

CO-TORREFACTION OF BIOMASS AND PLASTIC WASTE: RECENT ADVANCES AND CIRCULAR ECONOMY PERSPECTIVES

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Abstract

The increasing problem of biomass residues from agriculture and plastic waste presents a challenge for sustainable waste management practices, which have to tackle issues of pollution and renewable energy production at the same time. Co-torrefaction is a new thermochemical pretreatment technique which shows potential in transforming these heterogeneous waste streams into energy-dense carbon-rich solid fuels that have improved physicochemical properties. It critically analyzes recent progresses in biomass-plastic co-torrefaction, considering the feedstock characteristics, thermal degradation mechanisms, synergistic interactions, reactor technologies, optimization of the process, characterization of the products and practical applications. Special attention is given on the effect of the process parameters such as temperature, residence time, biomass-to-plastic ratio and reactor configuration on the quality of the fuel, carbon retention, hydrophobicity, energy densification, and combustion performance. The review also underscores the potential of catalytic systems, microwave-assisted torrefaction, and data-driven optimization techniques to enhance the efficiency and quality of the torrefaction process. Furthermore, the different applications of co-torrefied products as solid biofuels, as gasification and pyrolysis bio-feedstocks, as activated carbons and as advanced carbon materials are discussed in detail. Circular economy principles, life-cycle assessment and techno-economic analysis, highlight the potential of co-torrefaction for resource recovery, and for minimizing reliance on fossil fuels, while achieving environmental sustainability. Although great advances have been made, problems with feedstocks that are not completely homogeneous, scaling up the reactor, durability of the catalysts, standardization of the products, and commercialization are not solved. Intelligent process control, further development of the reactors, standardized quality assessment and

integration with the new waste-to-energy technologies should be addressed in future research. In conclusion, biomass–plastic co-torrefaction is a promising and sustainable option for waste valorization, offering numerous benefits such as reduced reliance on fossil fuels and the creation of renewable energy.

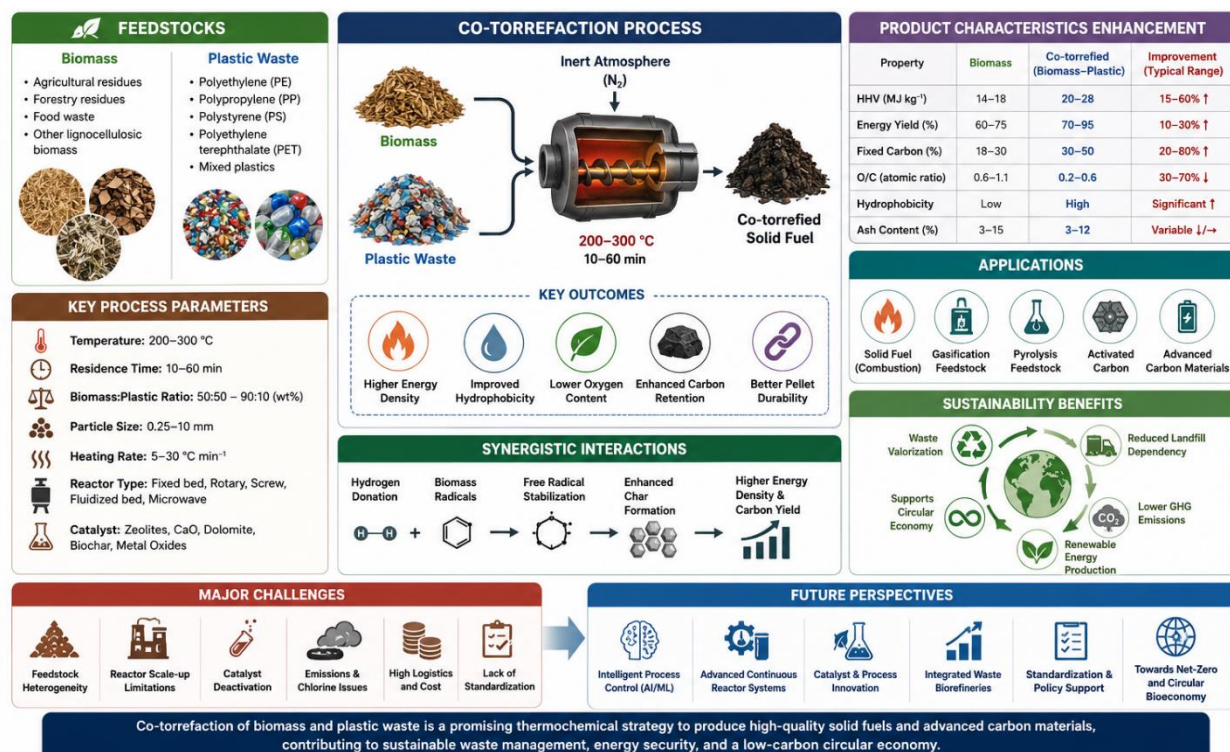


Figure 1 Graphical Abstract of the Study

INTRODUCTION

Increasing energy demand, speedy industrialization and population growth have led to the growth of biomass residues and plastic waste generation around the globe. Lignocellulosic residues generated during the agricultural processes such as rice husk, wheat straw, corn stover, sugarcane bagasse, and forestry residues, etc., annually generate several billion tons of biomass, of which only a small proportion is being utilized, or disposed of by open burning in fields. These practices are significant sources of Green House Gases (GHGs), particulate matter (PM) formation, and air quality degradation. At the same time, global plastic production has surpassed hundreds of millions of tons per year, and the rate

of plastic recycling is fairly low, resulting in the accumulation of long-lasting plastic waste in terrestrial and aquatic ecosystems (Saha et al., 2025). The traditional disposal options of landfill and incineration are becoming more environmentally problematic due to land space and toxic emissions as well as loss of resources. Such parallel waste streams are not only a heavy environmental load, but also a valuable carbon rich resource to be used for the generation of renewable carbon fuels and functional materials. Focus has increasingly turned to integrated waste valorization strategies which tackle the management of biomass residues, plastic waste and at the same time support the production of

renewable energy, resource efficiency and reduction of carbon emissions. The challenge of developing sustainable technologies to turn these heterogeneous waste resources into value added products has thus become a pressing need to advance circular resource utilization and make a step towards low carbon energy systems (Guo et al., 2023).

Torrefaction is a thermochemical pretreatment technology that has proven to be a viable technology to upgrade low-quality carbonaceous feedstocks to energy rich solid fuels. The process is typically carried out under an inert atmosphere and typically at temperatures between about 200 and 320 °C, and is selective for the decomposition of reactive components of biomass, mainly hemicellulose, while the cellulose and lignin structures are relatively preserved. The moisture content in the solid product is significantly decreased, the concentration of fixed carbon is increased, the hydrophobicity is increased, the grindability is improved and the higher heating value of the solid product is also increased (Granado, Conti, & Nanda, 2026). Torrefied biomass has better storage stability, lower transport costs and better suitability to existing coal-fired combustion and gasification facilities than untreated biomass. In recent years, however, the use of torrefaction has been extended to other waste materials such as plastic waste, with the aim of recovering the potential energy that is locked within the waste and to reduce the use of fossil energy sources. The versatility of torrefaction has also spurred the development of advanced reactor systems, catalytic processes, and microwave-assisted techniques that enhance process efficiencies and product quality. The process of torrefaction is attractive because of its low energy demand and ease of operation compared to high-temperature pyrolysis or gasification, making it potentially suitable for sustainable valorization of waste products, and a technology for producing upgraded fuels which can be used in high-temperature energy generation processes (Waheed, Naqvi, & Ali, 2022).

Biomass and plastic wastes have significant energy content, but there are some technical constraints for each of them being utilized separately. Raw biomass is typically high in moisture content, low in energy density, non-hydrophobic, and with a complex composition, while plastic waste is high in calorific value, low in oxygen, and has different thermal degradation properties (Adeleke et al., 2021). Co-torrefaction has thus received growing research focus as a method to take advantage of these complementary properties of these two feedstock classes. Carbon-carbon interactions between oxygenated compounds found in biomass and hydrogen-rich polymers of plastics during co-torrefaction can lead to synergistic effects to increase carbon retention, energy density, fuel quality, and the reduction of undesirable oxygen-containing functional groups in the final product (Moreira et al., 2024). The addition of plastics can also enhance mass yield, heating value and reduce some of the disadvantages of using torrefied biomass. In addition, co-processing is a comprehensive solution that can be used to process agricultural residues and post-consumer plastic waste together—a solution that facilitates resource recovery and minimizes environmental pollution. The effects of biomass type, plastic type, blending rate, reactor type and operating temperature on product properties have been shown in recent investigations, which emphasize the need to optimize the process conditions. In this context, co-torrefaction is a promising way to produce high quality solid fuels and to achieve sustainable waste management and renewable energy production (Mpungu et al., 2024).

This review will critically address recent progress in the co-torrefaction of biomass and plastic waste, focusing on the characteristics of the feedstock, potential reaction pathways, reactor technologies, process optimization and product characterization. It also analyzes the effect of operating conditions on fuel quality, reviews new applications of co-torrefied products and considers aspects of the environment, techno-economics and circular economy. Finally, current research gaps, technological challenges, and future

directions needed for the large-scale implementation and commercialization of the biomass-plastic co-torrefaction technology as a sustainable waste valorization technology are identified.

Fundamentals of Torrefaction

Principles and Mechanism of Torrefaction

Thermochemical conversion technology that involves heating carbonaceous feedstocks in an oxygen deficient or inert atmosphere to produce energy-rich solid fuels, called torrefaction. It is usually conducted at a temperature of 200-320 °C, at which not all the feedstock is converted, but only part. The purpose of torrefaction is different from combustion and pyrolysis, in which organic matter is fully oxidized and produced as a solid, respectively, in which it is reacted at much higher temperatures to maximize the production of liquid and gaseous products. When heating, free and bound moisture is removed, and then thermally unstable organic compounds are broken down, leading to the volatilization of water vapor, carbon dioxide, carbon monoxide, acetic acid, formic acid, methanol, and other light compounds containing oxygen (Rago, Collard, Görgens, Surroop, & Mohee, 2020). Hemicellulose has been degraded first and most, followed by cellulose to some degree, and finally, lignin is more resistant, due to its complex aromatic structure. The reactions gradually reduce the oxygen content to carbon, and the hydrogen to carbon ratio, increasing the carbon concentration and the calorific value of the torrefied material. The process also changes the pore structure, the hydrophobicity, increases the brittleness for easier grinding and the storage stability. Therefore, torrefaction has emerged as one of the pretreatment technologies of great interest for enhancing the fuel properties of various biomass

and waste-based feedstock (Lu et al., 2021).

Types of Torrefaction

The technology of torrefaction has developed significantly to suit various feed-stocks and industry needs, resulting in various process variants. The most common method is dry torrefaction, which involves heating of solid feedstocks in an oxygen-free atmosphere without the presence of water, yielding a carbon-rich solid material which has better fuel properties. Wet torrefaction (hydrothermal carbonization) is carried out in hot compressed water under high pressure, which is especially suitable for high moisture content biomass as the energy consumption required to dry the biomass prior to the torrefaction process can be reduced. Oxidative torrefaction involves the addition of carefully controlled amounts of oxygen to improve the process efficiency by partial exothermic reactions, however, it is necessary to be very careful in controlling the oxidation process and prevent the excess oxidation (Gizaw et al., 2024). Compared to the conventional heating technologies, the microwave-assisted torrefaction technology enables shorter torrefaction times, lower energy consumption, uniform and fast heating, etc. Catalytic torrefaction uses mineral or synthetic catalysts to increase the thermal decomposition rate, change the volatiles released and enhance the quality of the solid products. Recently, hybrid systems combining microwave technology, catalytic technology or hydrothermal technology have gained increasing attention due to the higher flexibility in process design, higher energy efficiency and higher product control over the characteristics of torrefaction products, which opens up the possibility for torrefaction of various biomass and plastic waste mixtures (Piersa et al., 2022).

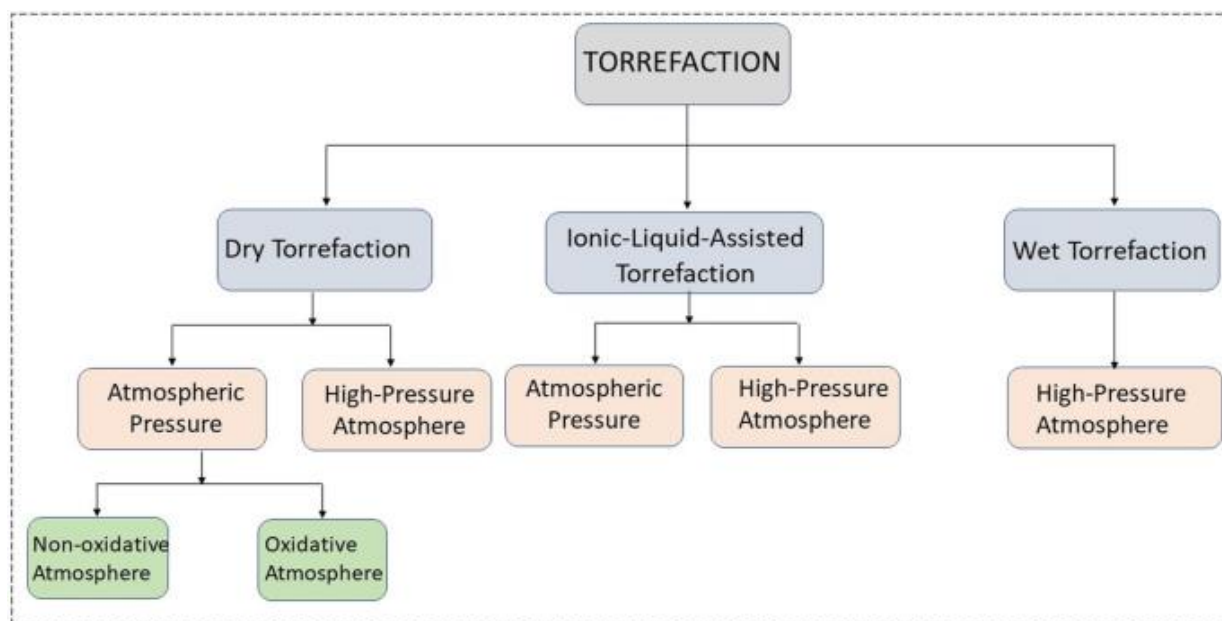


Figure 2 Classification flowchart of Torrefaction(Panwar & Divyangkumar, 2024)

Key Process Parameters

There are a number of operating parameters related to each other that determine the degree of thermal decomposition of the raw material and, therefore, the efficiency of the torrefaction process and the quality of the products. The most important variable is temperature, which has a significant effect on devolatilization, oxygen removal and carbon enrichment and is influenced by the increase of the temperature, but if the temperature is too high, it will significantly reduce the solid yield(Silveira, Luz, Candelier, Macedo, & Rousset, 2021). The residence time also has an important effect on the time of thermal exposure: longer times of thermal exposure generally lead to a better quality of fuel, but also to further loss of mass. The uniformity of the heat transfer and decomposition kinetics is affected by the heating rate: typically moderate heating rates give more uniform products than fast thermal treatment. The size of the feedstock has an influence on the internal heat and mass transfer: Smaller particles should be torrefacted faster and more evenly(Tumuluru, Ghiasi, Soelberg, & Sokhansanj, 2021). The composition of the

surrounding atmosphere (nitrogen, carbon dioxide, steam or recycled process gases) also affects the reaction pathways and volatiles evolution. Another parameter of importance for co-torrefaction systems is the biomass-to-plastic blending ratio that determines synergistic interaction, hydrogen transfer, and the product composition. Optimization of these variables is crucial to maximize energy yield, ensure sufficient solid recovery, enhance the higher heating value, lower oxygen content and create torrefied materials having properties suitable for the application of combustion, gasification or briquetting for downstream use(Cahyanti, Doddapaneni, & Kikas, 2020).

Chemical and Thermal Transformations

The torrefaction process causes a number of complex chemical and structural changes, thereby changing the composition and fuel properties of biomass and plastic feedstocks. Hemicellulose starts to break down at relatively low temperatures, depolymerizing and deacetylating to form CO₂, acetic acid, water and other oxygenated compounds, in lignocellulosic biomass. As the

severity of the processing increases, cellulose can be depolymerized, but lignin can be depolymerized more slowly in terms of breaking of ether linkages and retains a significant amount of its aromatic backbone. All of these changes cause the loss of hydroxyl and carboxyl functional groups, make it less hydrophilic, and increase the amount of aromatic carbon atoms (de Oliveira Brotto et al., 2023). Thermal properties vary from one type of plastic to another, depending on the structure of the polymer. The main mode of decomposition for polyethylene and polypropylene is random chain scission to yield hydrocarbon fragments with a high hydrogen content, while the main mode of decomposition for polyethylene terephthalate and polyvinyl chloride is through more complex means such as ester bond cleavage or dehydrochlorination, respectively (Massaro Sousa, Ogura, Anchieta, Morin, & Canabarro, 2024). The volatiles that are generated from biomass and plastics during co-torrefaction can participate in reactions with each other such as hydrogen transfer, radical stabilization, and secondary condensation reactions, which can result in higher carbon retention and better fuel quality. As a result of these physicochemical changes, torrefaction yields a solid product with higher fixed carbon, lower oxygen, better thermal stability, higher energy density and combustion performances than the untreated feedstocks, and thus, it is regarded as a promising upgrading process for heterogeneous waste resources (Olugbade & Ojo, 2020).

Biomass and Plastic Feedstocks

The efficiency of the co-torrefaction process and quality of the solid products obtained depend largely on the selection and properties of the feedstocks. Although biomass and plastic wastes are very different, both have complementary advantages and disadvantages in terms of their chemical composition, thermal properties and energy density that provide great potential for synergy in their conversion into valuable fuels. Biomass is one of the most abundant renewable carbon resources, and encompasses a variety of lignocellulosic materials produced through agriculture, forestry, industry and municipal activities. However, due to their high availability and relatively low market value, common agricultural residues like rice husk, wheat straw, corn stover, sugarcane bagasse, coconut shell, cotton stalk, sunflower stalk and oil palm residues are widely studied (Rago et al., 2020). Forestry residues, such as sawdust, wood chips, bark and pruning residues, have also been in great focus due to their relatively high lignin content and desirable fuel attributes. Other biomass feedstocks that can be used for thermochemical conversion have been increased, such as bamboo, miscanthus, switch grass, food wastes and sewage derived organic solids. Although there are many raw biomass materials available and are renewable, they often have a number of intrinsic disadvantages, such as high moisture content, low bulk density, high oxygen content, fibrous structure, hygroscopic properties, and relatively low calorific value. The major constituents of their chemical composition are cellulose, hemicellulose, and lignin, the amounts of which depend on the species of plants and their growth conditions (Guo et al., 2023).

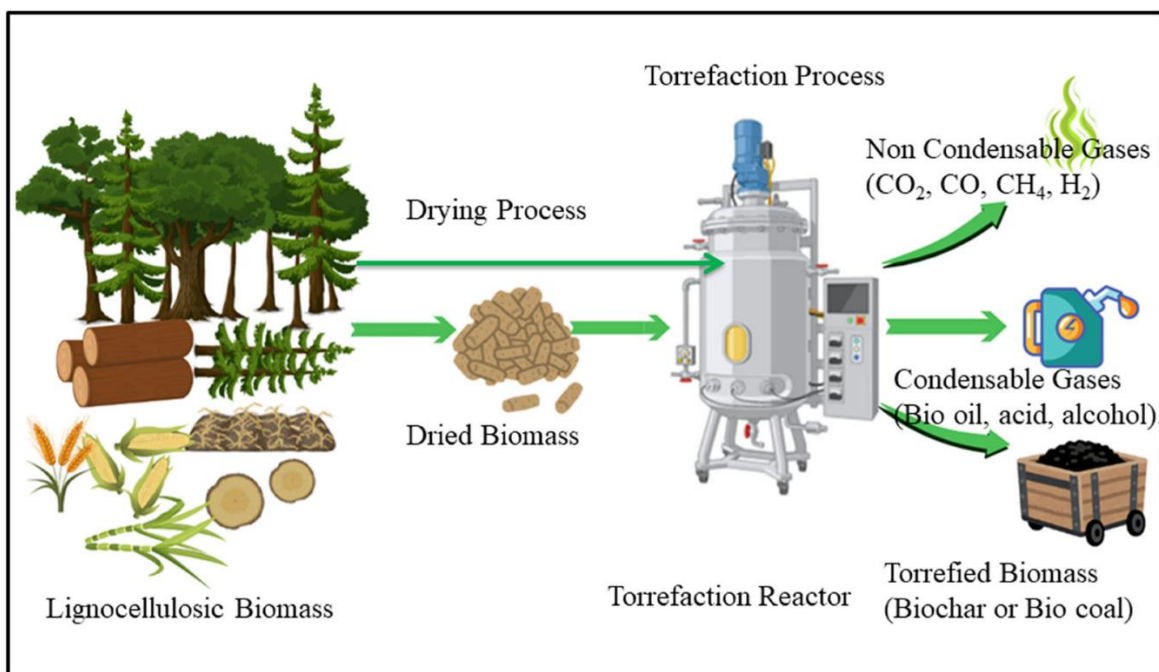


Figure 3 Torrefaction of Lignocellulosic Biomass: A Pathway to Renewable Energy(Chandrasekharan Nair, John, Geetha Bai, & Kikas, 2025)

Hemicellulose is the least thermally resistant, and it decomposes easily during torrefaction; cellulose is relatively thermally resistant, and lignin is part of the structure and fixed carbon of torrefied solid. The ash content, mineral composition and alkali metal concentration are additional parameters which also affect thermal degradation pathways, combustion behavior and ash-related operational problems. Therefore, it is important to know the composition of biomass to optimize the torrefaction conditions and to predict the performance of the product. Plastic waste has become another feedstock of relevance due to its high energy density and prevalence in municipal solid waste streams, which are dominated by carbon. Determination of high energy density and prevalence of plastic waste in municipal solid waste streams make it another carbon-rich feedstock(Potnuri et al., 2022). Industrialization, urbanization, and the rising demand for plastics has resulted in an ongoing surge in plastics production worldwide—and despite this, recycling

of many polymer categories has not proven to be effective. This generates a lot of plastics waste that is dumped in landfills, open burned or released into the environment, leading to long-term environmental pollution and substantial resource losses. Polyethylene (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and, to a lesser extent, polyvinyl chloride (PVC) are the most commonly explored plastics for co-torrefaction. Polyethylene and polypropylene are especially appealing as hydrogen donors in thermochemical conversion due to their high hydrogen to carbon ratio, low ash content and good calorific values(Allouzi, Lee, Gan, & Thangalazhy-Gopakumar, 2023).

PET materials also have oxygenated ester linkages that affect their decomposition products and distribution, while polystyrene has high energy density, but generates aromatic compounds upon decomposition. PVC is usually not used because the dehydrochlorination during heating, releases hydrogen chloride, which can cause equipment

corrosion, catalyst deactivation, and other environmental issues if suitable emission control equipment is not used. Application of mixed plastic waste streams (from household, commercial and industrial sources) has increased in importance due to their relative heterogeneity and the fact that they more closely reflect real-world waste management situations (Devaraja, Dissanayake, Gunarathne, & Chen, 2022). Co-torrefaction is the process where biomass is mixed with plastics and the complementary properties of both materials are used. While plastics contain high hydrogen atoms and high calorific value, which facilitates good interactions and results in high carbon retention, low oxygen content and high energy density, biomass contains oxygenated functional groups and a carbon framework that will be regenerated. These parameters, such as blending ratio, particle size distribution, moisture level, and compatibility of components, have a significant impact on heat transfer, volatile release and reaction rates, which in turn impact fuel quality and process efficiency. Selecting and blending appropriate feedstocks is therefore crucial to ensure a maximum synergistic effect, product consistency and to create an economically viable co-torrefaction system that can serve to simultaneously produce renewable energy and manage waste sustainably in the context of a circular economy (Xu et al., 2025).

Co-Torrefaction Process and Synergistic Mechanisms

Co-Torrefaction Process

Co-torrefaction is a thermochemical pretreatment method in which as the name implies, biomass and plastic wastes are both fed to a reactor, where

they are co-heated under an oxygen limited or inert atmosphere, to produce an upgraded solid fuel with improved physicochemical properties. Another approach is co-torrefaction, which makes use of the complementary properties of polymers and biomass, to enhance process efficiency and product quality, in contrast to traditional torrefaction, which handles a single feedstock. The method is usually a series of steps, such as: collecting feedstock, drying, crushing, homogenizing, blending at a targeted mass ratio, thermal treatment, cooling under an inert atmosphere, and final product characterization. Typical operating temperatures are from 220 to 320 °C, and the optimum temperature is dependent on the type of feedstock and the properties of the product (Liu et al., 2025). Both biomass and plastic materials will experience changes during the heating, such as dehydration of biomass, depolymerization, decarboxylation and devolatilization, and progressive softening, melting and initial chain scission of plastics, depending on polymer type. The process of evolution of condensable and non-condensable gases behind leaves a carbon enriched solid with higher energy density and lower oxygen than that of the condensables. Heat transfer and reaction progress is greatly affected by reactor configuration, residence time, heating rate and blending ratio. By controlling these operating conditions properly, it is possible to obtain torrefied solids with improved fuel properties (less moisture content, higher storage stability, better moisture repellency, and better suitability for combustion, gasification, or pelletization downstream) (Wang et al., 2025).

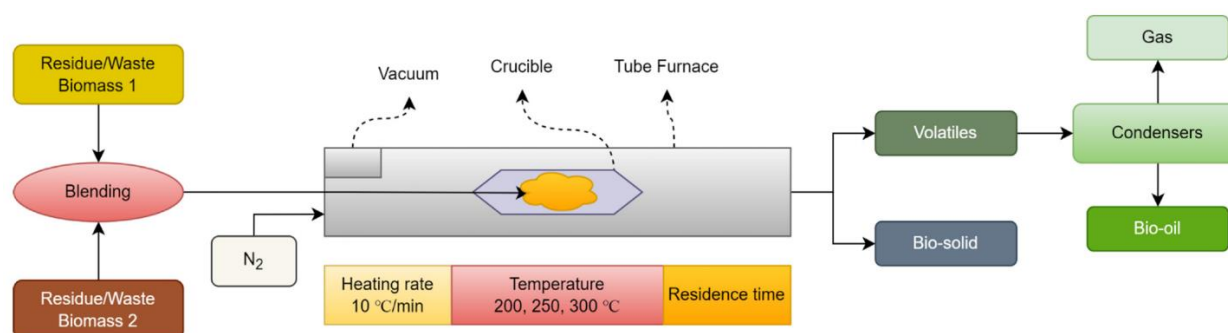


Figure 4 Co-Torrefaction Progress of Biomass(Cheong et al., 2022)

Thermal Degradation Behavior

Biomass and plastics have different molecular structures and have different thermal degradation characteristics, so simultaneous conversion strongly depends on the reaction temperature and the composition of the feedstocks. The degradation of biomass is a progressive process which starts with moisture evaporation, then hemicellulose degradation, partial degradation of cellulose, and gradual modification of the structure of lignin. The least thermally stable fraction is hemicellulose, which breaks down first to form carbon dioxide, water vapor, acetic acid and other oxygenated volatiles. Cellulose breaks down over a relatively broad temperature range via depolymerization reactions, while the lignin undergoes slow depolymerization of ether and carbon-carbon bonds leading to the development of aromatic carbon structures in the solid residue. There are various ways in which the plastic polymers can be broken down(Oliver, Conesa, & Fullana, 2024). In polyethylene and polypropylene, the dominant depolymerization pathways are random chain scission to yield hydrocarbon fragments containing a high proportion of hydrogen, whereas the depolymerization of polystyrene is mostly to aromatic fragments. The degradation of polyethylene terephthalate occurs by cleavage of the ester linkages, while the degradation of polyvinyl chloride begins with the release of hydrogen chloride and continues. Co-torrefaction is a process where the overlapping decomposition

intervals enable interactions between oxygenated compounds produced from biomass, and hydrocarbons from plastics, altering volatiles evolution and carbon retention. This degradation profile in turn will depend not only on the characteristics of the individual feedstock but also on intermolecular interactions that modify the rate of degradation, the thermal stability of the feedstock and the composition of the gaseous and solid products(Vanapalli et al., 2021).

Synergistic Interactions Between Biomass and Plastics

Co-torrefaction is the greatest benefit of synergy between biomass and plastic feedstocks during torrefaction. These interactions are not simply due to the independent decomposition of each material, but can actually result in solid fuels whose properties are better than those expected from the additive properties of the individual materials. One of the most important mechanisms is hydrogen transfer from hydrogen rich plastic polymers to oxygenated biomass intermediates, thus hydrogenation reactions and reduction of the excess carbon loss. This interaction leads to decreased formation of oxygen carriers and more carbon in the torrefied product and calorific value(Mamvura & Danha, 2020). At the same time, free radicals produced during biomass thermal decomposition might be neutralized by hydrocarbon fragments produced from plastics to prevent secondary cracking reactions and improve solid yield. The melting of thermoplastic polymers

also promotes the contact of feedstock particles, which will provide better heat transfer and promote more uniform reaction throughout the biomass matrix. Such synergies lead to higher energy yield, better hydrophobicity, reduced equilibrium moisture uptake and better grindability and thermal stability than torrefaction of biomass alone. These advantages are greatly dependent on the type of polymer, composition of the biomass, feedstock blend ratio, and the operating temperature. Therefore, it is important to understand these physicochemical interactions to design co-torrefaction systems to produce high quality renewable solid fuels with reproducible performance(Seshasayee & Savage, 2021).

Reaction Kinetics and Energy Balance

Reactional kinetics and energy balance are essential issues to consider for process efficiency and optimization of industrial co-torrefaction processes. Thermal decomposition reactions of biomass and plastics are multi-parallel and multi-consecutive reactions, and kinetic evaluation is crucial for understanding the reaction behavior under various operating conditions. The activation energy will change depending on the composition of feedstock, blending ratio, heating rate, and reaction temperature because each component of the feedstock will degrade in a

specific manner. Most of the biomass components have relatively low thermal stability, which means that they tend to decompose in a sequential manner affecting the overall kinetic profile of the biomass blends(Unyay et al., 2023). The activation energy, reaction order and conversions rates were estimated using various kinetic approaches such as model-fitting and model-free methods which are useful for further design of a reactor and process simulation. Co-torrefaction, from an energy point of view, aims to achieve the optimal energy densification with the minimum unnecessary mass loss. Engineered to achieve higher energy density, while still yielding a significant amount of solids, partial devolatilization necessarily lowers the amount of solids made, but the remaining solids are highly energy-dense, with a higher concentration of fixed carbon(Sarker, Nanda, Dalai, & Meda, 2021). The additional chemical energy in plastics can be attributed to the high hydrogen and carbon content which partly offsets mass losses of the biomass and thus boosts the overall energy yield from the torrefied material. As a consequence, extensive mass and energy balance studies are essential to reveal aspects of process sustainability, economical viability and optimization of process operating conditions needed for efficient large-scale waste valorization(Zhao, Chen, & Wang, 2025).

Table 1 Comparative Summary of Representative Published Studies on Biomass-Plastic Co-Torrefaction

Study	Biomass Feedstock	Plastic Feedstock	Reactor	Temp (°C)	Residence Time (min)	Plastic Ratio (%)	HHV (MJ kg ⁻¹)	Energy Yield (%)	Key Findings
(Imdad, Yadav, Vaidya, & Joshi, 2026)	Fungus bran	Polypropylene (PP)	Fluidized-bed	230.68	30	20	24.13	92.90	Multi-objective optimization produced fuel comparable to peat/lignite; PP acted as binder and

Study	Biomass Feedstock	Plastic Feedstock	Reactor	Temp (°C)	Residence Time (min)	Plastic Ratio (%)	HHV (MJ kg ⁻¹)	Energy Yield (%)	Key Findings
									reduced ash by 15.71%.
Guo et al. (2023)	Fungus bran	Polypropylene (PP)	Fluidized-bed	220	30	20	23.18	88.17	Optimization prioritizing energy yield produced high-quality briquettes with reduced ash (8.22 wt%).
Guo et al. (2024)	Fungus bran	Polypropylene (PP)	TG-FTIR combustion evaluation	220–300	—	10–20	—	—	PP addition and torrefaction improved combustion index, activation energy, pellet quality and combustion stability.
(Guo, Deng, Liu, Ge, & Lisak, 2024)	Polypropylene	—	Low-temperature thermal treatment	220–300	30–60	100	High calorific polymer	—	Demonstrated PP possesses substantially higher calorific value than lignocellulosic biomass, explaining the increase in HHV during co-torrefaction.
(Raj, Jain, &)	Rice husk	—	Conventional	220–300	30–60	—	13.48 – 17.88	64.82 – 78.96	Increasing temperature increased

Study	Biomass Feedstock	Plastic Feedstock	Reactor	Temp (°C)	Residence Time (min)	Plastic Ratio (%)	HHV (MJ kg ⁻¹)	Energy Yield (%)	Key Findings
Sharma, 2026)			torrefaction						HHV but reduced energy yield due to devolatilization.
(Wu et al., 2023)	Corn straw	—	Conventional torrefaction	275–375	60–120	—	16.90 – 19.80	35.40 – 66.20	Severe torrefaction enhanced carbonization but significantly reduced solid yield.
(Wang et al., 2025)	Wheat straw	—	Conventional torrefaction	250–300	30	—	19.17 – 24.32	64.91 – 80.80	Moderate temperatures produced the best balance between HHV and energy yield.
(Gizaw et al., 2024)	Bamboo residue	—	Conventional torrefaction	200–300	60	—	17.57 – 21.96	64.72 – 90.25	Low-temperature torrefaction preserved energy while improving fuel quality.
(Manatunga, Chalemsinsuwan, Kaewtrakulchai, Chao, & Li, 2023)	Agrobyproducts	—	Oxidative torrefaction	210–290	60	—	Increase of 0.14–20.02 %	63.78 – 96.93 %	Oxidative torrefaction improved calorific value while maintaining relatively high energy yields under optimized conditions.

Study	Biomass Feedstock	Plastic Feedstock	Reactor	Temp (°C)	Residence Time (min)	Plastic Ratio (%)	HHV (MJ kg ⁻¹)	Energy Yield (%)	Key Findings
(Guo et al., 2024)	Fungus bran + PP	Polypropylene	Fluidized-bed	192.7–327.3	19.8–70.2	6.6–23.4	R ² = 0.852 (HHV model)	R ² = 0.964 (EY model)	Response Surface Methodology accurately predicted HHV, mass yield and energy yield for process optimization.

Reactor Technologies and Process Optimization Reactor Configurations

The co-torrefaction is influenced by the reactor design, which has a significant effect on heat transfer, residence time, product uniformity and the overall energy efficiency. Fixed-bed reactors have been the most commonly used reactors in laboratory studies for their simplicity, ease of temperature control and the ability to assess the effect of operating parameters under well-controlled conditions. Yet a few studies have been conducted, reporting that a non-uniform torrefaction is likely to occur in fixed-bed systems when treating mixtures of heterogeneous biomass and plastics, especially at higher particle sizes, due to the formation of internal temperature gradients. Therefore, continuous mixing will improve heat transfer and ensure a homogeneous conversion of mixed feedstocks, so that rotary kiln reactors have gained more and more attention. Fluidized-bed reactors offer even higher heat transfer coefficients and shorter heating times, allowing for rapid and even treatment of mixtures of materials, without overheating (Panwar & Divyangkumar, 2024). Recent years have seen screw and auger reactors show great promise for continuous industrial processing due to the ability to control solids transport and to achieve reasonably stable residence times and relatively low operating complexity. Another major

improvement has been the introduction of microwave assisted reactors, which achieve volumetric microwave heating, reducing the thermal gradient and processing time over and above that which is possible using conventional conductive heating. Fixed-bed reactors are always essential for laboratory studies, while continuous rotary, screw, and microwave reactor systems offer better scalability, improved product consistency, and improved energy efficiency, making them better suited for commercial biomass-plastic co-torrefaction processes (Raj, Jain, & Verma, 2026).

Influence of Operating Parameters

The torrefaction temperature is the most significant variable of operation with respect to the product quality. The experimental studies have demonstrated that the increase of treatment temperature from around 220-240 °C to 280-300 °C can achieve higher fixed carbon content and higher heating value, but also cause the mass yield to decrease due to increased devolatilization. The same trend occurs with residence time, as increasing the time spent in the hot zone will yield more deoxygenation and more aromatic carbon, but also result in some additional loss of solids beyond the optimum range of processing time. Another important factor to consider is the blending ratio of feedstocks, which determines synergistic performance. The studies on

polyethylene and polypropylene showed that there were better fuel quality improvements than the oxygen containing plastics as they are rich in hydrogen which is required for the deoxygenation of biomass-derived intermediates. The size of the particles affects the internal heat transfer, where a fine particle size feedstock gives a more uniform torrefaction and a lesser temperature gradient (Xu et al., 2025). Volatile evolution and the secondary reactions are influenced by the heating rate, while oxygen exclusion and removal of condensable products are influenced by inert gas flow. These variables, in turn, collectively control the energy densification, hydrophobicity, grindability and carbon recovery. Comparative investigations also highlight that, rather than optimizing a single parameter, it is important to consider the balance between energy enhancement and the acceptable solid yield—otherwise, high severity in the torrefaction process can adversely affect the economics of the conversion process as a whole (Lu et al., 2021).

Catalytic and Microwave-Assisted Co-Torrefaction

Two promising methods for enhancing biomass-plastic thermochemical conversion are catalytic and microwave-assisted methods. Unlike conventional external heating, microwave heating heat is generated by the material, which is also called the volumetric heating, greatly reducing the heat transfer limitation, and the processing time is short. Recent investigations have shown that microwave-assisted thermochemical processing can provide increased uniformity of temperature, more efficient energy utilization and provide torrefied materials that yield higher energy content and have better fuel characteristics than those produced by the traditional approach when operating under similar conditions. Catalytic systems further aid in conversion by promoting deoxygenation, hydrogen transfer and selective cracking reactions (Cheong et al., 2022). Materials such as zeolites, activated carbon, biochar-based catalysts, dolomite and metal oxides have been extensively studied for their potential oxygenated

compound reduction and hydrocarbon formation and carbon retention. Studies with biomass-polyethylene mixtures have revealed that the type of catalyst used can significantly affect the product distribution and the properties of the solid product, porous catalysts favoring higher levels of aromatic products and improvement of the solid quality. The present investigations also suggest that microwave irradiation coupled with catalytic combustion is synergistic, i.e., it enhances the reaction rate, increases the efficiency of the catalyst and lowers energy use. Despite promising laboratory results, however, problems such as catalyst deactivation due to formation of coke, the necessity of regenerating the catalyst, and reactor integration are significant obstacles to commercial-scale implementation (Raj, Jain, & Sharma, 2026).

Process Optimization Approaches

There has been a recent trend in the research of determining individual operating variables and more recently in optimizing processes using integrated statistical and computational methods. One of the most popular method for achieving simultaneous optimization of temperature, residence time, blending ratio and heating rate with minimum number of experimental runs is Response Surface Methodology (RSM). It has been shown that interactions between process parameters often have a more significant effect on product quality than do individual process parameters acting alone by multi-variable optimization (Chen & Felix, 2024). Experimental data have also been used to predict higher heating value, mass yield, fixed carbon content and energy yield with high predictive accuracy, by using Artificial Neural Networks (ANNs). More recently, machine learning algorithms coupled with the particle swarm optimization, GAs and GPRs have led to rapid prediction of optimum operating conditions, while significantly decreasing the need for experimentation (Manatura et al., 2023). The data-driven approaches have demonstrated a capability to predict key product characteristics with high prediction coefficients ($R \geq 0.90$) in biomass-polymer thermochemical systems,

showing their potential of system modelling and scale-up. The growing significance of digital process control, real-time sensor integration and the use of digital twin technologies in improving operational stability and industrial automation are also highlighted in current reviews. These trends collectively suggest that co-torrefaction plants in

the future will increasingly depend on the intelligence of the optimization platforms, which can help maximize energy recovery, minimize operational costs and improve the consistency of the product with variable feedstocks (Viegas, Nobre, Correia, Gouveia, & Gonçalves, 2021).

Table 2 Influence of Process Parameters on the Characteristics of Co-Torrefied Products

Process Parameter	Typical Operating Range	Mass Yield (%)	Energy Yield (%)	HHV (MJ kg ⁻¹)	Fixed Carbon (%)	Hydrophobicity	Ash Behavior	Major Physicochemical Changes	Recommended Operating Window	References
Temperature	200–320 °C	95 → 50	95 → 65	17 → 28	18 → 45	Significantly increases due to removal of hydroxyl groups	Apparent ash concentration increases because of volatile loss	Strong deoxygenation, hemicellulose decomposition, aromatic carbon formation, increased carbonization	250–290 °C provides the best compromise between energy densification and solid recovery.	(Viegas et al., 2021)
Residence Time	10–60 min	90 → 60	93 → 72	19 → 25	22 → 40	Improves progressively with longer exposure	Minor influence	Greater devolatilization, increased carbon enrichment, lower O/C ratio	20–40 min generally maximizes fuel quality while limiting excessive mass loss.	(Potnuri et al., 2022)

Process Parameter	Typical Operating Range	Mass Yield (%)	Energy Yield (%)	HV (MJ kg ⁻¹)	Fixed Carbon (%)	Hydrophobicity	Ash Behavior	Major Physicochemical Changes	Recommended Operating Window	References
Heating Rate	5–30 °C min ⁻¹	70–90	75–92	20–25	24–38	Moderate improvement	Negligible effect	Controls volatile release, pore development and heat-transfer uniformity	10–20 °C min ⁻¹ is widely adopted for homogeneous torrefaction.	(Unyay et al., 2023)
Biomass:Plastic Ratio	90:10 to 50:50	65–90	75–95	21–30	28–46	Strongly enhanced because molten plastics reduce moisture uptake	Plastics dilute mineral ash in many blends	Higher hydrogen transfer, reduced oxygen content, improved carbon retention and pellet strength	80:20 or 70:30 frequently provides the best balance between fuel quality and process stability.	(Grana et al., 2026)
Particle Size	0.25–10 mm	70–88	78–92	20–25	25–38	Slight improvement	No significant change	Smaller particles improve internal heat transfer and conversion uniformity	1–3 mm is generally preferred for laboratory and pilot-scale reactors.	(Grana et al., 2026)

Process Parameter	Typical Operating Range	Mass Yield (%)	Energy Yield (%)	HHV (MJ kg ⁻¹)	Fixed Carbon (%)	Hydrophobicity	Ash Behavior	Major Physicochemical Changes	Recommended Operating Window	References
Carrier Gas Atmosphere	N ₂ , CO ₂ , Steam	65–90	72–93	20–27	24–40	Moderate improvement	Limited influence	Nitrogen minimizes oxidation; CO ₂ and steam modify devolatilization and gas evolution	Nitrogen remains the most widely used atmosphere for controlled co-torrefaction.	(Silveira et al., 2021)
Reactor Type	Fixed-bed, Rotary kiln, Screw, Fluidized-bed, Microwave	60–90	70–95	21–29	26–43	Depends on heating uniformity	Depends on feedstock mixing	Reactor design governs temperature uniformity, residence-time distribution and product consistency	Continuous rotary, screw, and microwave systems show superior industrial potential compared with batch fixed-bed reactors.	(Massaro Sousa et al., 2024)
Catalyst Addition	Biochar, Zeolite,	60–88	72–94	23–30	30–47	Improves through	Can reduce problem	Promotes hydrogen transfer,	Zeolites and biochar	(Tumuluru et

Process Parameter	Typical Operating Range	Mass Yield (%)	Energy Yield (%)	HV (MJ kg ⁻¹)	Fixed Carbon (%)	Hydrophobicity	Ash Behavior	Major Physicochemical Changes	Recommended Operating Window	References
	Dolomite, CaO, Metal oxides					enhanced deoxygenation	aromatic species depending on catalyst	catalytic cracking, oxygen removal and aromatic carbon formation	-derived catalysts are among the most effective for improving fuel quality and carbon retention.	al., 2021)

Characterization and Properties of Co-Torrefied Products

Fuel Properties

The most important criterion for evaluating the effectiveness of biomass-plastic co-torrefaction process still being fuel property evaluation. Co-torrefaction has yielded solid fuels with significantly higher calorific values than biomass feedstocks in a diverse set of feedstocks. Typically, raw agricultural residues have heating values in the range of 14–19 MJ kg⁻¹, but the addition of polyethylene, polypropylene or polystyrene can often increase the calorific value of the torrefied products to >22 MJ kg⁻¹, with some biomass-plastic mixtures reaching calorific values similar to those of low-rank coal. For wood/polyolefin blends, significant decreases in oxygen content and corresponding increases in fixed carbon content have been found with an improvement in energy densification ratios. The fixed carbon to volatile matter ratio (Fuel ratio) is generally improved with increasing severity of torrefaction, which means that combustion stability is increased

and combustion is slowed (Nwabunwanne et al., 2021). Another significant improvement is the decrease in the equilibrium moisture uptake. Co-torrefied products are much more hydrophobic than the untreated biomass, as functional groups that contain hydroxyl groups are removed by the process and melted plastic fractions cover the surfaces of biomass. This property is beneficial for storage and reduces degradation from biological sources in long-term storage. Moreover, it has been repeatedly observed that downstream fuel processing and production of pellets is made easier due to the increased brittleness and decreased grinding energy requirements. All of these enhancements show that co-torrefaction is a process that can yield solid fuels that are increasingly similar to those derived from fossil fuels (Guo et al., 2024).

Physicochemical Characterization

Physicochemical characterization is important to get the information about the changes in the fuel composition during co-torrefaction and as the

basis of the evaluation of the efficiency of the fuel upgrading. The amount of volatile matter always decreases with increasing torrefaction severity while the proportion of fixed carbon increases. Blends of biomass with plastics, when torrefied under moderate conditions, often yield high energy content, which is the main requirement for a biofuel, and good carbon enrichment (Azarpour, Zendeboudi, & Saady, 2025). Another feature of the Ultimate analysis is that it shows a progressive decrease in the amount of oxygen present and the oxygen-to-carbon atomic ratio, which directly increases the heating value and the combustion performance. Van Krevelen analysis has proved to be especially helpful for showing such changes in composition; as the deoxygenation progresses co-torrefied products are generally found to be in the coal side of the diagram. However, the ash content is very much biomass dependent as agricultural residues may have higher amounts of silica, potassium and calcium than woody materials (Nwabunwanne et al., 2021). Generally, the introduction of plastics into the fuel results in a reduction of minerals that form ash in the fuel and an improvement in fuel quality. There are also marked enhancements when compared to raw biomass, as shown in bulk density and energy density measurements, especially if thermoplastic polymers are added. The softened plastic phase provided an intrinsic binder in the densification process and in several investigations, the pellets were found to be stronger with improved durability. These physicochemical changes play a key role in evaluating the potential of co-torrefied products for transportation, storage, combustion and industrial fuel uses (Y. L. Lin, Zheng, Lin, & Chang, 2025).

Structural and Morphological Analysis

The structural and morphological characterization techniques have given a valuable insight into the mechanisms involved in the fuel upgrading process in co-torrefaction. Thermal treatment is always shown to result in a decrease in hydroxyl, carbonyl and carboxyl functional groups as consistently revealed by Fourier Transform

Infrared Spectroscopy (FTIR) analyses. At the same time, many times higher amounts of aromatic carbon signals appear, reflecting the continuing carbonization and structure stabilization. The X-ray diffraction analysis has shown some disruption of the crystalline cellulose structure in biomass and an increase of amorphous carbon content with severity of torrefaction (Sukiran et al., 2021). In many cases the changes in surface morphology, such as the appearance of cracks, pores and fragmented structures, due to the release of volatiles and degradation of the cell wall are particularly discernible in Scanning Electron Microscopy (SEM) images. For biomass-plastic blends, SEM images can frequently show that surface voids are partially filled and polymer is also present on the surfaces of the biomass particles leading to more compact and homogeneous structures. The treatment has also been shown to increase the aromaticity and structural ordering of the carbon matrices by Raman spectroscopy. The trends that have been reported for Brunauer-Emmett-Teller (BET) surface area, as a function of feedstock composition and process conditions, have been different, but moderate increases in porosity have often been achieved due to devolatilization. Overall, these characterization techniques have shown that co-torrefaction process causes significant structural reorganization, which can ultimately lead to better fuel properties, decreased hydrophilicity and increased thermal stability (Vasileiadou, 2024).

Thermal Stability and Combustion Performance

Co-torrefaction has always been shown to have a positive impact on the thermal characteristics of biomass fuels, as indicated by thermogravimetric and combustion tests. When using Thermogravimetric Analysis (TGA), typically the moisture content will be low in the low-temperature end, and thermally unstable compounds will be removed during torrefaction, which results in lower mass loss in that range. The initial decomposition step is generally a higher temperature suggesting higher thermal stability

and increased resistance to premature decomposition. The peak intensities from Differential Thermogravimetric (DTG) curves for hemicellulose breakdown are also found to be reduced, indicating that significant devolatilization has already taken place during the pretreatment (Zheng, Lee, & Lin, 2020). Co-torrefied products also have higher ignition temperature and longer burn-out time, which is also consistent with their higher fixed carbon content and better fuel quality as indicated by combustion studies. Plastic derived hydrocarbons are often present, and increase the stability of the flame and provide additional energy during combustion. There have been several investigations that have found that the amount of smoke formed and the combustion efficiency is improved over raw biomass fuels. In addition, lower oxygen levels and higher carbon levels will help to achieve more complete combustion and increase the energy release. Co-combustion tests using coal have also shown good compatibility and co-torrefied fuel combustion characteristics are very close to those of traditional fossil fuels. The results indicate the potential of co-torrefied products as stable solid fuels for industrial boilers and power generation systems, and for other thermochemical energy conversion processes (Y.-L. Lin & Zheng, 2021).

Application of Co-Torrefied Products

Solid Biofuel Production

The most studied potential use for co-torrefied biomass-plastic products is in the high quality solid biofuels for domestic heating, industrial boilers, cement kilns and coal firing power plants. Several studies have shown that mixing biomass with other plastics that contain hydrogen, like polyethylene (PE) and polypropylene (PP), in the torrefaction process has a beneficial effect on the quality of the solid product. The energy density, equilibrium moisture uptake and oxygen content of co-torrefied fuels is higher and lower than of untreated agricultural residues, respectively, and the fixed carbon content is higher, which renders them less susceptible to biological degradation

during storage. Improved hydrophobicity reduces reabsorption of moisture and results in little deterioration during long distance transport and outdoor storage. Moreover, better grindability decreases milling energy consumption before combustion and higher fuel chain handling is easier due to higher pellet durability. A number of combustion studies have also indicated that co-torrefied pellets have combustion properties similar to low rank coals, meaning that it is possible to replace a fraction of coals without significant changes to the combustion processes and equipment. These benefits can draw the attention of companies towards co-torrefied fuels for decentralized and decarbonized heat and electricity generation as well as valorization of agricultural residues and post-consumer plastic waste (Zore et al., 2026).

Gasification and Pyrolysis Feedstock

The co-torrefied products have proven to show high potential as upgraded feedstocks for gasification and pyrolysis, because of their higher thermal stability and optimized chemical composition. The removal of a significant amount of functional groups containing oxygen before the secondary thermochemical conversion in the torrefaction process leads to reduced tar and tar yield in the gasification process, which leads to process efficiency. The higher fixed carbon content and calorific value leads to higher syngas productivity and stable operation of the reactor. In pyrolysis applications, the biomass-plastic co-torrefied feedstocks typically yield bio-oils with a lower oxygen content and higher heating value than biomass feedstocks (Nwabunwanne et al., 2021). Hydrogen-rich plastics facilitate the deoxygenation reactions and result in the creation of hydrocarbon-rich liquid fractions. In addition, several investigations have been conducted and reported results of reduced water content and acidity in pyrolysis oils, which improves the stability of storing the oil and its need for upgrading. Moreover, co-torrefied materials have a uniform composition which helps to minimize the bridging and inconsistent flow frequently

observed with raw fibrous biomass in continuous reactors. Co-torrefied feedstocks are especially well suited for integrated thermochemical biorefineries for producing renewable fuels and chemicals, owing to these characteristics(Wu et al., 2023).

Carbon Materials and Activated Carbon

The carbon-enriched structure of co-torrefied products makes the material a good precursor for further production of activated carbon and other advanced carbon materials. The devolatilization and carbonization that occurs during the torrefaction process makes it more aromatic and more carbonized, which results in favorable conditions for subsequent physical and/or chemical activation. The co-torrefied biomass-plastic mixture has been proven to yield activated carbon with a well-developed pore structure, high adsorption capacity and good mechanical stability. These materials have shown to be effective for the removal of heavy metals, dyes, pharmaceutical contaminants and organic pollutants from wastewater. Additionally, the use of plastic derived carbon results in improved structural integrity and carbon yield in activation process. In addition to environmental remediation, co-torrefied carbon materials have been called to serve as energy storage materials such as electrodes for supercapacitors and lithium-ion batteries, due to their conductive carbon framework, and tunable pore properties. Their applications as a catalyst support and carbon dioxide adsorbents have also been investigated. The co-torrefaction of high value applications, which are much more than just fuel production, greatly increase the economic potential of co-torrefaction(Biswas & Chen, 2025).

Environmental and Industrial Applications

In addition to energy production, co-torrefied products have a wide range of environmental and industrial uses which enable sustainable resource management and circular economy goals. They consume significant amounts of ag residues and plastic waste, which helps to avoid landfill and open burning, thereby lowering the amount of

greenhouse gas emissions, particulate pollution and uncontrolled waste. Co-torrefied fuels are more compatible and efficient to be combusted in high volume industrial plants that require thermal energy, such as cement production, steel processing, brick production and lime kilns, and therefore more attractive as a partial coal replacement(Mutamima et al., 2025). Furthermore, it has been found that the torrefied carbon materials can be used for wastewater treatment, soil remediation and purification of industrial gases as adsorbents. They also have superior hydrophobicity and chemical stability, which makes them ideal for long-term storage and transportation of biomass as opposed to untreated biomass. Recent sustainability evaluations have shown that the co-torrefaction process provides a chance to simultaneously increase resource recovery, decrease virgin fossil fuels consumption, and increase the overall economic value of bio-wastes and plastic waste streams. Co-torrefied products are thus increasingly being considered as a versatile material that can be used for renewable energy production and in industrial decarbonization strategies(Granado et al., 2026).

Circular Economy and Sustainability Perspectives

Waste Valorization

Co-torrefaction of two of the world's largest waste streams, namely, the lignocellulosic biomass and the post-consumer plastics, has been shown to be an effective waste valorization pathway to produce value-added carbonaceous fuels. Agricultural residues and plastic wastes are not landfilled, burned or dumped, but rather reused as a secondary raw material in the production process. This will ensure that the carbon is used to its full extent and minimize wastage that needs to be disposed of at the end of the day. Industrial feasibility studies show that co-torrefaction can significantly enhance the amount of resources recovered in the municipal solid waste and agro-industrial waste management processes, and it enables to achieve closed loop material utilization,

in line with the principles of circular economy(Lee et al., 2024).

Environmental Benefits

Co-torrefaction is not only beneficial to the environment in the production of renewable fuels. The process reduces CH₄ emissions from biomass decomposition, reduces the particulate pollution from open field burning, and eliminates the waste of persistent plastics in aquatic systems and landfill. The conversion of biomass into energy-dense, hydrophobic fuels also enhances transportation efficiency and decreases energy use for biomass storage and logistics. In addition, the use of co-torrefied fuels for a part of the fossil coal significantly reduces the net carbon emission of industrial heat and power production. The total environmental benefits are a function of the feedstock source, distance the feedstock is transported, efficiency of the reactor, and downstream use routes(Rizkiana et al., 2020).

Life Cycle Assessment (LCA)

The Life Cycle Assessment is now a key instrument to assess the environmental sustainability of biomass-plastic co-torrefaction systems. Modern LCA studies consider the greenhouse gas emissions, the cumulative energy demand, fossil resource depletion, acidification potential, eutrophication, and overall environmental impact in the whole process chain from the collection of the feedstock to the end use applications. Generally, comparisons show that waste-derived feedstocks result in significantly better environmental performance than virgin fossil fuels. But, transportation logistics, drying needs, electricity power supply, and the energy consumption in the reactor are still huge factors in life-cycle impacts and need to be optimized for commercial-scale application(Y.-L. Lin & Zheng, 2021).

Techno-Economic Analysis (TEA)

The techno-economic analysis is a quantitative tool to evaluate the commercial viability of co-torrefaction technologies. The availability of

feedstock, transportation costs, reactor configuration, process scale, energy consumption, product yield and market value of torrefied products are the main factors that affect the economic performance of the process. Feedstock logistics and thermal energy needs have been identified as significant cost drivers in recent assessments and steady operation of a reactor has the potential to positively affect the process economics through higher throughput and lower operational costs. The use of premium solid fuels, activated carbon and carbon materials in the production of the same also contributes in supporting the economic competitiveness of integrated co-torrefaction facilities(Purnama et al., 2025).

Contribution to Circular Bioeconomy

Co-torrefaction can directly contribute to the transition to a circular bioeconomy by converting renewable biomass residues and non-biodegradable plastic waste into marketable energy products, with minimal resource losses. The technology allows for the recycling of carbon, longer value chains for materials and less reliance on virgin fossil resources. The industrial symbiosis of integration with biorefineries, municipal waste treatment facilities and industrial energy systems further enhances the resource efficiency. Linkages to renewable electricity, carbon capture technologies and digital process optimization will be expected to be used for future implementation, resulting in sustainable waste-to-resource systems that are in line with the goals of global decarbonization and the circular economy(Vasileiadou, 2024).

Challenges and Future Perspectives

Technical Challenges

Although biomass-plastic co-torrefaction is a technology with significant development, there are still a number of technical challenges that need to be overcome to enable its large-scale applications. One major challenge is the heterogeneity of the feedstock, which involves the differences in moisture content, particle size, chemical

composition, ash content and thermal degradation behavior of agricultural residues and municipal plastic wastes. Due to these differences, the heat transfer is often uneventful, the torrefaction is not always uniform and the product quality varies. The presence of mixed plastic waste makes the situation more complex because there is more than one polymer present with different melting and degradation temperatures. The potential for polyvinyl chloride (PVC) to exist is especially worrisome because it can dehydrochlorinate to produce hydrogen chloride, which can cause corrosion of equipment, catalyst deactivation, and emissions issues. Another problem is reactor scale-up because in continuous systems, uniform temperature and residence time is difficult to achieve and increases with scale-up. In addition, lack of understanding of biomass-plastic interaction mechanisms under industrial operating conditions restricts process modelling and optimization of reactor designs(Raj, Jain, & Verma, 2026).

Environmental and Economic Constraints

While co-torrefaction is a step towards sustainable waste management, the environmental and economic challenges need to be addressed before the process can become a reality. Moving low density biomass over long distances can be very energy intensive and generate a lot of greenhouse gas emissions which decreases the benefits to the environment. Other processing operations such as drying, shredding and particle size reduction also add to the cost of operations. Capital investment and maintenance cost are higher with the necessity of emission control systems when it comes to processing chlorine-containing plastics or contaminated waste streams. These factors are also influenced by the seasonal availability of biomass, variability of plastic waste composition, market demand for torrefied fuels, and energy prices in the area. Based on current techno-economic evaluation, cost of feedstock logistics and energy input to the reactor are significant contributors to overall production costs. Therefore, decentralized processing facilities situated close to biomass and

plastic waste production sites are becoming more and more attractive to be implemented to achieve better process economy and less environmental impact from transport(Yaseen et al., 2024).

Research Gaps

Although biomass-plastic co-torrefaction research has progressed over the past few years, there are still several important research gaps that need to be addressed. Compared to this, few studies have investigated heterogeneous municipal waste under continuous industrial conditions and most of the published investigations have been performed at the laboratory scale with simplified feedstock mixtures. The operational stability of the continuous reactors and the durability of the catalysts are not well understood, as are the performance of the equipment. Moreover, there are no standardized methods to assessing the quality of fuels, energy densification, hydrophobicity or environmental performance, which hinders direct comparison of the studies. Likewise, not much information exists about the fate of trace contaminants, chlorine compounds, heavy metals and microplastics in co-torrefaction. Moreover, there is limited number of integrated assessments covering reaction kinetics and life cycle assessment, techno-economic analysis and process simulation. The solution of these knowledge gaps will be crucial for increasing the reliability of the processes, enable technology transfer and aid in commercialization of co-torrefaction systems.

Future Research Directions

Further work is needed to design integrated, intelligent and industry scalable co-torrefaction systems to maximize the utilization of all the resources while minimizing environmental impacts. To increase the practical applicability of future studies, more attention should be given to laboratory test feedstocks as well as realistic mixed biomass and municipal plastic wastes. The following advanced reactor engineering features should be considered: continuous rotary, screw and fluidized-bed systems, high heat transfer,

automated feed systems, and accurate residence-time control. To process mixed plastic wastes that contain PVC without damaging the environment or increasing the wear on equipment, the catalysis and efficient gas-cleaning technologies will be key. AI, machine learning, digital twins, and real-time sensor networks should increasingly be incorporated into reactors control systems, to optimize their operating conditions and product

quality in a predictive way, and at the same time improve energy efficiency. Furthermore, future research are needed to couple co-torrefaction with other complementary technologies, such as hydrothermal carbonization, pyrolysis, gasification, renewable hydrogen production, carbon capture and utilization (CCU), to create fully integrated waste-to-energy platforms.

Table 3 Challenges, Research Gaps, Technological Advances, and Future Research Priorities in Biomass-Plastic Co-Torrefaction

Research Area	Current Status	Major Challenge	Research Gap	Recent Advance	Future Priority	Industrial Impact
Feedstock Selection	Agricultural residues, forestry biomass, PE, PP, PS, PET	Feedstock heterogeneity	Standardized blending protocols	AI-assisted sorting	Universal feedstock standards	Consistent fuel quality
Feedstock Pretreatment	Drying, shredding, grinding	High preprocessing energy	Moisture optimization	Automated preprocessing	Low-energy pretreatment	Lower operating cost
Reactor Design	Fixed-bed, rotary kiln, screw, fluidized-bed	Heat-transfer limitations	Continuous industrial validation	Microwave reactors	Continuous automated reactors	Large-scale commercialization
Process Optimization	Temperature, time, blend ratio optimization	Multi-variable interaction	Real-time optimization	ANN, RSM, ML models	Digital twin technology	Higher process efficiency
Catalytic Co-Torrefaction	Zeolite, CaO, dolomite, biochar catalysts	Catalyst deactivation	Catalyst lifetime	Nano-catalysts	Regenerable catalysts	Higher carbon retention
Microwave Torrefaction	Rapid volumetric heating	High capital cost	Industrial-scale design	Hybrid microwave systems	Energy-efficient microwave reactors	Reduced energy consumption
Product Characterization	FTIR, SEM, XRD, BET, TGA, Raman	Non-uniform testing methods	Lack of standard protocols	Advanced spectroscopy	Global characterization standards	Better quality assurance

Research Area	Current Status	Major Challenge	Research Gap	Recent Advance	Future Priority	Industrial Impact
Fuel Performance	Improved HHV, FC, hydrophobicity	Ash-related problems	Long-term combustion studies	Advanced combustion modelling	Commercial co-firing trials	Coal replacement potential
Gasification & Pyrolysis	Improved syngas and bio-oil quality	Tar formation	Integrated process evaluation	Multi-stage reactors	Hybrid thermochemical systems	Higher energy recovery
Carbon Materials	Activated carbon, adsorbents	Pore structure control	Scale-up studies	Heteroatom doping	Battery-grade carbon materials	High-value products
Environmental Assessment	LCA and carbon footprint studies	Variable system boundaries	Harmonized methodologies	Dynamic LCA	Global sustainability framework	Improved environmental assessment
Techno-Economic Analysis	Pilot-scale TEA available	Logistics cost	Commercial feasibility	Integrated simulation	Full-scale economic assessment	Investment confidence
Circular Economy	Waste-to-energy integration	Policy limitations	Regulatory framework	Industrial symbiosis	International standards	Sustainable commercialization
Commercialization	Demonstration projects	Scale-up risk	Long-term operational data	Smart manufacturing	Industrial deployment	Market penetration

As a material, producing COT products as activated carbons, carbon nanotube precursors, electrode materials, catalyst supports, and carbon dioxide adsorbents instead of solid fuels will significantly aid to the process economics. In the future, comprehensive life cycle assessment, techno-economic and exergy analyses should be incorporated into more of the evaluations to determine the optimum process configuration for the environment and economy. Last but not least, international feedstock classification, product quality and emission monitoring and sustainability assessment standards should be developed in order to support technology commercialization, industrial uptake and reinforce the biomass-plastic co-torrefaction value chain in the global net-zero carbon economy and circular economy.

Conclusion

The co-torrefaction has proven to be an effective solution to tackle two of the most pressing challenges nowadays: the sustainable management of the lignocellulosic biomass residues and the increasing amount of plastic waste. The evidence compiled in this review indicates that torrefaction of biomass with hydrogen-rich plastics improves these properties, including carbon retention, energy densification, hydrophobicity and combustion properties, and mitigates certain challenges of biomass that are caused by its inherently moisture-rich nature. New reactor technologies, catalytic systems, microwave heating and computational optimization have significantly increased process efficiencies and product quality, which opens the applications of co-torrefied materials in renewable energy systems and high value carbon products. In addition to fuel

production, co-torrefied products have demonstrated great potential as feedstock for gasification and pyrolysis processes, as precursors to activated carbon and functional carbon based materials, and as renewable replacements in the generation of industrial heat. In terms of sustainability, the technology is very similar to the principles of the circular economy, as it supports waste valorization, resource efficiency, a reduction of landfill reliance and greenhouse gas mitigation. However, a few challenges remain with commercialization: feedstocks are variable, they are not demonstrated at a continuous scale, the catalyst deactivates and there is still a lack of product standardization and uncertainty about the economic performance. The responses to these challenges will involve the efforts of multiple disciplines, including revolutionary advances in reactor engineering, intelligent process optimization, standardized characterization protocols, comprehensive life-cycle and techno-economic assessments and policy support. Industrial deployment is projected to grow with the integration of co-torrefaction with digital manufacturing, AI, CCS and biorefinery concepts in the future. All of these advances make biomass-plastic co-torrefaction a promising waste-to-resource technology that can help produce renewable energy, decarbonize industrial processes, and enable the global transition to a sustainable circular bioeconomy.

REFERENCES

- Adeleke, A. A., Odusote, J. K., Ikubanni, P. P., Lasode, O. A., Malathi, M., & Paswan, D. (2021). Essential basics on biomass torrefaction, densification and utilization. *International Journal of Energy Research*, 45(2), 1375-1395.
- Allouzi, M. M. A., Lee, L. Y., Gan, S., & Thangalazhy-Gopakumar, S. (2023). Torrefaction of olive pomace with low-density polyethylene (LDPE) plastic and its interactive effects. *Thermochimica Acta*, 724, 179495.
- Azarpour, A., Zendehboudi, S., & Saady, N. M. C. (2025). Deterministic models for performance analysis of lignocellulosic biomass torrefaction. *ACS omega*, 10(7), 6470-6501.
- Biswas, P. P., & Chen, W.-H. (2025). Production of Biochar from Food Waste *Biochar and the Circular Economy* (pp. 73-95): CRC Press.
- Cahyanti, M. N., Doddapaneni, T. R. K. C., & Kikas, T. (2020). Biomass torrefaction: An overview on process parameters, economic and environmental aspects and recent advancements. *Bioresource technology*, 301, 122737.
- Chandrasekharan Nair, S., John, V., Geetha Bai, R., & Kikas, T. (2025). Torrefaction of Lignocellulosic Biomass: A Pathway to Renewable Energy, Circular Economy, and Sustainable Agriculture. *Sustainability*, 17(17), 7738.
- Chen, W.-H., & Felix, C. B. (2024). Thermo-kinetics study of microalgal biomass in oxidative torrefaction followed by machine learning regression and classification approaches. *Energy*, 301, 131677.
- Cheong, K. Y., Kong, S. H., Liew, R. K., Wong, C. C., Wong, C. S., Ngu, H. J., & Yek, P. N. Y. (2022). Integration of microwave co-torrefaction with helical lift for pellet fuel production. *Green Processing and Synthesis*, 11(1), 404-410.
- de Oliveira Brotto, J., Cruz, T. A., de Oliveira Pereira, I., Ienczak, J. L., Peralta, R. A., Lazaro-Martinez, J. M., . . . Moreira, R. d. F. P. M. (2023). Mechanistic insights and kinetics of torrefaction of pine wood biomasses using solid-state NMR. *Journal of Analytical and Applied Pyrolysis*, 172, 106019.
- 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.

- Gizaw, D. G., Periyasamy, S., Baylie, H., Redda, Z. T., Asaithambi, P., Jayakumar, M., . . . Pugazhendhi, A. (2024). Advances in solid biofuels production through torrefaction: Potential biomass, types of torrefaction and reactors, influencing process parameters and future opportunities–A review. *Process Safety and Environmental Protection*, 186, 1307-1319.
- Granado, M. P. P., Conti, A. C. D., & Nanda, S. (2026). Advances in Torrefaction and Densification of Biomass to Produce Biofuel Pellets and Briquettes: A Review. *BioEnergy Research*, 19(1), 49.
- Guo, S., Deng, X., Liu, L., Ge, L., & Lisak, G. (2024). Comprehensive analysis of combustion behavior, kinetics, and gas emissions of fungus bran biofuel through torrefaction pretreatment and polypropylene addition. *Fuel*, 364, 131014.
- Guo, S., Liu, L., Zhao, D., Zhao, C., Li, X., & Li, G. (2023). Optimization of briquette fuels by co-torrefaction of residual biomass and plastic waste using response surface methodology. *Molecules*, 28(6), 2568.
- Imdad, S., Yadav, M. D., Vaidya, P. D., & Joshi, J. (2026). Minor steps with major impact on biomass thermochemical conversion through drying and torrefaction. *Drying Technology*, 1-40.
- Lee, K.-T., Gabriela, S., Chen, W.-H., Ong, H. C., Rajendran, S., & Tran, K.-Q. (2024). Co-torrefaction and synergistic effect of spent coffee grounds and tea waste for sustainable waste remediation and renewable energy. *Renewable Energy*, 233, 121181.
- Lin, Y.-L., & Zheng, N.-Y. (2021). Biowaste-to-biochar through microwave-assisted wet co-torrefaction of blending mango seed and passion shell with optoelectronic sludge. *Energy*, 225, 120213.
- Lin, Y. L., Zheng, N. Y., Lin, W. H., & Chang, C. C. (2025). Economic and environmentally efficient biochar production via microwave-assisted co-torrefaction of fruit residue and waste oil. *Renewable and Sustainable Energy Reviews*, 209, 115100.
- Liu, M., Li, X., Li, J., Ni, X., Zhu, L., Cen, K., & Chen, D. (2025). Experimental study on the synergy between lignin and cellulose during co-torrefaction and its impact on the properties and structural characteristics of pyrolysis biochar. *Industrial Crops and Products*, 224, 120383.
- Lu, H., Gong, Y., Areeprasert, C., Ding, L., Guo, Q., Chen, W.-H., & Yu, G. (2021). Integration of biomass torrefaction and gasification based on biomass classification: a review. *Energy Technology*, 9(5), 2001108.
- Mamvura, T. A., & Danha, G. (2020). Biomass torrefaction as an emerging technology to aid in energy production. *Heliyon*, 6(3).
- Manatura, K., Chalermisinsuwan, B., Kaewtrakulchai, N., Chao, Y.-C., & Li, Y.-H. (2023). Co-torrefaction of rice straw and waste medium density fiberboard: a process optimization study using response surface methodology. *Results in Engineering*, 18, 101139.
- Massaro Sousa, L., Ogura, A. P., Anchietta, C. G., Morin, M., & Canabarro, N. I. (2024). Biomass torrefaction for renewable energy: From physicochemical, bulk properties, and flowability to future perspectives and applications. *Energy & Fuels*, 38(19), 18367-18385.
- Moreira, B. R. d. A., Cruz, V. H., Barbosa Junior, M. R., Meneses, M. D., Lopes, P. R. M., & da Silva, R. P. (2024). Agro-residual biomass and disposable protective face mask: a merger for converting waste to plastic-fiber fuel via an integrative carbonization-pelletization framework. *Biomass Conversion and Biorefinery*, 14(12), 12785-12806.

- Mpungu, I. L., Maube, O., Nziu, P., Mwasiagi, J. I., Dulo, B., & Bongomin, O. (2024). Optimizing waste for energy: exploring municipal solid waste variations on torrefaction and biochar production. *International Journal of Energy Research*, 2024(1), 4311062.
- Mutamima, A., Sunarno, S., Purnama, I., Nurfatihayati, N., Novendri, A., Anesta, R., & Irianty, R. S. (2025). High-efficiency biochar production from oil palm fronds using acidic pretreatment and co-torrefaction with waste cooking oil. *Waste Disposal & Sustainable Energy*, 7(2), 229-242.
- Nwabunwanne, N., Vuyokazi, T., Olagoke, A., Mike, O., Patrick, M., & Anthony, O. (2021). Torrefaction characteristics of blended ratio of sewage sludge and sugarcane bagasse for energy production. *Applied Sciences*, 11(6), 2654.
- Oliver, I., Conesa, J. A., & Fullana, A. (2024). Thermal decomposition of bio-based plastic materials. *Molecules*, 29(13), 3195.
- Olugbade, T. O., & Ojo, O. T. (2020). Biomass torrefaction for the production of high-grade solid biofuels: a review. *BioEnergy Research*, 13(4), 999-1015.
- Panwar, N. L., & Divyangkumar, N. (2024). An overview of recent advancements in biomass torrefaction. *Environment, Development and Sustainability*, 1-48.
- Piersa, P., Unyay, H., Szufa, S., Lewandowska, W., Modrzewski, R., Ślęzak, R., & Ledakowicz, S. (2022). An extensive review and comparison of modern biomass torrefaction reactors vs. biomass pyrolysis—Part 1. *Energies*, 15(6), 2227.
- Potnuri, R., Suriapparao, D. V., Rao, C. S., Sridevi, V., Kumar, A., & Shah, M. (2022). The effect of torrefaction temperature and catalyst loading in Microwave-Assisted in-situ catalytic Co-Pyrolysis of torrefied biomass and plastic wastes. *Bioresource technology*, 364, 128099.
- Purnama, I., Mutamima, A., Sunarno, S., Nasution, I. A. U., Syaputra, E., & Aziz, M. (2025). Scalable biochar production from oil palm fronds and waste cooking oil: Techno-economic and policy-oriented evaluation for rural deployment. *Journal of Cleaner Production*, 527, 146682.
- Rago, Y. P., Collard, F.-X., Görgens, J. F., Surroop, D., & Mohee, R. (2020). Torrefaction of biomass and plastic from municipal solid waste streams and their blends: Evaluation of interactive effects. *Fuel*, 277, 118089.
- Raj, R. S., Jain, S., & Sharma, A. K. (2026). Process optimization and sustainability assessment of torrefaction of municipal solid waste and rice husk blends. *Energy Conversion and Management*, 359, 121558.
- Raj, R. S., Jain, S., & Verma, A. (2026). Torrefaction of Municipal Solid Waste: Advancing Biochar Quality Through Process Optimization. *Multi-scale Mechanics of High Entropy Alloys*, 421-439.
- Rizkiana, J., Zahra, A., Wulandari, W., Saputra, W., Andrayukti, R., Sianipar, A., & Sasongko, D. (2020). Effects of coal and biomass types towards the quality of hybrid coal produced via co-torrefaction. Paper presented at the IOP Conference Series: Materials Science and Engineering.
- Saha, N., Klinger, J., Fillerup, E., Williams, L., Emerson, R., Hartley, D., . . . Piloni, G. (2025). Synergistic torrefaction of plastic polymers and biomass. *Energy Conversion and Management*, 341, 120044.
- Sarker, T. R., Nanda, S., Dalai, A. K., & Meda, V. (2021). A review of torrefaction technology for upgrading lignocellulosic biomass to solid biofuels. *BioEnergy Research*, 14(2), 645-669.
- Seshasayee, M. S., & Savage, P. E. (2021). Synergistic interactions during hydrothermal liquefaction of plastics and biomolecules. *Chemical Engineering Journal*, 417, 129268.

- Silveira, E. A., Luz, S., Candelier, K., Macedo, L. A., & Rousset, P. (2021). An assessment of biomass torrefaction severity indexes. *Fuel*, 288, 119631.
- Sukiran, M. A., Daud, W. M. A. W., Abnisa, F., Nasrin, A. B., Aziz, A. A., & Loh, S. K. (2021). A comprehensive study on torrefaction of empty fruit bunches: characterization of solid, liquid and gas products. *Energy*, 230, 120877.
- Tumuluru, J. S., Ghiasi, B., Soelberg, N. R., & Sokhansanj, S. (2021). Biomass torrefaction process, product properties, reactor types, and moving bed reactor design concepts. *Frontiers in Energy Research*, 9, 728140.
- Unyay, H., Piersa, P., Zabochnicka, M., Romanowska-Duda, Z., Kuryło, P., Kuligowski, K., . . . Wrzesińska-Jędrusiak, E. (2023). Torrefaction of willow in batch reactor and co-firing of torrefied willow with coal. *Energies*, 16(24), 8083.
- Vanapalli, K. R., Bhattacharya, J., Samal, B., Chandra, S., Medha, I., & Dubey, B. K. (2021). Inhibitory and synergistic effects on thermal behaviour and char characteristics during the co-pyrolysis of biomass and single-use plastics. *Energy*, 235, 121369.
- Vasileiadou, A. (2024). From Organic wastes to Bioenergy, Biofuels, and value-added products for urban sustainability and circular economy: a review. *Urban Science*, 8(3), 121.
- Viegas, C., Nobre, C., Correia, R., Gouveia, L., & Gonçalves, M. (2021). Optimization of biochar production by co-torrefaction of microalgae and lignocellulosic biomass using response surface methodology. *Energies*, 14(21), 7330.
- Waheed, A., Naqvi, S. R., & Ali, I. (2022). Co-torrefaction progress of biomass residue/waste obtained for high-value bio-solid products. *Energies*, 15(21), 8297.
- Wang, Q., Li, Z., Gao, Y., Liu, X., Zhao, Y., Zhang, L., & Cao, Q. (2025). Synergistic enhancement of co-torrefaction on combustion characteristics of maize straw and algae blends: Kinetic and ash analysis. *Energy*, 138993.
- Wu, Q., Zhang, L., Ke, L., Zhang, Q., Cui, X., Fan, L., . . . Bob, K. (2023). Co-torrefaction of corncob and waste cooking oil coupled with fast co-pyrolysis for bio-oil production. *Bioresource technology*, 370, 128529.
- Xu, N., Wang, Z., Chen, G., Wang, Q., Li, Z., & Lei, T. (2025). Effect of torrefaction on the co-pyrolysis of pinewood with PET and HDPE: Impacts on products distribution. *Journal of the Energy Institute*, 102278.
- Yaseen, S., Azhar, U., Arif, M., Saqib, M., Riaz, A., & Yaqub, R. (2024). Potential risks, toxicology, stability, economic feasibility, and environmental impacts of biomass conversion *Nanomaterials in Biomass Conversion* (pp. 465-483): Elsevier.
- Zhao, Z., Chen, M., & Wang, L. (2025). Dechlorination Through Torrefaction: A Pretreatment for Co-Pyrolysis of PVC-Biomass Blends. *Processes*, 13(11), 3543.
- Zheng, N.-Y., Lee, M., & Lin, Y.-L. (2020). Co-processing textile sludge and lignocellulose biowaste for biofuel production through microwave-assisted wet torrefaction. *Journal of Cleaner Production*, 268, 122200.
- Zore, A. S., Singh, R., Chaudhary, S., Sahil, S., Lindenberger, C., Chawade, A., . . . Vivekanand, V. (2026). Thermal Conversion of Sugarcane Bagasse and Groundnut Shell Blends Into Efficient Solid Biofuel Using Microwave Torrefaction for Integration of Renewable Technologies in Cities. *Advanced Sustainable Systems*, 10(4), e00651.