Biomass Agricultural Wastes for Synthetic Natural Gas Production. *J. Anal. Appl. Pyrolysis* **2020**, *145*, 104753. [CrossRef]
78. Iminabo, M.; Yip, A.C.K.; Iminabo, J.T.; Pang, S. Application of MgO-Titanomagnetite Mixture in High-Temperature Catalytic Pyrolysis of Radiata Pine. *Biomass Convers. Biorefin.* **2023**, 1–15. [CrossRef]
79. Yu, H.; Wu, Z.; Chen, G. Catalytic Gasification Characteristics of Cellulose, Hemicellulose and Lignin. *Renew Energy* **2018**, *121*, 559–567. [CrossRef]
80. Cerone, N.; Zimbardi, F. Effects of Oxygen and Steam Equivalence Ratios on Updraft Gasification of Biomass. *Energies* **2021**, *14*, 2675. [CrossRef]
81. Wu, C.; Wang, Z.; Huang, J.; Williams, P.T. Pyrolysis/Gasification of Cellulose, Hemicellulose and Lignin for Hydrogen Production in the Presence of Various Nickel-Based Catalysts. *Fuel* **2013**, *106*, 697–706. [CrossRef]
82. Bandara, J.C.; Jaiswal, R.; Nielsen, H.K.; Moldestad, B.M.E.; Eikeland, M.S. Air Gasification of Wood Chips, Wood Pellets and Grass Pellets in a Bubbling Fluidized Bed Reactor. *Energy* **2021**, *233*, 121149. [CrossRef]
83. Maglinao, A.L.; Capareda, S.C.; Nam, H. Fluidized Bed Gasification of High Tonnage Sorghum, Cotton Gin Trash and Beef Cattle Manure: Evaluation of Synthesis Gas Production. *Energy Convers. Manag.* **2015**, *105*, 578–587. [CrossRef]
84. Mansur, F.Z.; Faizal, C.K.M.; Samad, N.A.F.A.; Atnaw, S.M.; Sulaiman, S.A. Gasification Performance of Sawdust, Pelletized Sawdust and Sub-Bituminous Coal in a Downdraft Gasifier. *SN Appl. Sci.* **2020**, *2*, 1543. [CrossRef]
85. Chen, P.; Xie, Q.; Addy, M.; Zhou, W.; Liu, Y.; Wang, Y.; Cheng, Y.; Li, K.; Ruan, R. Utilization of Municipal Solid and Liquid Wastes for Bioenergy and Bioproducts Production. *Bioresour. Technol.* **2016**, *215*, 163–172. [CrossRef]
86. EPA, U.S. *Advancing Sustainable Materials Management: 2014 Fact Sheet*; United States Environmental Protection Agency, Office of Land and Emergency: Washington, DC, USA, 2015.
87. EPA, U.S. *Clean Watersheds Needs Survey (CWNS) 2012 Report to Congress*; United States Environmental Protection Agency: Washington, DC, USA, 2016.
88. EPRI, U.S. *Electricity Consumption for Water Supply & Treatment—The Next Half Century*; EPRI: Palo Alto, CA, USA, 2013.
89. EPA, U.S. *Inventory of US Greenhouse Gas Emissions and Sinks: 1990–2012*; The Air Pollution Consultant: New York, NY, USA, 2014; Volume 24, pp. 1_17–1_22.
90. Kohansal, K.; Toor, S.; Sharma, K.; Chand, R.; Rosendahl, L.; Pedersen, T.H. Hydrothermal Liquefaction of Pre-Treated Municipal Solid Waste (Biopulp) with Recirculation of Concentrated Aqueous Phase. *Biomass Bioenergy* **2021**, *148*, 106032. [CrossRef]
91. Katakojwala, R.; Kopperi, H.; Kumar, S.; Venkata Mohan, S. Hydrothermal Liquefaction of Biogenic Municipal Solid Waste under Reduced H2 Atmosphere in Biorefinery Format. *Bioresour. Technol.* **2020**, *310*, 123369. [CrossRef]
92. Chen, W.-H.; Lin, Y.-Y.; Liu, H.-C.; Baroutian, S. Optimization of Food Waste Hydrothermal Liquefaction by a Two-Step Process in Association with a Double Analysis. *Energy* **2020**, *199*, 117438. [CrossRef]
93. Aierzhati, A.; Stablein, M.J.; Wu, N.E.; Kuo, C.-T.; Si, B.; Kang, X.; Zhang, Y. Experimental and Model Enhancement of Food Waste Hydrothermal Liquefaction with Combined Effects of Biochemical Composition and Reaction Conditions. *Bioresour. Technol.* **2019**, *284*, 139–147. [CrossRef]
94. Maag, A.R.; Paulsen, A.D.; Amundsen, T.J.; Yelvington, P.E.; Tompsett, G.A.; Timko, M.T. Catalytic Hydrothermal Liquefaction of Food Waste Using CeZrOx. *Energies* **2018**, *11*, 564. [CrossRef]

95. He, C.; Zhang, Z.; Ge, C.; Liu, W.; Tang, Y.; Zhuang, X.; Qiu, R. Synergistic Effect of Hydrothermal Co-Carbonization of Sewage Sludge with Fruit and Agricultural Wastes on Hydrochar Fuel Quality and Combustion Behavior. *Waste Manag.* **2019**, *100*, 171–181. [CrossRef] [PubMed]
96. Vardon, D.R.; Sharma, B.K.; Scott, J.; Yu, G.; Wang, Z.; Schideman, L.; Zhang, Y.; Strathmann, T.J. Chemical Properties of Biocrude Oil from the Hydrothermal Liquefaction of Spirulina Algae, Swine Manure, and Digested Anaerobic Sludge. *Bioresour. Technol.* **2011**, *102*, 8295–8303. [CrossRef] [PubMed]
97. Prestigiacomo, C.; Costa, P.; Pinto, F.; Schiavo, B.; Siragusa, A.; Scialdone, O.; Galia, A. Sewage Sludge as Cheap Alternative to Microalgae as Feedstock of Catalytic Hydrothermal Liquefaction Processes. *J. Supercrit. Fluids* **2019**, *143*, 251–258. [CrossRef]
98. Shao, Y.; Long, Y.; Zhou, Y.; Jin, Z.; Zhou, D.; Shen, D. 5-Hydroxymethylfurfural Production from Watermelon Peel by Microwave Hydrothermal Liquefaction. *Energy* **2019**, *174*, 198–205. [CrossRef]
99. Minowa, T.; Murakami, M.; Dote, Y.; Ogi, T.; Yokoyama, S. Oil Production from Garbage by Thermochemical Liquefaction. *Biomass Bioenergy* **1995**, *8*, 117–120. [CrossRef]
100. Śliz, M.; Czerwińska, K.; Magdziarz, A.; Lombardi, L.; Wilk, M. Hydrothermal Carbonization of the Wet Fraction from Mixed Municipal Solid Waste: A Fuel and Structural Analysis of Hydrochars. *Energies* **2022**, *15*, 6708. [CrossRef]
101. Śliz, M.; Tuci, F.; Czerwińska, K.; Fabrizi, S.; Lombardi, L.; Wilk, M. Hydrothermal Carbonization of the Wet Fraction from Mixed Municipal Solid Waste: Hydrochar Characteristics and Energy Balance. *Waste Manag.* **2022**, *151*, 39–48. [CrossRef]
102. Parshetti, G.K.; Liu, Z.; Jain, A.; Srinivasan, M.P.; Balasubramanian, R. Hydrothermal Carbonization of Sewage Sludge for Energy Production with Coal. *Fuel* **2013**, *111*, 201–210. [CrossRef]
103. Reza, M.T.; Coronella, C.; Holtman, K.M.; Franqui-Villanueva, D.; Poulson, S.R. Hydrothermal Carbonization of Autoclaved Municipal Solid Waste Pulp and Anaerobically Treated Pulp Digestate. *ACS Sustain. Chem. Eng.* **2016**, *4*, 3649–3658. [CrossRef]
104. Zheng, C.; Ma, X.; Yao, Z.; Chen, X. The Properties and Combustion Behaviors of Hydrochars Derived from Co-Hydrothermal Carbonization of Sewage Sludge and Food Waste. *Bioresour. Technol.* **2019**, *285*, 121347. [CrossRef]
105. Gaur, R.Z.; Khoury, O.; Zohar, M.; Poverenov, E.; Darzi, R.; Laor, Y.; Posmanik, R. Hydrothermal Carbonization of Sewage Sludge Coupled with Anaerobic Digestion: Integrated Approach for Sludge Management and Energy Recycling. *Energy Convers. Manag.* **2020**, *224*, 113353. [CrossRef]
106. Danso-Boateng, E.; Shama, G.; Wheatley, A.D.; Martin, S.J.; Holdich, R.G. Hydrothermal Carbonisation of Sewage Sludge: Effect of Process Conditions on Product Characteristics and Methane Production. *Bioresour. Technol.* **2015**, *177*, 318–327. [CrossRef]
107. Gao, N.; Li, Z.; Quan, C.; Miskolczi, N.; Egedy, A. A New Method Combining Hydrothermal Carbonization and Mechanical Compression In-Situ for Sewage Sludge Dewatering: Bench-Scale Verification. *J. Anal. Appl. Pyrolysis* **2019**, *139*, 187–195. [CrossRef]
108. Hejna, M.; Świechowski, K.; Rasaq, W.A.; Białowiec, A. Study on the Effect of Hydrothermal Carbonization Parameters on Fuel Properties of Chicken Manure Hydrochar. *Materials* **2022**, *15*, 5564. [CrossRef]
109. Kim, D.; Lee, K.; Park, K.Y. Hydrothermal Carbonization of Anaerobically Digested Sludge for Solid Fuel Production and Energy Recovery. *Fuel* **2014**, *130*, 120–125. [CrossRef]
110. Velghe, I.; Carleer, R.; Yperman, J.; Schreurs, S. Study of the Pyrolysis of Municipal Solid Waste for the Production of Valuable Products. *J. Anal. Appl. Pyrolysis* **2011**, *92*, 366–375. [CrossRef]
111. Ateş, F.; Miskolczi, N.; Borsodi, N. Comparision of Real Waste (MSW and MPW) Pyrolysis in Batch Reactor over Different Catalysts. Part I: Product Yields, Gas and Pyrolysis Oil Properties. *Bioresour. Technol.* **2013**, *133*, 443–454. [CrossRef] [PubMed]
112. Miskolczi, N.; Ateş, F.; Borsodi, N. Comparison of Real Waste (MSW and MPW) Pyrolysis in Batch Reactor over Different Catalysts. Part II: Contaminants, Char and Pyrolysis Oil Properties. *Bioresour. Technol.* **2013**, *144*, 370–379. [CrossRef]
113. Ding, K.; Zhong, Z.; Zhong, D.; Zhang, B.; Qian, X. Pyrolysis of Municipal Solid Waste in a Fluidized Bed for Producing Valuable Pyrolytic Oils. *Clean Technol. Environ. Policy* **2016**, *18*, 1111–1121. [CrossRef]
114. Syamsiro, M.; Saptoadi, H.; Norsujianto, T.; Noviasri, P.; Cheng, S.; Alimuddin, Z.; Yoshikawa, K. Fuel Oil Production from Municipal Plastic Wastes in Sequential Pyrolysis and Catalytic Reforming Reactors. *Energy Procedia* **2014**, *47*, 180–188. [CrossRef]
115. Gandidi, I.M.; Susila, M.D.; Mustofa, A.; Pambudi, N.A. Thermal—Catalytic Cracking of Real MSW into Bio-Crude Oil. *J. Energy Inst.* **2018**, *91*, 304–310. [CrossRef]
116. Sotoudehnia, F.; Baba Rabiu, A.; Alayat, A.; McDonald, A.G. Characterization of Bio-Oil and Biochar from Pyrolysis of Waste Corrugated Cardboard. *J. Anal. Appl. Pyrolysis* **2020**, *145*, 104722. [CrossRef]
117. Tokmurzin, D.; Kuspangaliyeva, B.; Aimbetov, B.; Abylkhani, B.; Inglezakis, V.; Anthony, E.J.; Sarbassov, Y. Characterization of Solid Char Produced from Pyrolysis of the Organic Fraction of Municipal Solid Waste, High Volatile Coal and Their Blends. *Energy* **2020**, *191*, 116562. [CrossRef]
118. Wang, N.; Qian, K.; Chen, D.; Zhao, H.; Yin, L. Upgrading Gas and Oil Products of the Municipal Solid Waste Pyrolysis Process by Exploiting In-Situ Interactions between the Volatile Compounds and the Char. *Waste Manag.* **2020**, *102*, 380–390. [CrossRef]
119. Tang, F.; Yu, Z.; Li, Y.; Chen, L.; Ma, X. Catalytic Co-Pyrolysis Behaviors, Product Characteristics and Kinetics of Rural Solid Waste and Chlorella Vulgaris. *Bioresour. Technol.* **2020**, *299*, 122636. [CrossRef]
120. Wang, N.; Chen, D.; Arena, U.; He, P. Hot Char-Catalytic Reforming of Volatiles from MSW Pyrolysis. *Appl. Energy* **2017**, *191*, 111–124. [CrossRef]
121. Tursunov, O. A Comparison of Catalysts Zeolite and Calcined Dolomite for Gas Production from Pyrolysis of Municipal Solid Waste (MSW). *Ecol. Eng.* **2014**, *69*, 237–243. [CrossRef]

122. He, M.; Xiao, B.; Liu, S.; Hu, Z.; Guo, X.; Luo, S.; Yang, F. Syngas Production from Pyrolysis of Municipal Solid Waste (MSW) with Dolomite as Downstream Catalysts. *J. Anal. Appl. Pyrolysis* **2010**, *87*, 181–187. [CrossRef]
123. Gao, N.; Sipra, A.T.; Quan, C. Thermogravimetric Analysis and Pyrolysis Product Characterization of Municipal Solid Waste Using Sludge Fly Ash as Additive. *Fuel* **2020**, *281*, 118572. [CrossRef]
124. He, M.; Hu, Z.; Xiao, B.; Li, J.; Guo, X.; Luo, S.; Yang, F.; Feng, Y.; Yang, G.; Liu, S. Hydrogen-Rich Gas from Catalytic Steam Gasification of Municipal Solid Waste (MSW): Influence of Catalyst and Temperature on Yield and Product Composition. *Int. J. Hydrogen Energy* **2009**, *34*, 195–203. [CrossRef]
125. Kwak, T.-H.; Lee, S.; Maken, S.; Shin, H.-C.; Park, J.-W.; Yoo, Y.D. A Study of Gasification of Municipal Solid Waste Using a Double Inverse Diffusion Flame Burner. *Energy Fuels* **2005**, *19*, 2268–2272. [CrossRef]
126. Kessas, S.A.; Esteves, T.; Hemati, M. Products Distribution During Sewage Sludge Pyrolysis in a Sand and Olivine Fluidized Bed Reactor: Comparison with Woody Waste. *Waste Biomass Valorization* **2021**, *12*, 3459–3484. [CrossRef]
127. Luo, S.; Xiao, B.; Hu, Z.; Liu, S. Effect of Particle Size on Pyrolysis of Single-Component Municipal Solid Waste in Fixed Bed Reactor. *Int. J. Hydrogen Energy* **2010**, *35*, 93–97. [CrossRef]
128. Da Silva Filho, V.F.; Batistella, L.; Alves, J.L.F.; da Silva, J.C.G.; Althoff, C.A.; Moreira, R.d.F.P.M.; José, H.J. Evaluation of Gaseous Emissions from Thermal Conversion of a Mixture of Solid Municipal Waste and Wood Chips in a Pilot-Scale Heat Generator. *Renew Energy* **2019**, *141*, 402–410. [CrossRef]
129. EPA US EPA Plastics: Material-Specific Data. Available online: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/plastics-material-specific-data (accessed on 10 July 2023).
130. PlasticsEurope Plastics Europe The Facts 2021. Available online: https://plasticseurope.org/knowledge-hub/plastics-the-facts-2021/ (accessed on 10 July 2023).
131. Eur. Com. A European Strategy for Plastics in a Circular Economy. 2018. Available online: https://www.switch-asia.eu/resource/a-european-strategy-for-plastics-in-a-circular-economy/ (accessed on 10 July 2023).
132. OECD. *Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options*; OECD Publishing: Paris, France, 2022.
133. Hamilton, L.A.; Feit, S. *Plastic & Climate: The Hidden Costs of a Plastic Planet*; CIEL: Washington, DC, USA, 2019.
134. Liebmann, B.; Köppel, S.; Königshofer, P.; Bucsics, T.; Reiberger, T.; Schwabl, P. Assessment of Microplastic Concentrations in Human Stool: Final Results of a Prospective Study. In Proceedings of the Conference on Nano and Microplastics in Technical and Freshwater Systems, Ascona, Switzerland, 28–31 October 2018; pp. 28–31.
135. Sharma, S.; Chatterjee, S. Microplastic Pollution, a Threat to Marine Ecosystem and Human Health: A Short Review. *Environ. Sci. Pollut. Res.* **2017**, *24*, 21530–21547. [CrossRef] [PubMed]
136. European Commission. Circular Economy Action Plan. Available online: https://environment.ec.europa.eu/strategy/circular-economy-action-plan_en (accessed on 10 July 2023).
137. Lomwongsopon, P.; Varrone, C. Contribution of Fermentation Technology to Building Blocks for Renewable Plastics. *Fermentation* **2022**, *8*, 47. [CrossRef]
138. Mishra, S.; Zope, V.S.; Goje, A.S. Kinetics and Thermodynamics of Hydrolytic Depolymerization of Poly(Ethylene Terephthalate) at High Pressure and Temperature. *J. Appl. Polym. Sci.* **2003**, *90*, 3305–3309. [CrossRef]
139. Karayannidis, G.P.; Chatziavgoustis, A.P.; Achilias, D.S. Poly(Ethylene Terephthalate) Recycling and Recovery of Pure Terephthalic Acid by Alkaline Hydrolysis. *Adv. Polym. Technol.* **2002**, *21*, 250–259. [CrossRef]
140. Sato, O.; Arai, K.; Shirai, M. Hydrolysis of Poly(Ethylene Terephthalate) and Poly(Ethylene 2,6-Naphthalene Dicarboxylate) Using Water at High Temperature: Effect of Proton on Low Ethylene Glycol Yield. *Catal. Today* **2006**, *111*, 297–301. [CrossRef]
141. Tagaya, H.; Katoh, K.; Kadokawa, J.; Chiba, K. Decomposition of Polycarbonate in Subcritical and Supercritical Water. *Polym. Degrad. Stab.* **1999**, *64*, 289–292. [CrossRef]
142. Ikeda, A.; Katoh, K.; Tagaya, H. Monomer Recovery of Waste Plastics by Liquid Phase Decomposition and Polymer Synthesis. *J. Mater. Sci.* **2008**, *43*, 2437–2441. [CrossRef]
143. Watanabe, M.; Matsuo, Y.; Matsushita, T.; Inomata, H.; Miyake, T.; Hironaka, K. Chemical Recycling of Polycarbonate in High Pressure High Temperature Steam at 573 K. *Polym. Degrad. Stab.* **2009**, *94*, 2157–2162. [CrossRef]
144. Jin, H.; Bai, B.; Wei, W.; Chen, Y.; Ge, Z.; Shi, J. Hydrothermal Liquefaction of Polycarbonate (PC) Plastics in Sub-/Supercritical Water and Reaction Pathway Exploration. *ACS Sustain. Chem. Eng.* **2020**, *8*, 7039–7050. [CrossRef]
145. Iwaya, T.; Sasaki, M.; Goto, M. Kinetic Analysis for Hydrothermal Depolymerization of Nylon 6. *Polym. Degrad. Stab.* **2006**, *91*, 1989–1995. [CrossRef]
146. Dai, Z.; Hatano, B.; Kadokawa, J.; Tagaya, H. Effect of Diaminotoluene on the Decomposition of Polyurethane Foam Waste in Superheated Water. *Polym. Degrad. Stab.* **2002**, *76*, 179–184. [CrossRef]
147. Watanabe, M.; Hirakoso, H.; Sawamoto, S.; Adschiri, T.; Arai, K. Polyethylene Conversion in Supercritical Water. *J. Supercrit. Fluids* **1998**, *13*, 247–252. [CrossRef]
148. Chen, W.-T.; Jin, K.; Linda Wang, N.-H. Use of Supercritical Water for the Liquefaction of Polypropylene into Oil. *ACS Sustain. Chem. Eng.* **2019**, *7*, 3749–3758. [CrossRef]
149. Jin, K.; Vozka, P.; Gentilcore, C.; Kilaz, G.; Wang, N.-H.L. Low-Pressure Hydrothermal Processing of Mixed Polyolefin Wastes into Clean Fuels. *Fuel* **2021**, *294*, 120505. [CrossRef]
150. Čolnik, M.; Kotnik, P.; Knez, Ž.; Škerget, M. Hydrothermal Decomposition of Polyethylene Waste to Hydrocarbons Rich Oil. *J. Supercrit. Fluids* **2021**, *169*, 105136. [CrossRef]

151. Torres-Zapata, T.; Lozano-Martinez, P.; Martinez-Lorenzo, M.V.; Buey, R.M.; Martin-Sanchez, N. Hydrothermally Processed Polyethylene as Starting Point for Fermentative Production of Triglycerides. *J. Environ. Chem. Eng.* **2022**, *10*, 108683. [CrossRef]
152. Kwak, H.; Shin, H.-Y.; Bae, S.-Y.; Kumazawa, H. Characteristics and Kinetics of Degradation of Polystyrene in Supercritical Water. *J. Appl. Polym. Sci.* **2006**, *101*, 695–700. [CrossRef]
153. Bai, B.; Jin, H.; Fan, C.; Cao, C.; Wei, W.; Cao, W. Experimental Investigation on Liquefaction of Plastic Waste to Oil in Supercritical Water. *Waste Manag.* **2019**, *89*, 247–253. [CrossRef] [PubMed]
154. Dos Passos, J.S.; Glasius, M.; Biller, P. Screening of Common Synthetic Polymers for Depolymerization by Subcritical Hydrothermal Liquefaction. *Process Saf. Environ. Prot.* **2020**, *139*, 371–379. [CrossRef]
155. Iñiguez, M.E.; Conesa, J.A.; Fullana, A. Hydrothermal Carbonization (HTC) of Marine Plastic Debris. *Fuel* **2019**, *257*, 116033. [CrossRef]
156. Yao, Z.; Ma, X. A New Approach to Transforming PVC Waste into Energy via Combined Hydrothermal Carbonization and Fast Pyrolysis. *Energy* **2017**, *141*, 1156–1165. [CrossRef]
157. Poerschmann, J.; Weiner, B.; Woszidlo, S.; Koehler, R.; Kopinke, F.-D. Hydrothermal Carbonization of Poly(Vinyl Chloride). *Chemosphere* **2015**, *119*, 682–689. [CrossRef] [PubMed]
158. Zhao, X.; Xia, Y.; Zhan, L.; Xie, B.; Gao, B.; Wang, J. Hydrothermal Treatment of E-Waste Plastics for Tertiary Recycling: Product Slate and Decomposition Mechanisms. *ACS Sustain. Chem. Eng.* **2019**, *7*, 1464–1473. [CrossRef]
159. Lu, X.; Ma, X.; Chen, X.; Yao, Z.; Zhang, C. Co-Hydrothermal Carbonization of Polyvinyl Chloride and Corncob for Clean Solid Fuel Production. *Bioresour. Technol.* **2020**, *301*, 122763. [CrossRef] [PubMed]
160. Zhang, X.; Zhang, L.; Li, A. Co-Hydrothermal Carbonization of Lignocellulosic Biomass and Waste Polyvinyl Chloride for High-Quality Solid Fuel Production: Hydrochar Properties and Its Combustion and Pyrolysis Behaviors. *Bioresour. Technol.* **2019**, *294*, 122113. [CrossRef] [PubMed]
161. Shen, Y.; Yu, S.; Ge, S.; Chen, X.; Ge, X.; Chen, M. Hydrothermal Carbonization of Medical Wastes and Lignocellulosic Biomass for Solid Fuel Production from Lab-Scale to Pilot-Scale. *Energy* **2017**, *118*, 312–323. [CrossRef]
162. Islam, M.T.; Reza, M.T. Evaluation of Fuel and Combustion Properties of Hydrochar Derived from Co-Hydrothermal Carbonization of Biomass and Plastic. *Biomass Bioenergy* **2023**, *172*, 106750. [CrossRef]
163. Xu, Z.; Qi, R.; Zhang, D.; Gao, Y.; Xiong, M.; Chen, W. Co-Hydrothermal Carbonization of Cotton Textile Waste and Polyvinyl Chloride Waste for the Production of Solid Fuel: Interaction Mechanisms and Combustion Behaviors. *J. Clean Prod.* **2021**, *316*, 128306. [CrossRef]
164. Vasile, C.; Pakdel, H.; Mihai, B.; Onu, P.; Darie, H.; Ciocâlteu, S. Thermal and Catalytic Decomposition of Mixed Plastics. *J. Anal. Appl. Pyrolysis* **2001**, *57*, 287–303. [CrossRef]
165. Donaj, P.J.; Kaminsky, W.; Buzeto, F.; Yang, W. Pyrolysis of Polyolefins for Increasing the Yield of Monomers' Recovery. *Waste Manag.* **2012**, *32*, 840–846. [CrossRef]
166. Escola, J.M.; Aguado, J.; Serrano, D.P.; García, A.; Peral, A.; Briones, L.; Calvo, R.; Fernandez, E. Catalytic Hydroreforming of the Polyethylene Thermal Cracking Oil over Ni Supported Hierarchical Zeolites and Mesostructured Aluminosilicates. *Appl. Catal. B* **2011**, *106*, 405–415. [CrossRef]
167. Huang, W.-C.; Huang, M.-S.; Huang, C.-F.; Chen, C.-C.; Ou, K.-L. Thermochemical Conversion of Polymer Wastes into Hydrocarbon Fuels over Various Fluidizing Cracking Catalysts. *Fuel* **2010**, *89*, 2305–2316. [CrossRef]
168. Zhang, Y.; Duan, D.; Lei, H.; Villota, E.; Ruan, R. Jet Fuel Production from Waste Plastics via Catalytic Pyrolysis with Activated Carbons. *Appl. Energy* **2019**, *251*, 113337. [CrossRef]
169. Grause, G.; Matsumoto, S.; Kameda, T.; Yoshioka, T. Pyrolysis of Mixed Plastics in a Fluidized Bed of Hard Burnt Lime. *Ind. Eng. Chem. Res.* **2011**, *50*, 5459–5466. [CrossRef]
170. Li, K.; Lei, J.; Yuan, G.; Weerachanchai, P.; Wang, J.-Y.; Zhao, J.; Yang, Y. Fe-, Ti-, Zr- and Al-Pillared Clays for Efficient Catalytic Pyrolysis of Mixed Plastics. *Chem. Eng. J.* **2017**, *317*, 800–809. [CrossRef]
171. Areeprasert, C.; Khaobang, C. Pyrolysis and Catalytic Reforming of ABS/PC and PCB Using Biochar and e-Waste Char as Alternative Green Catalysts for Oil and Metal Recovery. *Fuel Process. Technol.* **2018**, *182*, 26–36. [CrossRef]
172. Li, K.; Lee, S.W.; Yuan, G.; Lei, J.; Lin, S.; Weerachanchai, P.; Yang, Y.; Wang, J.-Y. Investigation into the Catalytic Activity of Microporous and Mesoporous Catalysts in the Pyrolysis of Waste Polyethylene and Polypropylene Mixture. *Energies* **2016**, *9*, 431. [CrossRef]
173. Sun, K.; Huang, Q.; Meng, X.; Chi, Y.; Yan, J. Catalytic Pyrolysis of Waste Polyethylene into Aromatics by H3PO4-Activated Carbon. *Energy Fuels* **2018**, *32*, 9772–9781. [CrossRef]
174. Al-asadi, M.; Miskolczi, N. High Temperature Pyrolysis of Municipal Plastic Waste Using Me/Ni/ZSM-5 Catalysts: The Effect of Metal/Nickel Ratio. *Energies* **2020**, *13*, 1284. [CrossRef]
175. Miandad, R.; Rehan, M.; Barakat, M.A.; Aburiazaiza, A.S.; Khan, H.; Ismail, I.M.I.; Dhavamani, J.; Gardy, J.; Hassanpour, A.; Nizami, A.-S. Catalytic Pyrolysis of Plastic Waste: Moving Toward Pyrolysis Based Biorefineries. *Front. Energy Res.* **2019**, *7*, 27. [CrossRef]
176. He, M.; Xiao, B.; Hu, Z.; Liu, S.; Guo, X.; Luo, S. Syngas Production from Catalytic Gasification of Waste Polyethylene: Influence of Temperature on Gas Yield and Composition. *Int. J. Hydrogen Energy* **2009**, *34*, 1342–1348. [CrossRef]
177. Arena, U.; Zaccariello, L.; Mastellone, M.L. Fluidized Bed Gasification of Waste-Derived Fuels. *Waste Manag.* **2010**, *30*, 1212–1219. [CrossRef] [PubMed]

178. Saebea, D.; Ruengrit, P.; Arpornwichanop, A.; Patcharavorachot, Y. Gasification of Plastic Waste for Synthesis Gas Production. *Energy Rep.* **2020**, *6*, 202–207. [CrossRef]
179. Arena, U.; Di Gregorio, F. Energy Generation by Air Gasification of Two Industrial Plastic Wastes in a Pilot Scale Fluidized Bed Reactor. *Energy* **2014**, *68*, 735–743. [CrossRef]
180. Zaccariello, L.; Mastellone, M.L. Fluidized-Bed Gasification of Plastic Waste, Wood, and Their Blends with Coal. *Energies* **2015**, *8*, 8052–8068. [CrossRef]
181. Arena, U.; Di Gregorio, F. Fluidized Bed Gasification of Industrial Solid Recovered Fuels. *Waste Manag.* **2016**, *50*, 86–92. [CrossRef]
182. Sancho, J.A.; Aznar, M.P.; Toledo, J.M. Catalytic Air Gasification of Plastic Waste (Polypropylene) in Fluidized Bed. Part I: Use of in-Gasifier Bed Additives. *Ind. Eng. Chem. Res.* **2008**, *47*, 1005–1010. [CrossRef]
183. Kim, J.-W.; Mun, T.-Y.; Kim, J.-O.; Kim, J.-S. Air Gasification of Mixed Plastic Wastes Using a Two-Stage Gasifier for the Production of Producer Gas with Low Tar and a High Caloric Value. *Fuel* **2011**, *90*, 2266–2272. [CrossRef]
184. Cho, M.-H.; Mun, T.-Y.; Kim, J.-S. Production of Low-Tar Producer Gas from Air Gasification of Mixed Plastic Waste in a Two-Stage Gasifier Using Olivine Combined with Activated Carbon. *Energy* **2013**, *58*, 688–694. [CrossRef]
185. Martínez-Lera, S.; Torrico, J.; Pallarés, J.; Gil, A. Design and First Experimental Results of a Bubbling Fluidized Bed for Air Gasification of Plastic Waste. *J. Mater. Cycles Waste Manag.* **2013**, *15*, 370–380. [CrossRef]
186. Lee, J.W.; Yu, T.U.; Lee, J.W.; Moon, J.H.; Jeong, H.J.; Park, S.S.; Yang, W.; Lee, U. Do Gasification of Mixed Plastic Wastes in a Moving-Grate Gasifier and Application of the Producer Gas to a Power Generation Engine. *Energy Fuels* **2013**, *27*, 2092–2098. [CrossRef]
187. Cao, C.; Bian, C.; Wang, G.; Bai, B.; Xie, Y.; Jin, H. Co-Gasification of Plastic Wastes and Soda Lignin in Supercritical Water. *Chem. Eng. J.* **2020**, *388*, 124277. [CrossRef]
188. Cagnetta, G.; Zhang, K.; Zhang, Q.; Huang, J.; Yu, G. Augmented Hydrogen Production by Gasification of Ball Milled Polyethylene with Ca(OH)2 and Ni(OH)2. *Front. Environ. Sci. Eng.* **2019**, *13*, 11. [CrossRef]
189. Wang, Q.; Wu, S.; Cui, D.; Zhou, H.; Wu, D.; Pan, S.; Xu, F.; Wang, Z. Co-Hydrothermal Carbonization of Organic Solid Wastes to Hydrochar as Potential Fuel: A Review. *Sci. Total Environ.* **2022**, *850*, 158034. [CrossRef] [PubMed]
190. Lang, Q.; Liu, Z.; Li, Y.; Xu, J.; Li, J.; Liu, B.; Sun, Q. Combustion Characteristics, Kinetic and Thermodynamic Analyses of Hydrochars Derived from Hydrothermal Carbonization of Cattle Manure. *J. Environ. Chem. Eng.* **2022**, *10*, 106938. [CrossRef]
191. Wang, T.; Zhai, Y.; Zhu, Y.; Peng, C.; Wang, T.; Xu, B.; Li, C.; Zeng, G. Feedwater PH Affects Phosphorus Transformation during Hydrothermal Carbonization of Sewage Sludge. *Bioresour. Technol.* **2017**, *245*, 182–187. [CrossRef] [PubMed]
192. Sharma, H.B.; Sarmah, A.K.; Dubey, B. Hydrothermal Carbonization of Renewable Waste Biomass for Solid Biofuel Production: A Discussion on Process Mechanism, the Influence of Process Parameters, Environmental Performance and Fuel Properties of Hydrochar. *Renew. Sustain. Energy Rev.* **2020**, *123*, 109761. [CrossRef]
193. Wang, T.; Zhai, Y.; Zhu, Y.; Li, C.; Zeng, G. A Review of the Hydrothermal Carbonization of Biomass Waste for Hydrochar Formation: Process Conditions, Fundamentals, and Physicochemical Properties. *Renew. Sustain. Energy Rev.* **2018**, *90*, 223–247. [CrossRef]
194. Azzaz, A.A.; Khiari, B.; Jellali, S.; Ghimbeu, C.M.; Jeguirim, M. Hydrochars Production, Characterization and Application for Wastewater Treatment: A Review. *Renew Sustain. Energy Rev.* **2020**, *127*, 109882. [CrossRef]
195. Kalak, T. Potential Use of Industrial Biomass Waste as a Sustainable Energy Source in the Future. *Energies* **2023**, *16*, 1783. [CrossRef]
196. WBA. WBA Global Bioenergy Statistics 2018. 2023. Available online: https://www.worldbioenergy.org/uploads/181017%20WBA%20GBS%202018_Summary_hq.pdf (accessed on 10 July 2023).
197. Fan, Y.; Hornung, U.; Dahmen, N.; Kruse, A. Hydrothermal Liquefaction of Protein-Containing Biomass: Study of Model Compounds for Maillard Reactions. *Biomass Convers. Biorefin.* **2018**, *8*, 909–923. [CrossRef]
198. Maddi, B.; Panisko, E.; Wietsma, T.; Lemmon, T.; Swita, M.; Albrecht, K.; Howe, D. Quantitative Characterization of Aqueous Byproducts from Hydrothermal Liquefaction of Municipal Wastes, Food Industry Wastes, and Biomass Grown on Waste. *ACS Sustain. Chem. Eng.* **2017**, *5*, 2205–2214. [CrossRef]
199. Saengsuriwong, R.; Onsree, T.; Phromphithak, S.; Tippayawong, N. Conversion of Tobacco Processing Waste to Biocrude Oil via Hydrothermal Liquefaction in a Multiple Batch Reactor. *Clean Technol. Environ. Policy* **2023**, *25*, 397–407. [CrossRef] [PubMed]
200. Bayat, H.; Dehghanizadeh, M.; Jarvis, J.M.; Brewer, C.E.; Jena, U. Hydrothermal Liquefaction of Food Waste: Effect of Process Parameters on Product Yields and Chemistry. *Front. Sustain. Food Syst.* **2021**, *5*, 658592. [CrossRef]
201. Kostyukevich, Y.; Vlaskin, M.; Borisova, L.; Zherebker, A.; Perminova, I.; Kononikhin, A.; Popov, I.; Nikolaev, E. Investigation of Bio-Oil Produced by Hydrothermal Liquefaction of Food Waste Using Ultrahigh Resolution Fourier Transform Ion Cyclotron Resonance Mass Spectrometry. *Eur. J. Mass Spectrom.* **2018**, *24*, 116–123. [CrossRef]
202. Motavaf, B.; Savage, P.E. Effect of Process Variables on Food Waste Valorization via Hydrothermal Liquefaction. *ACS EST Eng.* **2021**, *1*, 363–374. [CrossRef]
203. Aydıncak, K.; Yumak, T.; Sınağ, A.; Esen, B. Synthesis and Characterization of Carbonaceous Materials from Saccharides (Glucose and Lactose) and Two Waste Biomasses by Hydrothermal Carbonization. *Ind. Eng. Chem. Res.* **2012**, *51*, 9145–9152. [CrossRef]
204. Mazaheri, H.; Lee, K.T.; Bhatia, S.; Mohamed, A.R. Subcritical Water Liquefaction of Oil Palm Fruit Press Fiber for the Production of Bio-Oil: Effect of Catalysts. *Bioresour. Technol.* **2010**, *101*, 745–751. [CrossRef] [PubMed]

205. Quitain, A.T.; Sato, N.; Daimon, H.; Fujie, K. Production of Valuable Materials by Hydrothermal Treatment of Shrimp Shells. *Ind. Eng. Chem. Res.* **2001**, *40*, 5885–5888. [CrossRef]
206. Hadhoum, L.; Balistrou, M.; Burnens, G.; Loubar, K.; Tazerout, M. Hydrothermal Liquefaction of Oil Mill Wastewater for Bio-Oil Production in Subcritical Conditions. *Bioresour. Technol.* **2016**, *218*, 9–17. [CrossRef] [PubMed]
207. Idowu, I.; Li, L.; Flora, J.R.V.; Pellechia, P.J.; Darko, S.A.; Ro, K.S.; Berge, N.D. Hydrothermal Carbonization of Food Waste for Nutrient Recovery and Reuse. *Waste Manag.* **2017**, *69*, 480–491. [CrossRef] [PubMed]
208. Pauline, A.L.; Joseph, K. Hydrothermal Carbonization of Crude Oil Sludge—Characterization of Hydrochar and Hydrothermal Liquor. *Process Saf. Environ. Prot.* **2021**, *154*, 89–96. [CrossRef]
209. Pauline, A.L.; Joseph, K. Hydrothermal Carbonization of Oily Sludge for Solid Fuel Recovery—Investigation of Chemical Characteristics and Combustion Behaviour. *J. Anal. Appl. Pyrolysis* **2021**, *157*, 105235. [CrossRef]
210. Atallah, E.; Kwapinski, W.; Ahmad, M.N.; Leahy, J.J.; Al-Muhtaseb, A.H.; Zeaiter, J. Hydrothermal Carbonization of Olive Mill Wastewater: Liquid Phase Product Analysis. *J. Environ. Chem. Eng.* **2019**, *7*, 102833. [CrossRef]
211. Basso, D.; Patuzzi, F.; Castello, D.; Baratieri, M.; Rada, E.C.; Weiss-Hortala, E.; Fiori, L. Agro-Industrial Waste to Solid Biofuel through Hydrothermal Carbonization. *Waste Manag.* **2016**, *47*, 114–121. [CrossRef]
212. Benavente, V.; Calabuig, E.; Fullana, A. Upgrading of Moist Agro-Industrial Wastes by Hydrothermal Carbonization. *J. Anal. Appl. Pyrolysis* **2015**, *113*, 89–98. [CrossRef]
213. Suárez, L.; Benavente-Ferraces, I.; Plaza, C.; de Pascual-Teresa, S.; Suárez-Ruiz, I.; Centeno, T.A. Hydrothermal Carbonization as a Sustainable Strategy for Integral Valorisation of Apple Waste. *Bioresour. Technol.* **2020**, *309*, 123395. [CrossRef]
214. Zhan, H.; Zhuang, X.; Zhang, S.; Chang, G.; Wang, X.; Zeng, Z. Evaluation on the Enhanced Solid Biofuel from Co-Hydrothermal Carbonization of Pharmaceutical Biowastes with Lignite. *Fuel* **2022**, *318*, 123626. [CrossRef]
215. Lin, Y.; Ge, Y.; Xiao, H.; He, Q.; Wang, W.; Chen, B. Investigation of Hydrothermal Co-Carbonization of Waste Textile with Waste Wood, Waste Paper and Waste Food from Typical Municipal Solid Wastes. *Energy* **2020**, *210*, 118606. [CrossRef]
216. Ma, D.; Zhang, G.; Zhao, P.; Areeprasert, C.; Shen, Y.; Yoshikawa, K.; Xu, G. Hydrothermal Treatment of Antibiotic Mycelial Dreg: More Understanding from Fuel Characteristics. *Chem. Eng. J.* **2015**, *273*, 147–155. [CrossRef]
217. Azzaz, A.A.; Matei Ghimbeu, C.; Jellai, S.; El-Bassi, L.; Jeguirim, M. Olive Mill By-Products Thermochemical Conversion via Hydrothermal Carbonization and Slow Pyrolysis: Detailed Comparison between the Generated Hydrochars and Biochars Characteristics. *Processes* **2022**, *10*, 231. [CrossRef]
218. Demiral, İ.; Şensöz, S. The Effects of Different Catalysts on the Pyrolysis of Industrial Wastes (Olive and Hazelnut Bagasse). *Bioresour. Technol.* **2008**, *99*, 8002–8007. [CrossRef]
219. Tiikma, L.; Tamvelius, H.; Luik, L. Coprocessing of Heavy Shale Oil with Polyethylene Waste. *J. Anal. Appl. Pyrolysis* **2007**, *79*, 191–195. [CrossRef]
220. Nunes, L.J.R.; Guimarães, L.; Oliveira, M.; Kille, P.; Ferreira, N.G.C. Thermochemical Conversion Processes as a Path for Sustainability of the Tire Industry: Carbon Black Recovery Potential in a Circular Economy Approach. *Clean Technol.* **2022**, *4*, 653–668. [CrossRef]
221. Zhao, C.; Chen, A.; Jiang, E.; Qin, L. Pyrolysis of Industrial Waste Lignin: Analysis of Product Yields and Character. *Energy Sources Part A Recovery Util. Environ. Eff.* **2017**, *39*, 458–464. [CrossRef]
222. Caglar, A.; Aydinli, B. The Pyrolysis of Industrial Alliaceous Plant Wastes: Illustration of Process and Characterization of Products. *Energy Explor. Exploit.* **2018**, *36*, 1692–1707. [CrossRef]
223. Wang, P.; Zhan, S.; Yu, H.; Xue, X.; Hong, N. The Effects of Temperature and Catalysts on the Pyrolysis of Industrial Wastes (Herb Residue). *Bioresour. Technol.* **2010**, *101*, 3236–3241. [CrossRef] [PubMed]
224. Rodriguez, J.A.; Lustosa Filho, J.F.; Melo, L.C.A.; de Assis, I.R.; de Oliveira, T.S. Influence of Pyrolysis Temperature and Feedstock on the Properties of Biochars Produced from Agricultural and Industrial Wastes. *J. Anal. Appl. Pyrolysis* **2020**, *149*, 104839. [CrossRef]
225. Önal, E.P.; Uzun, B.B.; Pütün, A.E. Steam Pyrolysis of an Industrial Waste for Bio-Oil Production. *Fuel Process. Technol.* **2011**, *92*, 879–885. [CrossRef]
226. Naqvi, S.R.; Ali, I.; Nasir, S.; Ali Ammar Taqvi, S.; Atabani, A.E.; Chen, W.-H. Assessment of Agro-Industrial Residues for Bioenergy Potential by Investigating Thermo-Kinetic Behavior in a Slow Pyrolysis Process. *Fuel* **2020**, *278*, 118259. [CrossRef]
227. Castillo Santiago, Y.; Pérez, J.F.; Sphaier, L.A. Reaction-Front and Char Characterization from a Palm Kernel Shell—Oil Sludge Mixture under Oxygen Lean Regimes in a Fixed-Bed Gasifier. *Fuel* **2023**, *333*, 126402. [CrossRef]
228. Ge, Z.; Cao, X.; Zha, Z.; Ma, Y.; Zeng, M.; Wu, Y.; Hou, Z.; Zhang, H. Establishment of Correlation between Reaction Kinetics and Carbon Structures in the Char Gasification Process. *Carbon Resour. Convers.* **2023**, *6*, 67–75. [CrossRef]
229. Tezer, Ö.; Karabağ, N.; Öngen, A.; Ayol, A. Gasification Performance of Olive Pomace in Updraft and Downdraft Fixed Bed Reactors. *Int. J. Hydrogen Energy* **2023**, *48*, 22909–22920. [CrossRef]
230. Ongen, A.; Ozcan, H.K.; Ozbaş, E.E.; Aydin, S.; Yesildag, I. Co-Gasification of Oily Sludge and Chicken Manure in a Laboratory-Scale Updraft Fixed Bed Gasifier. *Clean Technol. Env. Policy* **2022**, *24*, 2229–2239. [CrossRef]
231. Subramanian, A.S.R.; Gundersen, T.; Adams, T.A. Technoeconomic Analysis of a Waste Tire to Liquefied Synthetic Natural Gas (SNG) Energy System. *Energy* **2020**, *205*, 117830. [CrossRef]

232. Portofino, S.; Donatelli, A.; Iovane, P.; Innella, C.; Civita, R.; Martino, M.; Matera, D.A.; Russo, A.; Cornacchia, G.; Galvagno, S. Steam Gasification of Waste Tyre: Influence of Process Temperature on Yield and Product Composition. *Waste Manag.* **2013**, *33*, 672–678. [CrossRef]
233. Chen, Y.-H.; Lan Thao Ngo, T.N.; Chiang, K.-Y. Enhanced Hydrogen Production in Co-Gasification of Sewage Sludge and Industrial Wastewater Sludge by a Pilot-Scale Fluidized Bed Gasifier. *Int. J. Hydrogen Energy* **2021**, *46*, 14083–14095. [CrossRef]
234. Nguyen, V.-T.; Chiang, K.-Y. Sewage and Textile Sludge Co-Gasification Using a Lab-Scale Fluidized Bed Gasifier. *Int. J. Hydrogen Energy* **2022**, *47*, 40613–40627. [CrossRef]
235. Vera, D.; Jurado, F.; Margaritis, N.K.; Grammelis, P. Experimental and Economic Study of a Gasification Plant Fuelled with Olive Industry Wastes. *Energy Sustain. Dev.* **2014**, *23*, 247–257. [CrossRef]
236. Yan, J.; Yan, Y.; Lai, J.; Jia, D.; Jiao, Y.; Zhao, X.; Yang, L. Co-Gasification of Municipal Sewage Sludge and Cotton Stalk Enhanced by Metal-Enriched Texture Dyeing Sludge Additives for Syngas Production. *Fuel* **2023**, *341*, 127669. [CrossRef]
237. Wyszyński, Z.; Michalska-Klimczak, B.; Pągowski, K.; Kamińska, S. Biomass as the Main Source of Renewable Energy in Poland. In Proceedings of the International Scientific Conference: Renewable Energy and Energy Efficiency, Jelgava, Latvia, 28–30 May 2012; Latvia University of Agriculture: Jelgava, Latvia, 2012.
238. Habert, G.; Bouzidi, Y.; Chen, C.; Jullien, A. Development of a Depletion Indicator for Natural Resources Used in Concrete. *Resour. Conserv. Recycl.* **2010**, *54*, 364–376. [CrossRef]
239. Sönnichsen, N. Global Primary Energy Consumption 2000–2021. 2022. Available online: https://www.statista.com/statistics/265598/consumption-of-primary-energy-worldwide/ (accessed on 10 July 2023).
240. Sönnichsen, N. Energy Consumption Worldwide from 2000 to 2019, with a Forecast until 2050, by Energy Source. 2022. Available online: https://www-1statista-1com-1s8fui2pq12ae.han3.ue.poznan.pl/statistics/222066/projected-global-energy-consumptionby-source/ (accessed on 10 July 2023).
241. Wilson, D.C.; Velis, C.A.; Rodic, L. Integrated Sustainable Waste Management in Developing Countries. *Proc. Inst. Civ. Eng. Waste Resour. Manag.* **2013**, *166*, 52–68. [CrossRef]
242. Mishra, R.; Kumar, A.; Singh, E.; Kumar, S. Carbonaceous Nanocomposites Derived from Waste Material for Wastewater Treatment. In *Biorenewable Nanocomposite Materials, Vol. 2: Desalination and Wastewater Remediation Chapter*; American Chemical Society: Washington, DC, USA, 2022; Volume 3, pp. 43–73. [CrossRef]
243. Dhote, L.; Ganduri, J.; Kumar, S. Evaluation of pyrolysis and gasification of distillery sludge and bio-compost mixed with coal. *Fuel* **2022**, *319*, 123750. [CrossRef]
244. Bombaywala, S.; Mandpe, A.; Paliya, S.; Kumar, S. Antibiotic resistance in the environment: A critical insight on its occurrence, fate, and eco-toxicity. *Environ. Sci. Pollut. Res.* **2021**, *28*, 24889–24916. [CrossRef] [PubMed]
245. Nie, Y.; Bi, X. Life-cycle assessment of transportation biofuels from hydrothermal liquefaction of forest residues in British Columbia. *Biotechnol. Biofuels* **2018**, *11*, 23. [CrossRef]
246. Botas, J.A.; Moreno, J.; Espada, J.J.; Serrano, D.P.; Dufour, J. Recycling of used lubricating oil: Evaluation of environmental and energy performance by LCA. *Resour. Conserv. Recycl.* **2017**, *125*, 315–323. [CrossRef]
247. Lachos-Perez, D.; Torres-Mayanga, P.C.; Abaide, E.R.; Zabot, G.L.; De Castilhos, F. Hydrothermal carbonization and Liquefaction: Differences, progress, challenges, and opportunities. *Bioresour. Technol.* **2022**, *343*, 126084. [CrossRef] [PubMed]
248. Stobernack, N.; Mayer, F.; Malek, C.; Bhandari, R. Evaluation of the energetic and environmental potential of the hydrothermal carbonization of biowaste: Modeling of the entire process chain. *Bioresour. Technol.* **2020**, *318*, 124038. [CrossRef]
249. Bora, R.R.; Lei, M.; Tester, J.W.; Lehmann, J.; You, F. Life Cycle Assessment and Technoeconomic Analysis of Thermochemical Conversion Technologies Applied to Poultry Litter with Energy and Nutrient Recovery. *ACS Sustain. Chem. Eng.* **2020**, *8*, 8436–8447. [CrossRef]