Analysis of Biomass-Based Energy Conversion Technologies: Current Trends and Evaluations

Kerim MARTİN
University of Necmettin Erbakan

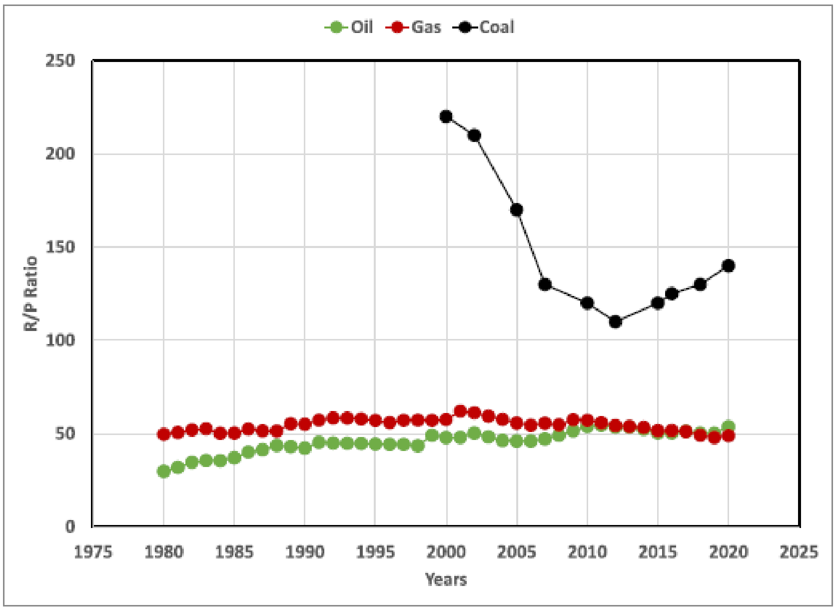
To Cite This Chapter:
Martin, K. (2025). Analysis of biomass-based energy conversion technologies: Current trends and evaluations. In F. Z. Saltan, H. Arıkan, & Y. Uzun (Eds.), *Current Studies in Technology, Engineering and Science* (pp. 231–253). ISRES Publishing.

Introduction

The use of fossil fuels dates back approximately 225 years (Kelkar, 2024). Technological advances have increased energy demand, and over the years, more fossil fuels have been extracted and used to meet this demand. **Figure 1** shows the ratio of oil, gas and coal reserves to production volumes over the last 40 years. An examination of the figure reveals that this ratio remained around 50 for oil and natural gas, while for coal it decreased and then increased from 2000 onwards, reaching around 150 in 2020. This means that, considering current demand levels, oil and natural gas have a remaining lifespan of 50 years each, while coal has a remaining lifespan of 150 years.

Figure 1

Reserve-to-Production Ratio for Oil, Natural Gas and Coal (last 40 years (Kelkar, 2024)



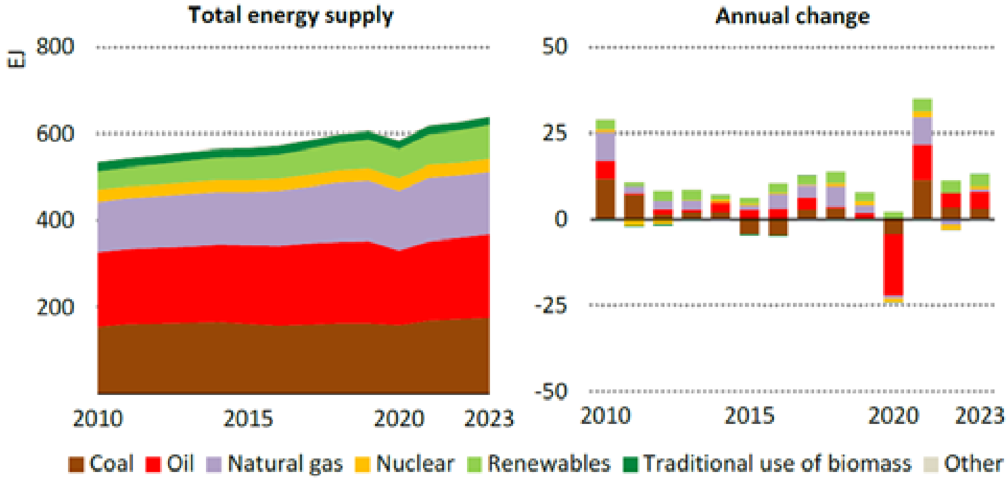
On the other hand, the sustainability of a fuel is of great importance for the future of the world. Researchers have recently placed great emphasis on sustainability and are conducting studies to ensure sustainability (Koul, Yakoob, & Shah, 2022), (Thirumalaivasan, Nangan, Kanagaraj, & Rajendran, 2024), (Happs et al., 2024), (Karvounis, Theotokatos, & Boulougouris, 2024), (Mehra, Goel, & Kumar, 2024), (Mbiankeu Nguea & Hervé Kaffo Fotio, 2024). The environmental sustainability of a material can be linked to its carbon footprint level(Akhtar, Krepl, & Ivanova, 2018). In this context, the sustainability of fossil fuels, which emit significant amounts of CO_2 into the environment when burned, thereby maintaining a very high carbon footprint level, is open to debate.

After the Industrial Revolution, fossil fuel use increased significantly, and atmospheric carbon concentration naturally increased as well. At the beginning of the Industrial Revolution, the atmospheric carbon concentration was 280 ppm, whereas it is currently at 420 ppm, and scientists predict that this value could reach 700 ppm by 2080. This situation causes climate change and leads to various health problems (Kabinesh et al., 2025). However, 85% of the world's energy needs are still met by carbon-based fuels. Meeting this need results in the annual release of 36 million tonnes of CO_2 into the atmosphere (Worku et al., 2024).

The use of renewable energy sources is increasing day by day. The graph in **Figure 2** is taken from the IEA 2024 report and shows the change in the global energy sources. The graph clearly shows that global energy usage are increasing (International Energy Agency, 2024). It is encouraging to note that the share of renewable energy sources has also increased to meet this growing demand.

Figure 2

World total energy demand 2010–2023 (International Energy Agency, 2024)



Renewable energy can be defined as an energy source that can be reused shortly after use, meaning it constantly renews itself over a short period of time. These energy sources include geothermal, solar, hydroelectric, wind, and biomass (Ibitoye, Mahamood, Jen, Loha, & Akinlabi, 2023). Research and applications have shown that renewable energy conversion technologies have developed significantly in recent times (Fang, Jiang, Li, Bai, & Chang, 2020), (Maheshwari, Kengne, & Bhat, 2023), (Irfan Sadaq, Mehdi, & Mohinoddin, 2023).

Among these renewable energy sources, biomass stands out due to its storability and its ability to be supplied throughout the year, at any time of day, with minimal impact from climate and season. Biomass is an energy source with a renewal period of approximately one year that reduces air pollution when used and slows the increase in atmospheric CO_2 content (Fülöp & Ecker, 2020).

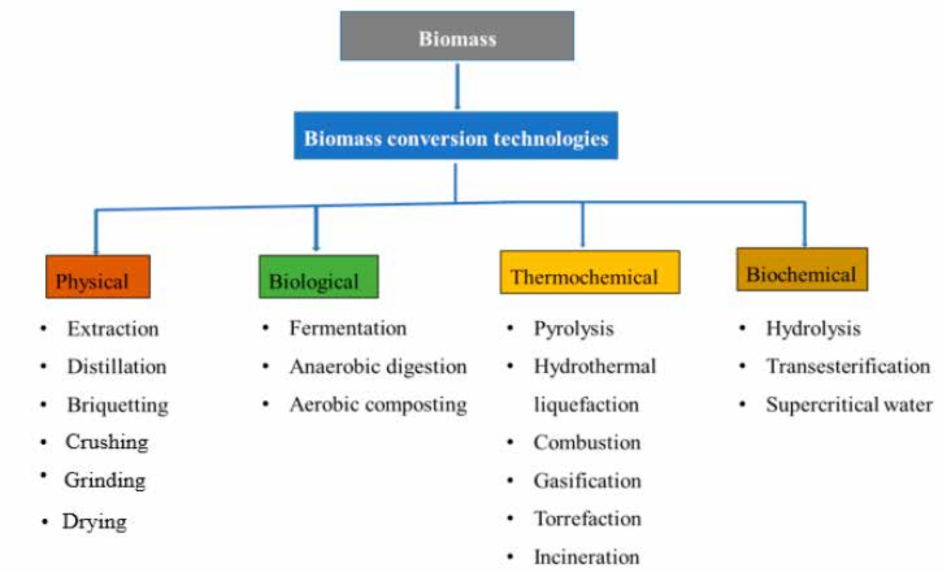
Biomass resources can be categorized under three headings: waste, forest products, and energy crops (Ozturk et al., 2017). Biomass can be transformed into three primary outputs., two of which are energy-related. These are heat/power production, fuels for transport, and chemical precursors. To transform biomass from waste into a useful product, it must be converted using specific techniques. The type and quantity of product produced will be determined by the chosen technique. Therefore, the method chosen in the biomass conversion process is of great importance. Two main technologies can be identified for the conversion of biomass into energy: thermochemical and biochemical conversion (Mckendry, 2002). In addition, physical and biological conversion techniques are also used.In this study, current research on biomass energy conversion processes was examined and an evaluation of efficiency improvement applications was made.

Overview Of Biomass-Based Energy Conversion Technologies

Several fundamental techniques stand out in biomass conversion. Studies on this topic have developed in parallel with technological advancements and continue to evolve. In light of new technologies, new techniques have emerged, and efforts have been made to improve biomass properties. This section of the study provides an assessment of conversion processes implemented in recent years. A review of the literature reveals that physical, biological, thermochemical, and biochemical techniques are used as conversion techniques. **Figure 3** provides a synopsis of conversion techniques.

Figure 3

The conversion technologies in biomass (Tshikovhi & Motaung, 2023)



Choosing these techniques is contingent on certain parameters such as the type of final product, biomass quality, quantity, and economics (El-Fawal et al., 2025). For dry biomass, properties including moisture level, heating value, and volatile fraction, ash content, and alkali metal content influence the choice of conversion technology. In the case of wet biomass, its moisture content and the cellulose/lignin balance influence this selection. (Mckendry, 2002).

Physical transformation techniques are primarily related to size reduction, consolidation, drying and densification processes. Among the most preferred methods within this technique are briquetting, drying and extraction (El-Fawal et al., 2025). Among biological conversion techniques, the most preferred method is anaerobic digestion. Fermentation generally uses microorganisms to produce bioethanol, biogas, and biohydrogen (Munasinghe & Khanal, 2010). The following sections will focus on thermochemical and biochemical conversion methods.

Thermochemical Conversion Methods

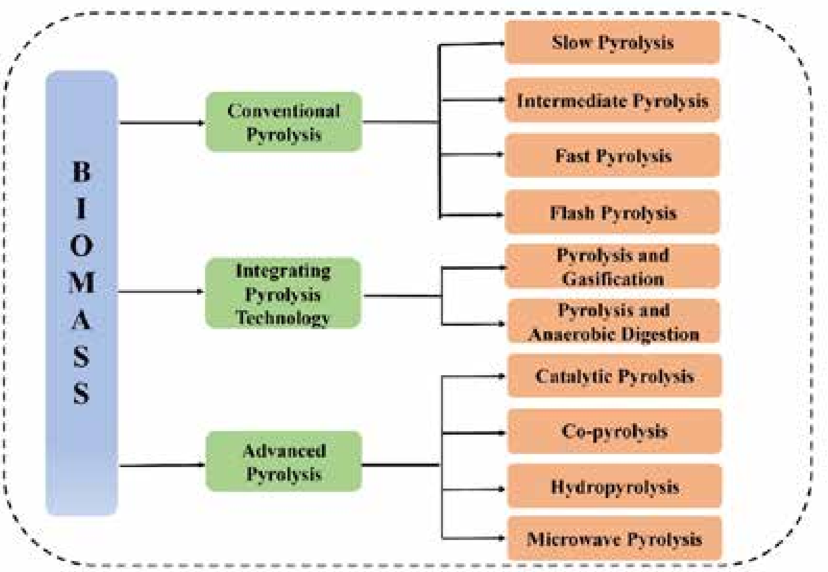
Thermochemical conversion methods play an important role in energy concentration by converting biomass resources into bio-oil and facilitate a carbon-neutral cycle (X. Zhang et al., 2025).

Pyrolysis

Pyrolysis involves the thermal disintegration of biomass in an oxygen-deficient environment. The process produces solid residue, liquid (bio-oil and water), and gas. This solid output, frequently referred to as biochar or charcoal, is a porous, carbon-dominant compound. (Suopajärvi et al., 2018). The traditional pyrolysis method can be divided into fast, slow, and flash pyrolysis processes (Shen, Wang, Ge, & Chen, 2016). Another pyrolysis classification by Cai et al. is shown in **Figure 4** (Cai et al., 2024). Here, new methods are listed alongside traditional pyrolysis.

Figure 4

Pyrolysis classification by (Cai et al., 2024)

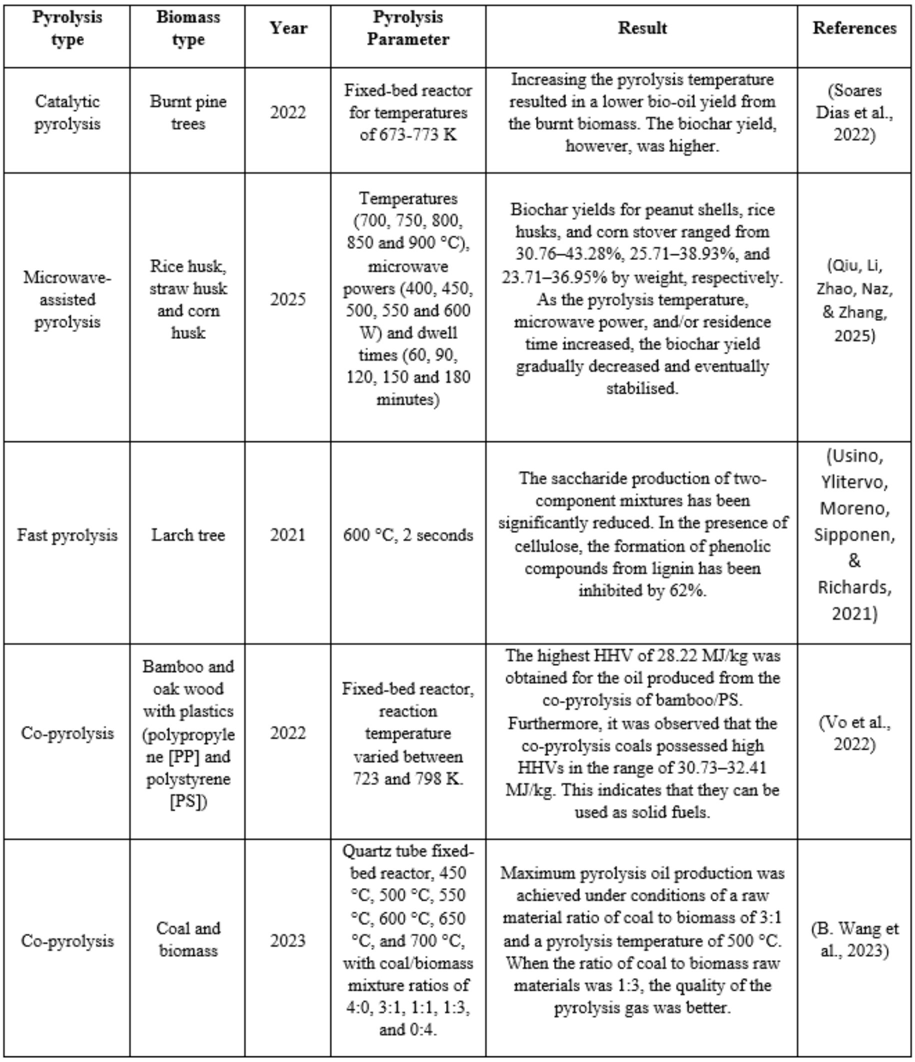


The pyrolysis of biomass has attracted considerable interest as a technology capable of simultaneously producing high-value-added energy and chemical products such as bio-oil, biochar, and combustible gas. It has been observed that catalysts also play a role in pyrolysis and that catalysts improve the distribution and properties of pyrolysis products (Cai et al., 2024). Studies have also demonstrated the effect of the catalytic method on fast pyrolysis, which is a subcategory of pyrolysis. Catalytic fast pyrolysis is a complex technology influenced by various parameters, including composition, interactions between components, catalysts, process, reactor, and biomass type or pretreatment method (El Bari et al., 2024).

Microwave-assisted pyrolysis is a technique that has recently gained popularity. It appears to be advantageous due to its high heating rate and ease of use. However, its potential for converting various biomass materials into biofuels has not yet been fully explored. Studies on this topic are ongoing (Bisht et al., 2026). Recent studies have focused on various types of pyrolysis. These include new and innovative techniques. Microwave-assisted pyrolysis, catalytic pyrolysis, and co-pyrolysis are among the areas where research in the literature is concentrated. The table below summarizes some of the studies conducted on this topic.

Table 1

Summary information on some studies related to the pyrolysis method



Pyrolysis type	Biomass type	Year	Pyrolysis Parameter	Result	References
Catalytic pyrolysis	Burnt pine trees	2022	Fixed-bed reactor for temperatures of 673-773 K	Increasing the pyrolysis temperature resulted in a lower bio-oil yield from the burnt biomass. The biochar yield, however, was higher.	(Soares Dias et al., 2022)
Microwave-assisted pyrolysis	Rice husk, straw husk and corn husk	2025	Temperatures (700, 750, 800, 850 and 900 °C), microwave powers (400, 450, 500, 550 and 600 W) and dwell times (60, 90, 120, 150 and 180 minutes)	Biochar yields for peanut shells, rice husks, and corn stover ranged from 30.76–43.28%, 25.71–38.93%, and 23.71–36.95% by weight, respectively. As the pyrolysis temperature, microwave power, and/or residence time increased, the biochar yield gradually decreased and eventually stabilised.	(Qiu, Li, Zhao, Naz, & Zhang, 2025)
Fast pyrolysis	Larch tree	2021	600 °C, 2 seconds	The saccharide production of two-component mixtures has been significantly reduced. In the presence of cellulose, the formation of phenolic compounds from lignin has been inhibited by 62%.	(Usino, Ylitervo, Moreno, Sipponen, & Richards, 2021)
Co-pyrolysis	Bamboo and oak wood with plastics (polypropylene [PP] and polystyrene [PS])	2022	Fixed-bed reactor, reaction temperature varied between 723 and 798 K.	The highest HHV of 28.22 MJ/kg was obtained for the oil produced from the co-pyrolysis of bamboo/PS. Furthermore, it was observed that the co-pyrolysis coals possessed high HHVs in the range of 30.73–32.41 MJ/kg. This indicates that they can be used as solid fuels.	(Vo et al., 2022)
Co-pyrolysis	Coal and biomass	2023	Quartz tube fixed-bed reactor, 450 °C, 500 °C, 550 °C, 600 °C, 650 °C, and 700 °C, with coal/biomass mixture ratios of 4:0, 3:1, 1:1, 1:3, and 0:4.	Maximum pyrolysis oil production was achieved under conditions of a raw material ratio of coal to biomass of 3:1 and a pyrolysis temperature of 500 °C. When the ratio of coal to biomass raw materials was 1:3, the quality of the pyrolysis gas was better.	(B. Wang et al., 2023)

Hydrothermal liquefaction

Hydrothermal liquefaction offers a direct route to biomass utilization without drying, eliminating the energy and cost costs required for drying. Utilization of all biomass components can be achieved with this technology and subsequent processes (Hao et al., 2023). Studies using different types of hydrothermal liquefaction are available in the literature. Compared to traditional isothermal hydrothermal liquefaction, fast hydrothermal liquefaction uses a rapid heating process to prevent undesirable secondary reactions and achieves higher biofuel yields in short reaction times. Fast hydrothermal liquefaction has recently attracted the attention of researchers (Ni et al., 2022).

In recent years, microwave-assisted hydrothermal liquefaction has been one of the most studied methods, and a gap in this area was identified in an article by Zhuang et al. In the same article, researchers conducted a study using microwave-assisted hydrothermal liquefaction and demonstrated that microwave radiation facilitated the liquefaction process, resulting in approximately 39.8–43.9% improvement in yield, 3.9–4.0% in calorific value, and 46.6–59.0% improvement in energy recovery efficiency compared to biopulp obtained from conventional liquefaction under similar conditions (Zhuang, Liu, Wang, Zhang, & Ma, 2022).

In a study where catalyst and solvent were used together and their effects on the hydrothermal liquefaction process were investigated, it was concluded that the maximum yields of bio-oil and biochar were 65.0% and 32.0%, respectively, and the calorific values of bio-oil and biochar were 31.2 MJ/kg and 26.5 MJ/kg, respectively. The study also evaluated that alkali catalysts and 1.4-butanediol-triethanolamine mixed solvent could be useful in bioenergy production (X. Zhou, Zhao, Chen, Zhao, & Wu, 2022).

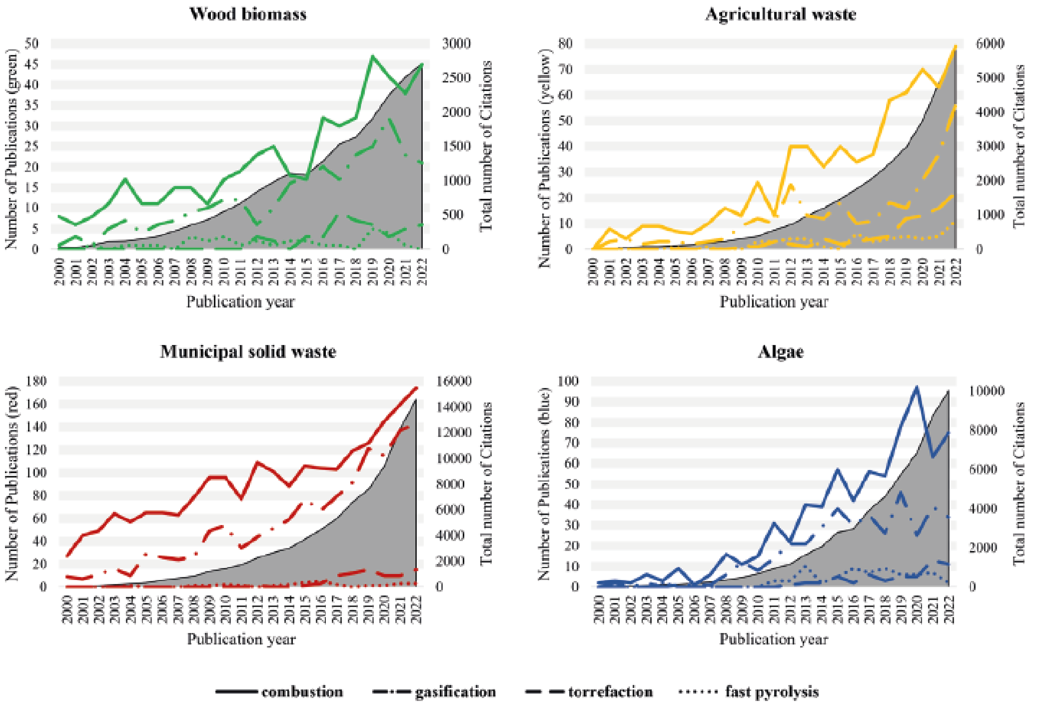
In another study on hydrothermal liquefaction, a two-stage process was applied, first involving a subcritical water reaction followed by a supercritical water reaction. This demonstrated that a greater amount of bio-oil was obtained compared to processing biomass directly with supercritical water. The highest bio-oil yield obtained with the two-stage process was achieved at a was 25.44% by weight in the experiment conducted at a 1:10 biomass/water ratio, and this process was obtained from a subcritical water reaction lasting 30 minutes at 250°C, followed by a second supercritical water reaction lasting 60 minutes at 400°C [37]. When new studies are examined in the literature, it is seen that catalytic hydrothermal liquefaction (Baloch et al., 2021), (Durak, Genel, & Genel, 2026), (Divyabharathi, Subramanian, & Kamaraj, 2025), co-hydrothermal liquefaction (Biswas et al., 2022), (Rawat et al., 2023), (Hongthong, Raikova, Leese, & Chuck, 2020), (Mukundan et al., 2022), (Eladnani et al., 2023) and hydrothermal liquefaction methods using nanoparticles as catalysts (Zhu, Zhao, Tian, Zhang, & Wei, 2022), (Ding, Mahadevan Subramanya, Wang, & Savage, 2023), (Jena, Eboibi, & Das, 2022) are used. This indicates that there is a search for new methods rather than traditional hydrothermal liquefaction processes.

Combustion

Combustion is regarded as a heat-generating process in which the carbon and nitrogen in the biomass react with oxygen in the air. This technique is the oldest, simplest, and most common method used to produce heat and electricity from biomass. The energy content or calorific value of biomass is an important factor and functions as the heat released during combustion under certain conditions (Tekin, Karagöz, & Bektaş, 2014). The biomass combustion method is an ancient and widely used method (Tshikovhi & Motaung, 2023). The fact that the combustion process can be used for all types of biomass provides the greatest benefit. However, combustion is only possible with moisture content below 50% (Tripathi, Sahu, & Ganesan, 2016). A researcher investigating the number of publications and citations between 2000 and 2022 obtained the following graph for thermochemical conversion technologies (Svedovs, Dzikevics, & Kirsanovs, 2023).

Figure 5

Comparison of the number of publications and citations on thermochemical conversion technologies according to biomass type (Svedovs et al., 2023)



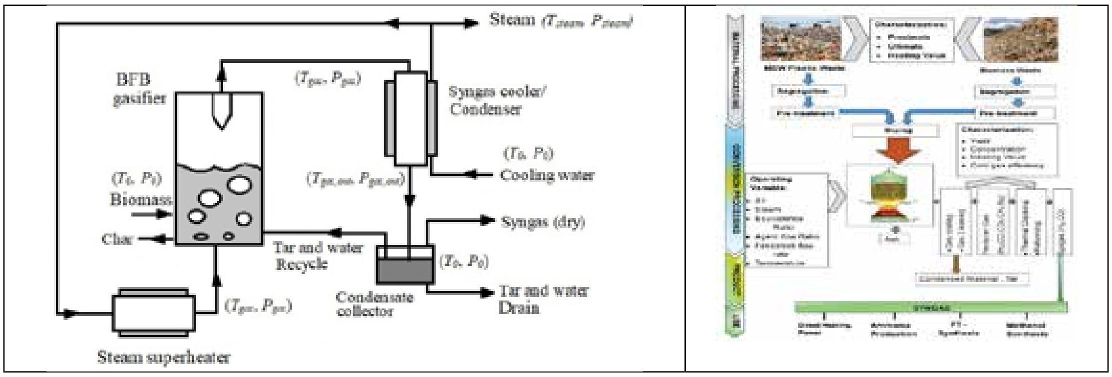
When examining the graphs in **Figure 5**, it is observed that the number of studies and citations on the combustion method has increased more consistently compared to other methods. In addition to traditional combustion methods, there are also studies that integrate new technologies. A study conducted in 2024 mentioned that it is difficult to monitor biomass during its combustion in boilers due to its non-homogeneity, and an online monitoring method was proposed as a solution. The study stated that optical identification allows for the instantaneous and efficient measurement of multiple parameters and that the number of studies in this field is increasing (Yan et al., 2024). Another method is co-combustion. This method involves the simultaneous combustion of multiple biomasses. This method has also been frequently studied by researchers (Xia, Zhang, Tang, & Pan, 2023), (Fan et al., 2024), (Liu et al., 2024).

Gasification

In the gasification process, waste is indirectly converted into fuel or synthetic gases in the presence of oxidants. Part of the fuel is burned to produce heat energy, resulting in hot fuel gases with low heat value (Banu, Sharmila, Ushani, Amudha, & Kumar, 2020). Gasification is a widely preferred method among thermochemical conversion processes and has been extensively studied (Verma et al., 2023). A diagram of co-gasification and steam-based methods, which are subcategories of gasification methods, is shown in **Figure 6**. The products obtained at the end of gasification are also shown here. Various gasification methods have been studied in the literature. These include methods involving a gasification agent (W. Zhang et al., 2025), (Marzoughi, Samimi, & Rahimpour, 2022), (Mojaver, Khalilarya, Chitsaz, & Jafarmadar, 2024), gasification with steam and CO_2 (Castro, Leaver, & Pang, 2026), (S. Zhang et al., 2022), (Hejazi, 2022) gasification with supercritical water (Panichkittikul, Mariyappan, Wu, & Patcharavorachot, 2024) and co-gasification (Khumalo & Patel, 2025), (Xiao, Wang, Cai, Zhang, & Yu, 2024). **Figure 6** shows a schematic representation of the steam gasification method, the steps of the gasification process, and the resulting products.

Figure 6

a) Steam gasification (Hejazi, 2022), b) Steps of the co-gasification process and resulting products (Khumalo & Patel, 2025)



Torrefaction

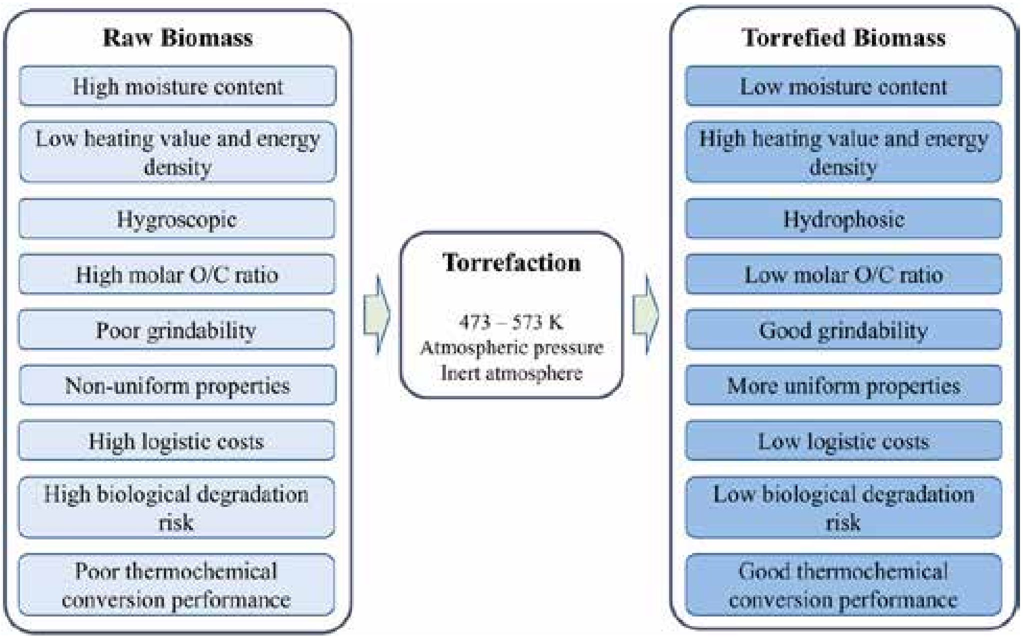
Torrefaction is an extremely important pre-treatment technology for thermochemical applications such as pyrolysis, gasification and liquefaction, and is one of the current topics in the field of renewable energy (Devaraja, Dissanayake, Gunarathne, & Chen, 2022). Pre-treatment techniques such as drying, concentration and roasting aim to improve biomass properties and eliminate some of the problems encountered during conversion. Thermal decomposition at 473–573 K, technically referred to as roasting, significantly improves the properties of biomass. At this temperature range, biomass releases most of its moisture content and a small portion of its volatile matter (Soria-Verdugo, Cano-Pleite, Panahi, & Ghoniem, 2022).

Torrefaction is a mild pyrolysis process that occurs between 473 and 573 K during a holding period of several minutes to an hour, resulting in partial devolatilization of 0–60% by weight of the original dry raw material. During roasting, the release of volatile substances is combined with other changes in physical and chemical structure. The resulting new solid has a higher specific energy density, greater resistance to degradation, and lower milling energy requirements (Bates & Ghoniem, 2014). Torrefacted biomass is essentially hydrophobic. Its hydrophobicity facilitates its handling and processing, particularly by reducing logistics costs (Yantao Yang et al., 2023).

Figure 7 shows the effects of the torrefaction process on biomass. Examining the diagram in **Figure 7**, the differences in properties between raw and torrefaction biomass, as well as the parameters that demonstrate the positive impact of this process on biomass, are clearly visible. The most important of these parameters are moisture content, high calorific value and energy density, low O/C ratio, and improved thermochemical conversion properties.

Figure 7

Effects of torrefaction on biomass (Yantao Yang et al., 2023)



Biochemical Conversion Methods

The biochemical degradation of plant-based biomass (lignocellulosic) is a rather challenging process due to the complex structure of plants. Lignocellulosic biomass typically has a composition of 40–80% cellulose, 15–30% hemicellulose, and 10–25% lignin, with varying suitability for biological conversion. Biochemical methods such as fermentation and anaerobic digestion utilise the various metabolic effects of microorganisms to break down the organic components of biomass into a range of valuable products. A 2022 study revealed that bioethanol and biogas are the most commercially viable products obtained from the biochemical conversion of biomass (Hakeem et al., 2023). Biochemical methods involve the use of microorganisms, enzymes, and genetically modified organisms to convert biomass into fuel (Poornima et al., 2024).

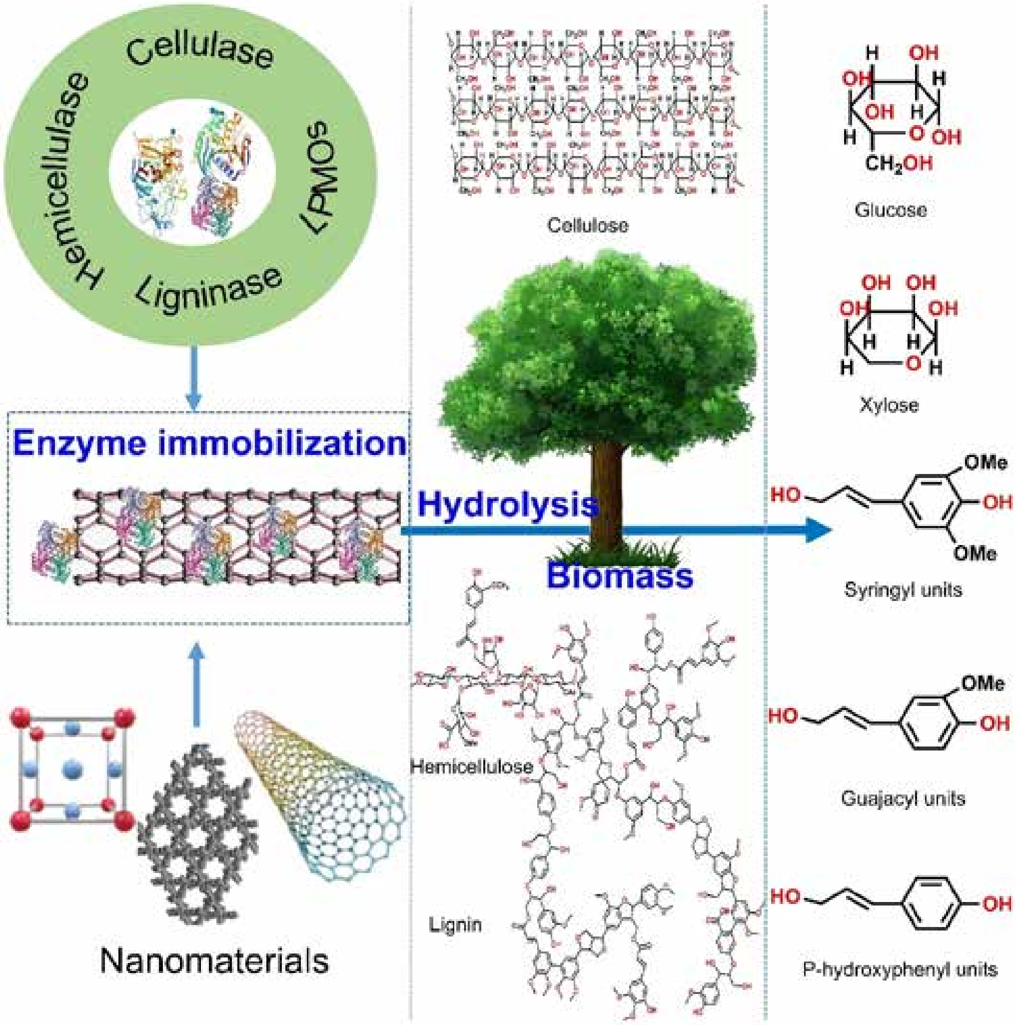
Hydrolysis

Biomass hydrolysis technologies, including acid and enzymatic hydrolysis, are applied to break down feedstock into simple sugars (Tshikovhi & Motaung, 2023). Concentrated acid hydrolysis is often performed by first adding 70–77% sulphuric acid ($H_2SO_4H_2SO_4$)

to break intra- and interchain hydrogen bonds in the biomass, then adding water to dilute the acid to 20–30% and release fermentable sugars (N. Zhou, Zhang, Wu, Gong, & Wang, 2011). Hydrolysis, especially enzyme hydrolysis, is an important process in the conversion of biomass to energy. In the context of biorefining, this process generally involves the decomposition of biomass components into their constituents by using reagents such as enzymes or acids. Examples include the decomposition of polysaccharides into sugars or proteins into amino acids (Wongsirichot, 2024). Hydrolysis has always been a topic of interest for researchers. In recent years, hydrolysis technology has improved, and methods that are more efficient have been investigated. Among these, as seen in **Figure 8**, the studies in which nanoparticles were used (Kotwal, Pathania, Singh, Din Sheikh, & Kothari, 2024), (Luo et al., 2022), (Y. Chen et al., 2021) and pretreatment techniques were applied before the hydrolysis stage (Fu et al., 2021), (Yang Yang, Zhang, Zhao, & Wang, 2023), (Zheng et al., 2022) stand out.

Figure 8

Usage of nanomaterials in hydrolysis method (Luo et al., 2022)



Transesterification

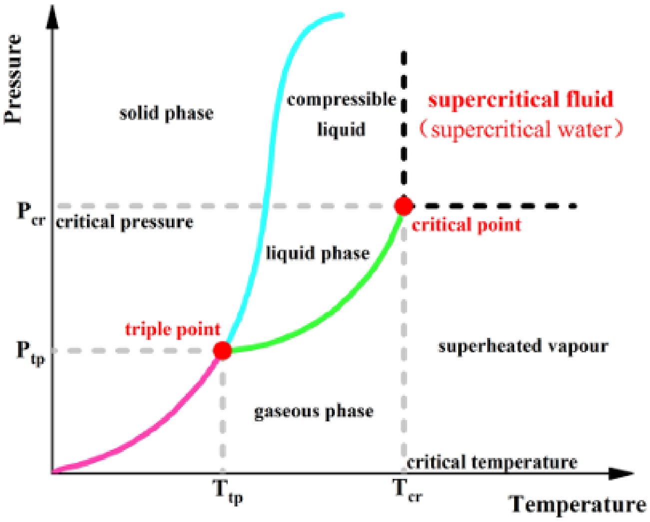
Transesterification involves a series of reversible reactions in which lipids/triglycerides react with alcohol (most commonly methanol), yielding glycerol, monoglycerides, diglycerides, and fatty acid methyl esters—the components of biodiesel—at each step (Tshikovhi & Motaung, 2023). Transesterification is the most popular and cost-effective method of biodiesel production, utilising an acid, an alkali, or an enzyme as a catalyst. Here, triglycerides and primary alcohol are combined in the presence of a catalyst [81]. Lipase, one of the enzymes, exhibits enhanced stability, specificity, enantioselectivity, catalytic effect, and site selectivity. Therefore, it is more suitable for the enzymatic transesterification process in biodiesel production (Aybastier & Demir, 2010). When new studies in the literature are examined, it is seen that transesterification is a technique mostly used in biodiesel studies, applied to various biomasses (Sallet et al., 2025), (Singh, Kumar, Goyal, & Moholkar, 2022), (Bed, Kumar, & RaviKumar, 2025).

Supercritical water

The most abundant substance on Earth is water, which exists in three different phases in nature: solid (ice), liquid, and vapour. Water is found in a supercritical state at a pressure of 22.07 MPa and a temperature higher than 373.9 °C around hydrothermal vents on the sea floor. Water in this state is supercritical water (Z. Chen et al., 2023). **Figure 9** shows the critical regions of water (Q. Wang et al., 2023).

Figure 9

Critical point properties of water (Q. Wang et al., 2023)



Supercritical water gasification effectively converts biomass into gaseous products using water as the reaction medium. This method does not require drying of the feedstock. Thus, in addition to wet biomass such as microalgae and lignocellulosic, wet organic waste products with high moisture content such as sewage sludge and animal manure can also be converted (Dutzi, Boukis, & Sauer, 2023). Supercritical water gasification of biomass in various reactors, such as tubular, batch, and continuous stirred tank reactors, has been widely investigated in recent decades. The walls of these reactors are made of stainless steel or nickel-based alloys, which mostly play a catalytic role in the biomass processing (C. Wang, Zhu, Huang, Jin, & Lian, 2022).

Conclusion

In parallel with the growing world population, energy consumption is also increasing. With this rising consumption, serious damage is being caused to the environment, and plans are being made to increase the share of alternative energy sources, with incentives being provided in this direction. Among these alternative energy sources, biomass energy stands out due to its unique advantages, such as being sustainable and carbon neutral. The intensity of studies in the literature indicates that there are many different methods and techniques for converting biomass into energy. This study focuses on current research into biomass energy conversion methods, particularly thermochemical and biochemical conversion methods.

Recent studies have highlighted that advances in thermochemical and biochemical conversion methods for biomass have led to significant progress in both fundamental science and applied process development. The review found that there have been notable advances in thermochemical approaches (pyrolysis, gasification, hydrothermal processes), developments in catalyst technologies, the use of nanomaterials, and process integration studies. In biochemical conversion methods, the effectiveness of pre-treatment methods, enzymes and the use of nanomaterials has been observed to increase the production efficiency of biofuels. In addition, studies using multiple methods together (hybrid) demonstrate efforts to develop new and innovative methods.

References

Akhtar, A., Krepl, V., & Ivanova, T. (2018, July 19). A Combined Overview of Combustion, Pyrolysis, and Gasification of Biomass. *Energy and Fuels*. American Chemical Society. doi:10.1021/acs.energyfuels.8b01678

Aybastier, Ö., & Demir, C. (2010). Optimization of immobilization conditions of Thermomyces lanuginosus lipase on styrene-divinylbenzene copolymer using response surface methodology. *Journal of Molecular Catalysis B: Enzymatic*, *63*(3–4), 170–178. doi:10.1016/j.molcatb.2010.01.013

Baloch, H. A., Siddiqui, M. T. H., Nizamuddin, S., Mubarak, N. M., Khalid, M., Srinivasan, M. P., & Griffin, G. J. (2021). Catalytic co-liquefaction of sugarcane bagasse and polyethylene for bio-oil production under supercritical conditions: Effect of catalysts. *Journal of Analytical and Applied Pyrolysis*, *153*. doi:10.1016/j.jaap.2020.104944

Banu, J. R., Sharmila, V. G., Ushani, U., Amudha, V., & Kumar, G. (2020). Impervious and influence in the liquid fuel production from municipal plastic waste through thermo-chemical biomass conversion technologies - A review. *Science of the Total Environment*, *718*. doi:10.1016/j.scitotenv.2020.137287

Bates, R. B., & Ghoniem, A. F. (2014). Modeling kinetics-transport interactions during biomass torrefaction: The effects of temperature, particle size, and moisture content. *Fuel*, *137*, 216–229. doi:10.1016/j.fuel.2014.07.047

Bed, R. K., Kumar, V. R., & RaviKumar, A. (2025). Aspergillus terreus variant TB21 wet biomass optimized by in-situ transesterification for biodiesel production. *AMB Express*, *15*(1). doi:10.1186/s13568-024-01772-7

Bisht, P., Mishra, A., Anand, V., Singh, A., Tiwari, H., Shobana, S., … Prajapati, S. K. (2026, January 1). Microwave-assisted pyrolysis of biomass for bioenergy production. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2025.116344

Biswas, B., Sahoo, D., Sukumaran, R. K., Krishna, B. B., Kumar, J., Reddy, Y. S., … Bhaskar, T. (2022). Co-hydrothermal liquefaction of phumdi and paragrass an aquatic biomass: Characterization of bio-oil, aqueous fraction and solid residue. *Journal of the Energy Institute*, *102*, 247–255. doi:10.1016/j.joei.2022.03.013

Cai, J., Lin, N., Li, Y., Xue, J., Li, F., Wei, L., … Li, W. (2024). Research on the application of catalytic materials in biomass pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *177*. doi:10.1016/j.jaap.2023.106321

Castro, J., Leaver, J., & Pang, S. (2026). Modelling of enhanced dual fluidized bed steam gasification with integration of biomass-specific devolatilization. *Biomass and Bioenergy*, *204*. doi:10.1016/j.biombioe.2025.108445

Chen, Y., Yang, Y., Orr, A. A., Makam, P., Redko, B., Haimov, E., … Gazit, E. (2021). Self-Assembled Peptide Nano-Superstructure towards Enzyme Mimicking Hydrolysis. *Angewandte Chemie - International Edition*, *60*(31), 17164–17170. doi:10.1002/anie.202105830

Chen, Z., Chen, H., Xu, Y., Hu, M., Hu, Z., Wang, J., & Pan, Z. (2023, January 1). Reactor for biomass conversion and waste treatment in supercritical water: A review. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2022.113031

Devaraja, U. M. A., Dissanayake, C. L. W., Gunarathne, D. S., & Chen, W. H. (2022). Oxidative torrefaction and torrefaction-based biorefining of biomass: a critical review. *Biofuel Research Journal*, *9*(3), 1672–1696. doi:10.18331/BRJ2022.9.3.4

Ding, X., Mahadevan Subramanya, S., Wang, Y., & Savage, P. E. (2023). Hydrothermal liquefaction of starch using homogeneous and heterogeneous co-catalysts. *Chemical Engineering Journal*, *468*. doi:10.1016/j.cej.2023.143570

Divyabharathi, R., Subramanian, P., & Kamaraj, A. (2025). Catalytic hydrothermal liquefaction of lignocellulosic biomass for biocrude production and process optimization. *The Canadian Journal of Chemical Engineering*. doi:10.1002/cjce.70154

Durak, H., Genel, S., & Genel, Y. (2026). Hydrothermal liquefaction of sinapis arvensis biomass using TiO_2-supported metal catalysts: A study on bio-oil yield and composition. *Journal of Supercritical Fluids*, *227*. doi:10.1016/j.supflu.2025.106745

Dutzi, J., Boukis, N., & Sauer, J. (2023). Process Effluent Recycling in the Supercritical Water Gasification of Dry Biomass. *Processes*, *11*(3). doi:10.3390/pr11030797

Eladnani, I., Bracciale, M. P., Damizia, M., Mousavi, S., De Filippis, P., Lakhmiri, R., & de Caprariis, B. (2023). Catalytic Hydrothermal Liquefaction of Brachychiton populneus Biomass for the Production of High-Value Bio-Crude. *Processes*, *11*(2). doi:10.3390/pr11020324

El Bari, H., Fanezoune, C. K., Dorneanu, B., Arellano-Garcia, H., Majozi, T., Elhenawy, Y., … Ashour, F. H. (2024, March 1). Catalytic fast pyrolysis of lignocellulosic biomass: Recent advances and comprehensive overview. *Journal of Analytical and Applied Pyrolysis*. Elsevier B.V. doi:10.1016/j.jaap.2024.106390

El-Fawal, E. M., El Naggar, A. M. A., El-Zahhar, A. A., Alghandi, M. M., Morshedy, A. S., El Sayed, H. A., & Mohammed, A. elshifa M. E. (2025, April 22). Biofuel production from waste residuals: comprehensive insights into biomass conversion technologies and engineered biochar applications. *RSC Advances*. Royal Society of Chemistry. doi:10.1039/d5ra00857c

Fang, S., Jiang, L., Li, P., Bai, J., & Chang, C. (2020). Study on pyrolysis products characteristics of medical waste and fractional condensation of the pyrolysis oil. *Energy*, *195*. doi:10.1016/j.energy.2020.116969

Fan, H., Zhang, H., Zhang, X., Zhou, D., Jia, C., Luo, Z., … Zhang, S. (2024). Study on the Co-combustion characteristics and synergistic effect of semi-coke and dust coal produced from biomass briquette in fluidized bed gasification. *Journal of the Energy Institute*, *114*. doi:10.1016/j.joei.2024.101594

Fülöp, L., & Ecker, J. (2020, July 22). An overview of biomass conversion: Exploring new opportunities. *PeerJ*. PeerJ Inc. doi:10.7717/peerj.9586

Fu, Q., Xiao, C., Liao, Q., Huang, Y., Xia, A., & Zhu, X. (2021). Kinetics of hydrolysis of microalgae biomass during hydrothermal pretreatment. *Biomass and Bioenergy*, *149*. doi:10.1016/j.biombioe.2021.106074

Hakeem, I. G., Sharma, A., Sharma, T., Sharma, A., Joshi, J. B., Shah, K., … Surapaneni, A. (2023, May 1). Techno-economic analysis of biochemical conversion of biomass to biofuels and platform chemicals. *Biofuels, Bioproducts and Biorefining*. John Wiley and Sons Ltd. doi:10.1002/bbb.2463

Hao, B., Xu, D., Wei, Y., Diao, Y., Yang, L., Fan, L., & Guo, Y. (2023, May 1). Mathematical models application in optimization of hydrothermal liquefaction of biomass. *Fuel Processing Technology*. Elsevier B.V. doi:10.1016/j.fuproc.2023.107673

Happs, R. M., Hanes, R. J., Bartling, A. W., Field, J. L., Harman-Ware, A. E., Clark, R. J., … Davison, B. H. (2024). Economic and Sustainability Impacts of Yield and Composition Variation in Bioenergy Crops: Switchgrass (Panicum virgatum L.). *ACS Sustainable Chemistry and Engineering*, *12*(5), 1897–1910. doi:10.1021/acssuschemeng.3c05770

Hejazi, B. (2022). Heat integration and waste minimization of biomass steam gasification in a bubbling fluidized bed reactor. *Biomass and Bioenergy*, *159*. doi:10.1016/j.biombioe.2022.106409

Hongthong, S., Raikova, S., Leese, H. S., & Chuck, C. J. (2020). Co-processing of common plastics with pistachio hulls via hydrothermal liquefaction. *Waste Management*, *102*, 351–361. doi:10.1016/j.wasman.2019.11.003

Ibitoye, S. E., Mahamood, R. M., Jen, T. C., Loha, C., & Akinlabi, E. T. (2023, November 1). An overview of biomass solid fuels: Biomass sources, processing methods, and morphological and microstructural properties. *Journal of Bioresources and Bioproducts*. KeAi Communications Co. doi:10.1016/j.jobab.2023.09.005

International Energy Agency. (2024). *2024 World Energy Outlook*. Retrieved from www.iea.org/terms

Irfan Sadaq, S., Mehdi, S. N., & Mohinoddin, M. (2023). *Experimental analysis on solar photovoltaic (SPV) panel for diverse slope angles at different wind speeds*.

In *Materials Today: Proceedings*. Elsevier Ltd. doi:10.1016/j.matpr.2023.04.265

Jena, U., Eboibi, B. E., & Das, K. C. (2022). Co-Solvent Assisted Hydrothermal Liquefaction of Algal Biomass and Biocrude Upgrading. *Fuels*, *3*(2), 326–341. doi:10.3390/fuels3020020

Kabinesh, V., Suwethaasri, D., Baranidharan, K., Ravi, R., Tilak, M., Kalpana, M., … Eniya, A. (2025). A critical review of exploring the recent trends and technological advancements in forest biomass estimation. *Plant Science Today*. Horizon e-Publishing Group. doi:10.14719/pst.6695

Karvounis, P., Theotokatos, G., & Boulougouris, E. (2024). Environmental-economic sustainability of hydrogen and ammonia fuels for short sea shipping operations. *International Journal of Hydrogen Energy*, *57*, 1070–1080. doi:10.1016/j.ijhydene.2024.01.058

Kelkar, M. (2024). Demise of fossil fuels part I: Supply and demand. *Heliyon*, *10*(20). doi:10.1016/j.heliyon.2024.e39200

Khumalo, N. L., & Patel, B. (2025). Synergistic Effects of Biomass-polyethylene Co-gasification: A Simulation Approach. *Periodica Polytechnica Chemical Engineering*, *69*(3), 445–456. doi:10.3311/PPch.39516

Kotwal, N., Pathania, D., Singh, A., Din Sheikh, Z. U., & Kothari, R. (2024, September 1). Enzyme immobilization with nanomaterials for hydrolysis of lignocellulosic biomass: Challenges and future Perspectives. *Carbohydrate Research*. Elsevier Ltd. doi:10.1016/j.carres.2024.109208

Koul, B., Yakoob, M., & Shah, M. P. (2022). Agricultural waste management strategies for environmental sustainability. *Environmental Research*, *206*. doi:10.1016/j.envres.2021.112285

Liu, Y., Tan, W., liang, S., Bi, X., Sun, R., & Pan, X. (2024). Comparative study on the co-combustion behavior of torrefied biomass blended with different rank coals. *Biomass Conversion and Biorefinery*, *14*(1), 781–793. doi:10.1007/s13399-022-02368-6

Luo, H., Liu, X., Yu, D., Yuan, J., Tan, J., & Li, H. (2022, September 14). Research Progress on Lignocellulosic Biomass Degradation Catalyzed by Enzymatic Nanomaterials. *Chemistry - An Asian Journal*. John Wiley and Sons Ltd. doi:10.1002/asia.202200566

Maheshwari, Z., Kengne, K., & Bhat, O. (2023, July 1). A comprehensive review on wind turbine emulators. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2023.113297

Marzoughi, T., Samimi, F., & Rahimpour, M. R. (2022). Kinetic Modeling of Biomass Gasification in the Reduction Zone Using Various Gasification Agents. *Chemical Engineering and Technology*, *45*(4), 620–630. doi:10.1002/ceat.202100271

Mbiankeu Nguea, S., & Hervé Kaffo Fotio. (2024). Synthesizing the role of biomass energy consumption and human development in achieving environmental sustainability. *Energy*, *293*. doi:10.1016/j.energy.2024.130500

Mckendry, P. (2002). Energy production from biomass (part 2): conversion technologies. *Bioresource Technology*, (83), 47–54.

Mehra, K. S., Goel, V., & Kumar, R. (2024). An integrated multi-attribute decision framework for sustainability assessment of renewable diesel fuel production pathways. *Energy Conversion and Management*, *309*. doi:10.1016/j.enconman.2024.118461

Mojaver, P., Khalilarya, S., Chitsaz, A., & Jafarmadar, S. (2024). Upcycling of biomass using gasification process based on various biomass types and different gasifying agents: systematic multi-criteria decision and sensitivity analysis. *Biomass Conversion and Biorefinery*, *14*(12), 13157–13171. doi:10.1007/s13399-022-03280-9

Mukundan, S., Wagner, J. L., Annamalai, P. K., Ravindran, D. S., Krishnapillai, G. K., & Beltramini, J. (2022). hydrothermal co-liquefaction of biomass and plastic wastes into biofuel: Study on catalyst property, product distribution and synergistic effects. *Fuel Processing Technology*, *238*. doi:10.1016/j.fuproc.2022.107523

Munasinghe, P. C., & Khanal, S. K. (2010, July). Biomass-derived syngas fermentation into biofuels: Opportunities and challenges. *Bioresource Technology*. doi:10.1016/j.biortech.2009.12.098

Ni, J., Qian, L., Wang, Y., Zhang, B., Gu, H., Hu, Y., & Wang, Q. (2022, November 1). A review on fast hydrothermal liquefaction of biomass. *Fuel*. Elsevier Ltd. doi:10.1016/j.fuel.2022.125135

Ozturk, M., Saba, N., Altay, V., Iqbal, R., Hakeem, K. R., Jawaid, M., & Ibrahim, F. H. (2017). Biomass and bioenergy: An overview of the development potential in Turkey and Malaysia. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2017.05.111

Panichkittikul, N., Mariyappan, V., Wu, W., & Patcharavorachot, Y. (2024). Improvement of biohydrogen production from biomass using supercritical water gasification and CaO adsorption. *Fuel*, *361*. doi:10.1016/j.fuel.2023.130724

Poornima, S., Manikandan, S., Prakash, R., Deena, S. R., Subbaiya, R., Karmegam, N., … Govarthanan, M. (2024, September 15). Biofuel and biochemical production through biomass transformation using advanced thermochemical and biochemical processes – A review. *Fuel*. Elsevier Ltd. doi:10.1016/j.fuel.2024.132204

Qiu, T., Li, C., Zhao, W., Naz, M. Y., & Zhang, Y. (2025). Microwave-assisted pyrolysis of biomass: Influence of feedstock and pyrolysis parameters on porous biochar properties. *Biomass and Bioenergy*, *193*. doi:10.1016/j.biombioe.2024.107583

Rawat, J., Jaiswal, K. K., Das, N., Kumar, S., Gururani, P., Bisht, B., … Kumar, V. (2023). Hydrothermal liquefaction of freshwater microalgae biomass using Fe3O4 nanoparticle as a catalyst. *Energy Sources, Part A: Recovery, Utilization and Environmental Effects*, *45*(4), 12988–13000. doi:10.1080/15567036.2023.2277892

Sallet, D., Ugalde, G. A., Tres, M. V., Mazutti, M. A., Zabot, G. L., & Kuhn, R. C. (2025). Oil and Biodiesel Production from Mortierella isabellina Biomass by a Direct Near-Critical Fluid Extraction and Transesterification Method. *Biomass (Switzerland)*, *5*(1). doi:10.3390/biomass5010006

Shen, Y., Wang, J., Ge, X., & Chen, M. (2016, June 1). By-products recycling for syngas cleanup in biomass pyrolysis - An overview. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2016.01.077

Singh, N., Kumar, K., Goyal, A., & Moholkar, V. S. (2022). Ultrasound-assisted biodiesel synthesis by in–situ transesterification of microalgal biomass: Optimization and kinetic analysis. *Algal Research*, *61*. doi:10.1016/j.algal.2021.102582

Soares Dias, A. P., Rijo, B., Ramos, M., Casquilho, M., Rodrigues, A., Viana, H., & Rosa, F. (2022). Pyrolysis of burnt maritime pine biomass from forest fires. *Biomass and Bioenergy*, *163*. doi:10.1016/j.biombioe.2022.106535

Soria-Verdugo, A., Cano-Pleite, E., Panahi, A., & Ghoniem, A. F. (2022). Kinetics mechanism of inert and oxidative torrefaction of biomass. *Energy Conversion and Management*, *267*. doi:10.1016/j.enconman.2022.115892

Suopajärvi, H., Umeki, K., Mousa, E., Hedayati, A., Romar, H., Kemppainen, A., … Fabritius, T. (2018, March 1). Use of biomass in integrated steelmaking – Status quo, future needs and comparison to other low-CO2 steel production technologies.

Applied Energy. Elsevier Ltd. doi:10.1016/j.apenergy.2018.01.060

Svedovs, O., Dzikevics, M., & Kirsanovs, V. (2023). Bibliometric Analysis of the Alternative Biomass Types and Biomass Combustion Technologies. *Environmental and Climate Technologies*, *27*(1), 559–569. doi:10.2478/rtuect-2023-0041

Tekin, K., Karagöz, S., & Bektaş, S. (2014). A review of hydrothermal biomass processing. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2014.07.216

Thirumalaivasan, N., Nangan, S., Kanagaraj, K., & Rajendran, S. (2024, September 1). Assessment of sustainability and environmental impacts of renewable energies: Focusing on biogas and biohydrogen (Biofuels) production. *Process Safety and Environmental Protection*. Institution of Chemical Engineers. doi:10.1016/j.psep.2024.06.063

Tripathi, M., Sahu, J. N., & Ganesan, P. (2016, March 1). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews*. Elsevier Ltd. doi:10.1016/j.rser.2015.10.122

Tshikovhi, A., & Motaung, T. E. (2023, August 1). Technologies and Innovations for Biomass Energy Production. *Sustainability (Switzerland)*. Multidisciplinary Digital Publishing Institute (MDPI). doi:10.3390/su151612121

Usino, D. O., Ylitervo, P., Moreno, A., Sipponen, M. H., & Richards, T. (2021). Primary interactions of biomass components during fast pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *159*. doi:10.1016/j.jaap.2021.105297

Verma, S., Dregulo, A. M., Kumar, V., Bhargava, P. C., Khan, N., Singh, A., … Awasthi, M. K. (2023). Reaction engineering during biomass gasification and conversion to energy. *Energy*, *266*. doi:10.1016/j.energy.2022.126458

Vo, T. A., Tran, Q. K., Ly, H. V., Kwon, B., Hwang, H. T., Kim, J., & Kim, S. S. (2022). Co-pyrolysis of lignocellulosic biomass and plastics: A comprehensive study on pyrolysis kinetics and characteristics. *Journal of Analytical and Applied Pyrolysis*, *163*. doi:10.1016/j.jaap.2022.105464

Wang, B., Liu, N., Wang, S., Li, X., Li, R., & Wu, Y. (2023). Study on Co-Pyrolysis of Coal and Biomass and Process Simulation Optimization. *Sustainability (Switzerland)*, *15*(21). doi:10.3390/su152115412

Wang, C., Zhu, C., Huang, J., Jin, H., & Lian, X. (2022). Gasification of biomass model compounds in supercritical water: Detailed reaction pathways and mechanisms. *International Journal of Hydrogen Energy*, *47*(74), 31843–31851. doi:10.1016/j.ijhydene.2021.12.008

Wang, Q., Zhang, X., Cui, D., Bai, J., Wang, Z., Xu, F., & Wang, Z. (2023, March 1). Advances in supercritical water gasification of lignocellulosic biomass for hydrogen production. *Journal of Analytical and Applied Pyrolysis*. Elsevier B.V. doi:10.1016/j.jaap.2023.105934

Wongsirichot, P. (2024, February 15). Development and future potential of Computation Fluid Dynamics for improved biomass hydrolysis. *Chemical Engineering Journal*. Elsevier B.V. doi:10.1016/j.cej.2024.149032

Worku, A. K., Ayele, D. W., Deepak, D. B., Gebreyohannes, A. Y., Agegnehu, S. D., & Kolhe, M. L. (2024, May 1). Recent Advances and Challenges of Hydrogen Production Technologies via Renewable Energy Sources. *Advanced Energy and Sustainability Research*. John Wiley and Sons Inc. doi:10.1002/aesr.202300273

Xiao, H., Wang, Y., Cai, Z., Zhang, J., & Yu, G. (2024). The synergistic effecting mechanisms of biomass pyrolysis, biomass char gasification, and biomass ash on CO2 co-gasification of biomass and high-sulfur petroleum coke. *Fuel*, *365*. doi:10.1016/j.fuel.2024.131203

Xia, Y., Zhang, J., Tang, C., & Pan, W. (2023, June 1). Research and application of online monitoring of coal and biomass co-combustion and biomass combustion characteristics based on combustion flame. *Journal of the Energy Institute*. Elsevier B.V. doi:10.1016/j.joei.2023.101191

Yan, B., Lv, J., Zhou, S., Wu, Z., Liu, X., Li, B., … Chen, G. (2024, May 1). Application of optical diagnosis technology in biomass combustion. *Biomass and Bioenergy*. Elsevier Ltd. doi:10.1016/j.biombioe.2024.107198

Yang, Yang, Zhang, M., Zhao, J., & Wang, D. (2023). Effects of particle size on biomass pretreatment and hydrolysis performances in bioethanol conversion. *Biomass Conversion and Biorefinery*, *13*(14), 13023–13036. doi:10.1007/s13399-021-02169-3

Yang, Yantao, Qu, X., Huang, G., Ren, S., Dong, L., Sun, T., … Cai, J. (2023). Insight into lignocellulosic biomass torrefaction kinetics with case study of pinewood sawdust torrefaction. *Renewable Energy*, *215*. doi:10.1016/j.renene.2023.118941

Zhang, S., Yu, S., Li, Q., Mohamed, B. A., Zhang, Y., & Zhou, H. (2022). Insight into the relationship between CO2 gasification characteristics and char structure of biomass. *Biomass and Bioenergy*, *163*. doi:10.1016/j.biombioe.2022.106537

Zhang, W., Fang, Y., Qian, S., Chen, Y., Li, X., & Liu, N. (2025). Biomass gasification to syngas of phosphogypsum as gasification agent: Thermogravimetric analysis and gasification performance. *Fuel*, *385*. doi:10.1016/j.fuel.2024.134065

Zhang, X., Wu, H., He, Z., Xie, L., Chang, Y., Jin, Z., & Jiang, X. (2025, February 19). Application of swirl intensification technology in thermochemical conversion of biomass to high-value bio-oil: A review. *Separation and Purification Technology*. Elsevier B.V. doi:10.1016/j.seppur.2024.128795

Zheng, H., Wang, Y., Feng, X., Li, S., Leong, Y. K., & Chang, J. S. (2022). Renewable biohydrogen production from straw biomass – Recent advances in pretreatment/hydrolysis technologies and future development. *International Journal of Hydrogen Energy*, *47*(88), 37359–37373. doi:10.1016/j.ijhydene.2021.10.020

Zhou, N., Zhang, Y., Wu, X., Gong, X., & Wang, Q. (2011). Hydrolysis of Chlorella biomass for fermentable sugars in the presence of HCl and MgCl 2. *Bioresource Technology*, *102*(21), 10158–10161. doi:10.1016/j.biortech.2011.08.051

Zhou, X., Zhao, J., Chen, M., Zhao, G., & Wu, S. (2022). Influence of catalyst and solvent on the hydrothermal liquefaction of woody biomass. *Bioresource Technology*, *346*. doi:10.1016/j.biortech.2021.126354

Zhuang, X., Liu, J., Wang, C., Zhang, Q., & Ma, L. (2022). Microwave-assisted hydrothermal liquefaction for biomass valorization: Insights into the fuel properties of biocrude and its liquefaction mechanism. *Fuel*, *317*. doi:10.1016/j.fuel.2022.123462

Zhu, Y., Zhao, Y., Tian, S., Zhang, X., & Wei, X. (2022). Catalytic hydrothermal liquefaction of sewage sludge: Effect of metal support heterogeneous catalysts on products distribution. *Journal of the Energy Institute*, *103*, 154–159. doi:10.1016/j.joei.2022.04.008

About The Author

Kerim MARTİN graduated from Selçuk University (Konya Technical) with a degree in Mechanical Engineering. He completed his master’s degree in Energy Systems Engineering at the Institute of Science at Necmettin Erbakan University and his doctorate in Energy Systems Engineering at the Institute of Science at Gazi University in 2021. From January 2023 to January 2024, he served as Doctor in the Mechanical Programme at Elbistan Vocational School, Kahramanmaraş İstiklal University. He was awarded the title of Associate Professor in August 2023 and served as an Associate Professor in

the Mechanical Programme at Kahramanmaraş İstiklal University Elbistan Vocational School from January 2024 to July 2025. Since July 2025, he has been serving as an Associate Professor at Necmettin Erbakan University Seydişehir Ahmet Cengiz Faculty of Engineering. He has published a total of 18 articles, including 10 in international peer-reviewed journals and 8 in national peer-reviewed journals. He has also presented 17 papers at international scientific conferences. According to Web of Science data, other authors have cited his publications 159 times. The number of citations on Google Scholar is 269.

E-mail: kmartin@erbakan.edu.tr, **ORCID:** 0000-0002-1960-8070

Similarity Index:

The similarity index obtained from the plagiarism software for this book chapter is 9%.