

Progress on Biomass Processing and Conversion

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In the face of global warming and rising energy costs, increasing attention is being paid to the principles of the circular economy, in which the utilization of waste biomass plays a key role in reducing environmental impacts. Waste biomass generated by the agri-food industry has attracted considerable research interest worldwide, with its applications extending far beyond energy production [1–7].

To address the existing research gap concerning the utilization of waste biomass, a Special Issue of Processes dedicated to this topic was proposed. Entitled “Progress on Biomass Processing and Conversion,” this Special Issue collects the latest research on the potential applications of biomass, presenting various processing techniques and simulations of these processes. These studies address various approaches to converting biomass into energy carriers (biogas, hydrogen, and bioethanol) and producing value-added products, including biological and thermal processes, numerical modeling, and biorefinery concepts. Despite methodological differences, all the studies focus on improving the efficiency of using biomass as a renewable energy source. The findings highlight key directions in the development of bioenergy technologies: optimizing substrate preparation and process conditions, and integrating different biomass conversion stages within biorefinery systems. A brief overview of the published scientific articles is provided below:

Conversion of Biomass into Energy-Rich Gas via Catalyzed Pyrolysis in a Sealed Pressure Reactor

Straka and Cihlár [8] investigated the effect of Ru/Al₂O₃ and Pd/C catalysts on the composition of biomass pyrolysis products in a sealed pressure reactor, aiming to develop a method for producing high-energy-content gases and evaluate the influence of the catalysts on the composition of the gas phase. It was shown that the Ru/Al₂O₃ catalyst promoted the formation of methane-rich gas (up to 70 vol%), whereas the Pd/C catalyst favored hydrogen-rich gas production (up to 75 vol%). The results indicate that catalytic pressure pyrolysis of biomass enables effective conversion of lignocellulosic waste into valuable gaseous fuels and byproducts such as biochar and bio-oil [8].

The Effect of Particle Size on Biodegradability and Kinetics During Anaerobic Digestion of Fruit and Vegetable Waste

Viguera-Carmona et al. [9] investigated the effect of the particle size of fruit and vegetable waste on the biodegradability and kinetics of anaerobic digestion. They demonstrated that reducing particle size increased the availability of organic matter to microorganisms and enhanced methane production. However, excessively small particles (<500 µm) led to process inhibition due to the accumulation of intermediate products. The highest methane yield (approximately 310 mL CH₄/g VS) was obtained for particle sizes ranging from 500 to 1000 µm. The authors also observed that biodegradability and archaeal activity declined as the fermentation process progressed owing to the depletion of readily biodegradable organic fractions [9].



Received: 7 July 2026

Accepted: 9 July 2026

Published: 14 July 2026

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From Microalgae to Biofuels: Investigating Valorization Pathways Towards Biorefinery Integration

Chatzimaliakas et al. [10] investigated the potential of using microalgal biomass within an integrated biorefinery system for bioethanol and biomethane production. The authors aimed to optimize pretreatment and enzymatic hydrolysis methods to enhance the release of fermentable sugars and evaluate the potential of fermentation residues to produce biogas. The authors demonstrated that the sequential production of bioethanol and biomethane enables efficient utilization of microalgal biomass, thereby increasing the overall amount of energy recovered from the feedstock [10].

Numerical Study of Biomass Combustion Using a Transient -State Approach

Neves et al. [11] conducted a transient CFD study of biomass combustion in a combustion chamber, aiming to analyze the temporal evolution of temperature, flow velocity, and reaction mixture composition during the combustion process. The results showed that the temperature in the combustion chamber gradually increased and eventually stabilized at a high level, whereas biomass mass decreased concurrently with an increase in the water vapor content of the combustion products. The authors concluded that the transient CFD model provides a more accurate representation of the combustion process than the corresponding steady-state approach.

Effects of Sugar Beet Pulp Pretreatment Methods on Hydrogen Production via Dark Fermentation

Cieciura-Włoch et al. [12] investigated hydrogen production through dark fermentation using sugar beet pulp as a lignocellulosic substrate, aiming to evaluate the effect of different biomass pretreatment methods (alkaline, acidic, and enzymatic) on process performance and the release of fermentable sugars. The authors demonstrated that appropriate pretreatment significantly increased the concentration of available reducing sugars in the substrate, resulting in a substantial improvement in hydrogen production. The highest hydrogen yield ($229 \text{ dm}^3 \text{ H}_2/\text{kg VS}$) was achieved following acid hydrolysis, whereas the untreated substrate produced only $17 \text{ dm}^3 \text{ H}_2/\text{kg VS}$. In addition, the pretreatment methods enhanced anaerobic digestion potential by increasing methane production [12].

Biomass is an important renewable energy resource, and its conversion into energy carriers, such as biogas, hydrogen, and liquid and gaseous fuels, offers a promising alternative to fossil fuels. The studies presented in this Special Issue can be grouped into four main thematic areas:

- Biological processes;
- Thermochemical processes;
- Combustion process modeling;
- Biorefinery development, including microalga-based biorefineries.

The first thematic area comprises biological processes, including anaerobic digestion and dark fermentation. In anaerobic digestion, substrate structure, particularly particle size, is a key factor affecting methane yield. Reducing particle size increases the availability of organic matter; however, excessive size reduction may inhibit methanogenesis due to the accumulation of intermediate products [9,13]. In dark fermentation for hydrogen production, the pretreatment of lignocellulosic biomass plays a crucial role by increasing the availability of fermentable sugars and significantly enhancing hydrogen yield [12]. Biological processes are characterized by relatively low energy requirements; however, their efficiency strongly depends on feedstock properties and process conditions. Therefore, advanced and hybrid pretreatment techniques have been investigated as effective strategies for enhancing substrate biodegradability and increasing biogas production compared

with untreated feedstock, although their performance remains highly dependent on the characteristics of the treated biomass [14].

The second thematic area focuses on thermochemical biomass conversion, particularly the catalytic pyrolysis of biomass under elevated temperatures and pressure. In these processes, biomass is converted into methane- or hydrogen-rich gas as well as valuable by-products such as bio-oil and biochar. The use of metal catalysts along with appropriate process conditions enables the production of gas containing high concentrations of the desired components (up to 70 vol% CH₄ or 75 vol% H₂) [8]. Unlike biological processes, thermochemical conversion does not require microorganisms and enables rapid processing of a wide range of biomass feedstocks. However, it is associated with higher energy requirements due to the need to maintain elevated temperatures and pressures.

The third thematic area concerns the numerical modeling of biomass combustion using CFD methods. Such analyses enable the investigation of combustion dynamics, including changes in temperature, flow velocity, and reaction mixture composition over time. The simulation results highlight the important role of flow conditions and reaction kinetics in determining combustion efficiency and heat release. Although this approach does not directly lead to fuel production, it provides valuable insights into the processes involved in converting the chemical energy of biomass into thermal energy. CFD analyses of fixed-bed biomass combustion have demonstrated that numerical modeling can effectively predict temperature distribution and evaluate the influence of airflow conditions, air staging, and cooling strategies on combustion behavior. Such approaches support the optimization of biomass combustion systems by improving efficiency and reducing pollutant emissions [15].

The fourth thematic area entails adopting an integrated biorefinery approach based on microalgae, enabling the simultaneous production of bioethanol and biomethane as well as the subsequent production of methane from process residues, thereby maximizing energy recovery from a single substrate [10]. These activities are consistent with the principles of the circular economy. Other authors have emphasized the potential of agro-industrial residues, such as olive-derived biomass, as valuable feedstocks for integrated biorefinery systems. The combination of thermochemical, biochemical, and emerging conversion pathways enables the production of multiple energy carriers, chemicals, and bio-based materials, improving resource utilization and supporting circular economy principles [16]. Recent studies have also highlighted the potential of agricultural residues, such as sorghum biomass, for integration into circular biorefinery systems. The combination of biochemical, thermochemical, and hybrid conversion pathways enables the production of multiple energy carriers and value-added products, while cascading valorization strategies improve overall resource utilization and environmental performance [17].

Conclusions

In summary, these studies identify four main biomass conversion pathways: biological, thermochemical, computational modeling, and biorefinery-based approaches. Biological processes enable efficient biogas and hydrogen production with relatively low energy input, whereas thermochemical processes provide high conversion yields and feedstock flexibility. Computational modeling of combustion processes supports optimization and improves our understanding of energy conversion phenomena, while the biorefinery approach, through the integrated use of biomass in sequential processes, maximizes overall energy recovery. Which technology is appropriate depends on the type of biomass, the desired end product, and the available technological conditions. Regardless of the pathway selected, the overarching goal remains maximizing energy efficiency and fully using biomass as a renewable energy resource.

Funding: This research received no external funding.

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

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