Waste Materials and General Classification in Thermochemical Conversion

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Thermochemical techniques have emerged as promising and sustainable approaches for converting diverse waste materials into valuable products, including chemicals and fuels. This research 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 research 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.

biomass   environmental impact   industrial waste   municipal solid waste   plastic waste

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 [1]. 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 [1]. 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 [1].

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 [2][3].

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 [4]. 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) [5]. 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 [4][5].

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 [6][7].

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 [8]. Plastics are composed of different polymers, such as polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET), among others [8]. 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 [9].

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 [10][11].

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 [12]. 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 [13][14][15].

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 entry 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 [16]. 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 [17][18].

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% [16]. Carbon dioxide, the most dangerous greenhouse gas, is responsible for around 30% of the effects of global warming [19][20].

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 [21][22]. 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 [23][24].

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