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THE SIGNIFICANCE OF BIOMASS IN ACHIEVING A GLOBAL BIOECONOMY

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HIGHLIGHTS

- The pivotal role of biomass in shaping a global bioeconomy is reviewed.
- Bibliometric analysis reveals interdisciplinary insights in this research.
- The importance of biomass diversity and compositions in bioeconomy sectors is highlighted.
- Different technologies for converting biomass to value-added products are discussed.
- Future research in biomass applications to achieve a circular economy is presented.

GRAPHICAL ABSTRACT

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ABSTRACT

This manuscript explores the imperative role of biomass in shaping the global bioeconomy, necessitated by escalating energy demands and the consequent environmental challenges posed by fossil fuel dependency. This paper delineates the diverse forms of biomass — from lignocellulosic materials to organic waste and algae — each holding distinct chemical compositions and applications within the bioeconomy. Investigating biomass conversion technologies (i.e. thermochemical, biochemical and chemical) provides a comprehensive understanding of their merits and limitations in energy production and resource optimisation. Specifically, it delves into pyrolysis, gasification, hydrothermal liquefaction, torrefaction, anaerobic digestion and transesterification, elucidating their mechanisms and contributions to energy generation and biofuel production. Moreover, the study incorporates bibliometric analysis, depicting thematic clusters in biomass research and highlighting the evolving trends in its application within the bioeconomy. The primary focus of studies within the initial cluster revolves around utilising biomass for a global bioeconomy through thermochemical conversion methods. Overall, this review underscores the indispensable role of biomass as a renewable and adaptable resource, pivotal in steering the transition towards a sustainable bio-based economy amid global environmental and socio-economic challenges.

Introduction

The escalating use of fossil fuel to satisfy rapidly growing energy demand will accelerate climate change, posing risks to human health and wellbeing, besides disrupting the natural balance of ecosystems and biodiversity. Advocating for the integration of renewable sources into the global energy framework is a feasible strategy to reduce the dependence on fossil fuel reserves. Renewables, such as solar, wind, water, geothermal and biomass, occur naturally. The seamless compatibility of biomass energy with existing energy infrastructure renders it an ideal substitute for fossil fuel in numerous global utilities. Additionally, it is an attractive alternative due to its independence from geographical limitations, seasonal fluctuations and weather irregularities. Presently, bioenergy holds the status of being the most extensively utilised, comprising more than 70% of renewable energy generated worldwide (Röder & Welfle, 2019). Figure 1 illustrates the publication trend of biomass applications in achieving global bioeconomy from 2010 to 2023.

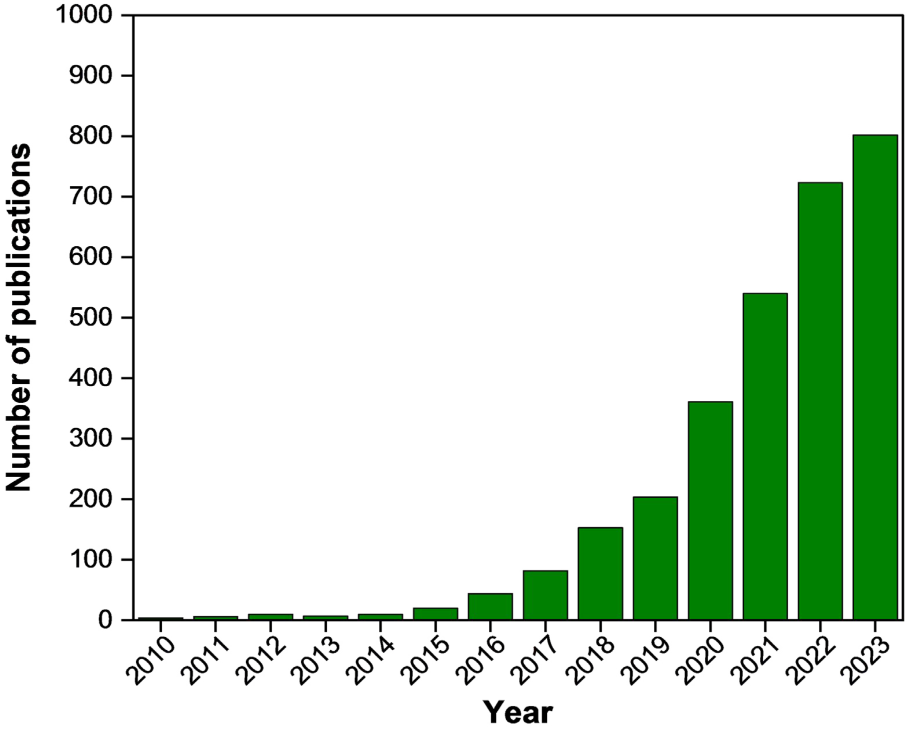


Figure 1: Number of articles published annually about the utilisation of biomass in achieving a global bioeconomy. The query used to search the Scopus database is described in the bibliometric analysis section

As a result of the intricate process of photosynthesis, organic materials will generate and store energy within their biomass. This encompasses a broad spectrum of organic resources, comprising crops intentionally cultivated for their energy-producing capabilities, organic waste, residual materials from forestry and specialised energy crops, such as miscanthus or switchgrass (Nabuurs *et al*., 2013). This diversity makes biomass a valuable renewable resource that can be used across multiple sectors. However, most biomass is traditionally used for cooking and heating in developing countries. Accordingly, the use of biomass in modern bioenergy systems should be expanded to enhance its contribution to the global energy mix (Tuck *et al*., 2012). The necessity in addressing prevailing global quandaries, encompassing climate alterations, energy safeguarding and the scarcity of resources necessitates the formulation of innovative resolutions. Biomass assumes a crucial role in this context due to its regenerative attributes, potential for carbon neutrality and adaptability across diverse applications.

The global bioeconomy presents a cutting-edge framework designed to utilise biological resources for fostering sustainable growth in various industries. It includes the application of biological concepts, processes and renewable resources to generate high-value goods, materials, energy and food (El-Chichakli *et al*., 2016). This expansion owes much to technological advancements in biotechnology, bioengineering and innovative processes, enabling a shift away from linear consumption models and reducing dependence on fossil fuels. The bioeconomy is primarily driven by significant industries, such as waste management, bioenergy, biotechnology, forestry, fisheries and agriculture (Yang *et al*., 2022) in planta accumulation and microbial production of bioproducts have never been systematically compared on an economic basis to identify optimal routes of production. A detailed technoeconomic analysis of four exemplar compounds (4-hydroxybenzoic acid [4-HBA], catechol, muconic acid, and 2-pyrone-4,6-dicarboxylic acid [PDC]. The transition towards a bio-based economy is aligned with global sustainability objectives, aiming to curtail carbon emissions, reduce waste generation and enhance resource efficiency. Most importantly, the bioeconomy addresses not only environmental concerns but also stimulates economic expansion and resilience amidst evolving social and environmental landscapes.

In recent decades, the global discourse has increasingly pivoted towards sustainable practices to counteract the escalating threats posed by climate change and depleting fossil fuel reserves. While various renewable energy sources have garnered attention, biomass stands out for its multi-faceted attributes that extend beyond energy production. By dissecting the historical evolution of biomass utilisation, evaluating its technological prospects, and dissecting its impact across diverse sectors, this study sheds light on a comprehensive approach to harnessing biomass potential. This analysis is poised to unravel novel perspectives, elucidate unexplored intersections and contribute substantively to the discourse on sustainable energy and resource utilisation.

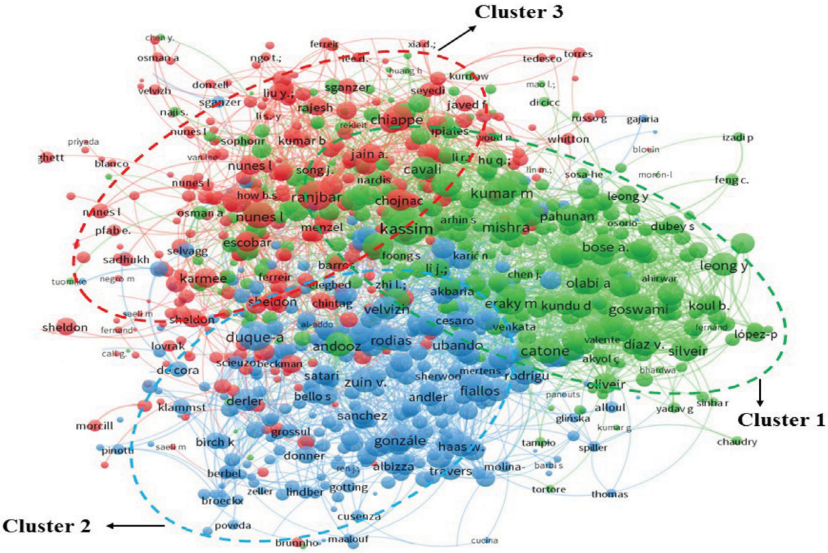
The aim is to delve into the multifaceted role that biomass plays in the global bioeconomy. It achieves this by understanding historical backgrounds, categorising biomass resources, evaluating technological conversion processes, analysing the applications across industries, scrutinising economic and environmental impacts, addressing current challenges, and projecting future advancements. Examining biomass through the lens of the global bioeconomy is crucial for comprehending the complexities of a sustainable future. Biomass energy has a pivotal role in transitioning to such economy — a resource that is renewable, adaptable and indispensable.

Bibliometric Analysis

Bibliographic analysis evaluates shared references among documents to clarify their relationships. Based on the similarity in their cited sources, this technique groups academic publications into topic clusters. Evaluating citation overlaps across texts indicates related themes and helps distinguish various knowledge domains within a given area (Shahbeig *et al*., 2022) from direct use to the synthesis of value-added biochemicals and biofuels. Due to the high capital/operating costs of the technology and the necessity for prudent management of thermal energy exchanges in the biomass gasification process, it is important to use advanced sustainability metrics to ensure that environmental and other sustainability factors are addressed beneficially. Consequently, various engineering techniques are being used to make decisions on endogenous and exogenous parameters of biomass gasification processes to find the most efficient, viable, and sustainable operations and conditions. Among available approaches, exergy methods have attracted much attention due to their scientific rigour in accounting for the performance, cost, and environmental impact of biomass gasification systems. Therefore, this review is devoted to critically reviewing and numerically scrutinising the use of exergy methods in analysing biomass gasification systems. First, a bibliometric analysis is conducted to systematically identify research themes and trends in exergy-based sustainability assessments of biomass gasification systems. Then, the effects of biomass composition, reactor type, gasifying agent, and operating parameters on the exergy efficiency of the process are thoroughly investigated and mechanistically discussed. Unlike oxygen, nitrogen, and ash contents of biomass, the exergy efficiency of the gasification process is positively correlated with the carbon and hydrogen contents of biomass. A mixed gasifying medium (CO2 and steam. This approach brings together documents with similar reference patterns, forming coherent clusters that make academic landscapes easier to perceive and comprehend. Bibliographic coupling clustering analysis is a valuable tool for academics and information experts, aiding in the discovery of new patterns, exploration of intellectual structures and enhancement of information retrieval systems (Donthu *et al*., 2021). Its utilisation fosters a deeper grasp of interconnections within the literature, thereby promoting essential insights for scholarly progress and interdisciplinary collaboration.

An appropriate search strategy should be defined to capture the maximum number of relevant studies in conducting bibliometric analysis, as emphasised by many scholars as one of the most important prerequisites. The bibliometric analysis methodology involved a systematic search in the Scopus database using specific keywords related to biomass and its role in the global bioeconomy. Accordingly, a combination of various keywords directly relating to the scope of the present review was obtained from the literature and elaborated to design the following search string: “biomass” OR “bioenergy” OR “bio energy” OR “bio-energy” AND “bioeconomy” OR “bio-economy” OR “circular economy” (search in the title, abstract and keywords). This search encompassed articles published between 2010 and 2023, aiming to capture the trends and evolution of research in this field. The retrieved data was subjected to rigorous screening based on relevance and inclusion criteria, ensuring a comprehensive dataset for analysis.

The VOSviewer software (version 1.6.18) was utilised to conduct a bibliographic coupling clustering analysis on the articles within the gathered sample. This aimed to generate a map outlining the emerging research themes by clustering articles according to the references they have in common. Based on the relatedness of the references, the extracted articles were clustered with a threshold of at least 10 citations for more visibility of the identified themes. Figure 2 illustrates three clusters formed based on the dataset. The initial cluster predominantly explores biomass application via thermochemical conversion routes, emphasising the nuanced impacts of various operating conditions, catalysts and biomass feedstock. Expanding on this cluster within the manuscript will involve delving deeper into the specific effects of these variables on bioeconomic outcomes and their implications for sustainability and efficiency. The second cluster highlights research primarily focused on leveraging biochemical conversion technologies for integrating biomass into the global bioeconomy. Elaborating on this cluster will involve elucidating the methodologies, advancements and potential outcomes within this realm, highlighting key findings and their significance. Lastly, the third cluster emphasises chemical conversion methods to produce high-quality biofuel. Further exploration within the manuscript will entail detailing the advancements, challenges and outcomes associated with these methods, underlining their relevance and potential contributions to the bioeconomy. Expanding on these clusters will enrich the manuscript by providing readers with comprehensive insights into the diverse avenues of biomass utilisation within the global bioeconomy, offering contextual clarity and enhancing the understanding of the research's multifaceted implications.



Cluster 1: Application of biomass in achieving global bioeconomy using thermochemical conversion technologies.

Cluster 2: Application of biomass in achieving global bioeconomy using biochemical conversion technologies.

Cluster 3: Application of biomass in achieving global bioeconomy using chemical technologies.

Figure 2: The most important research themes for biomass in achieving a global bioeconomy

Biomass Types and Characterisations

Biomass encompasses organic materials derived from living or recently deceased organisms that play a pivotal role in shaping the global bioeconomy due to its diversity and renewable nature. Understanding the various types of biomass is foundational to expand the utilisation of these resources. One primary classification is lignocellulosic biomass, sourced from wood, agricultural residues and specific energy crops, such as switchgrass or miscanthus. This biomass primarily comprises cellulose, hemicellulose and lignin, which are all essential structural components of plant cell walls (Figure 3). Cellulose, a chain-like arrangement of glucose units, forms a robust, fibrous structure that imparts strength and rigidity. Hemicellulose, comprised of various sugars in a heteropolymer, acts as a supporting framework by binding cellulose fibres and contributing to the biomass' flexibility. Lignin, a complex phenolic polymer, reinforces structural integrity by providing resistance against microbial degradation. Agricultural residues, like wheat straw, rice husk and corn stover, represent a significant biomass source rich in cellulose, hemicellulose and lignin-derived from agricultural processes. Moreover, crops grown explicitly for energy production, such as miscanthus and willow, offer essential biomass types due to their favourable energy traits and high yields, contributing significantly to the bioeconomy's resource pool.

Additionally, the classification of organic waste biomass encompasses a wide array of origins, such as municipal solid waste, food scraps, forestry leftovers and organic remnants from industrial operations. These sources contain organic materials ideal for either generating energy or transforming into high-value goods, thereby aiding in waste handling and resource optimisation. Algal biomass, an increasingly promising category, comprises various microorganisms abundant in lipids, proteins and carbohydrates. Algae boast significant potential in producing biofuels and diverse biotechnological uses due to their swift growth and adaptability to varying environmental conditions. Lipids function as concentrated energy reserves crucial for numerous biochemical processes. Proteins, made up of amino acids, serve structural and enzymatic roles, while carbohydrates (such as sugars and starches) act as vital energy sources and structural components. Each type of biomass possesses distinct chemical compositions, physical attributes and potential applications within the bioeconomy.

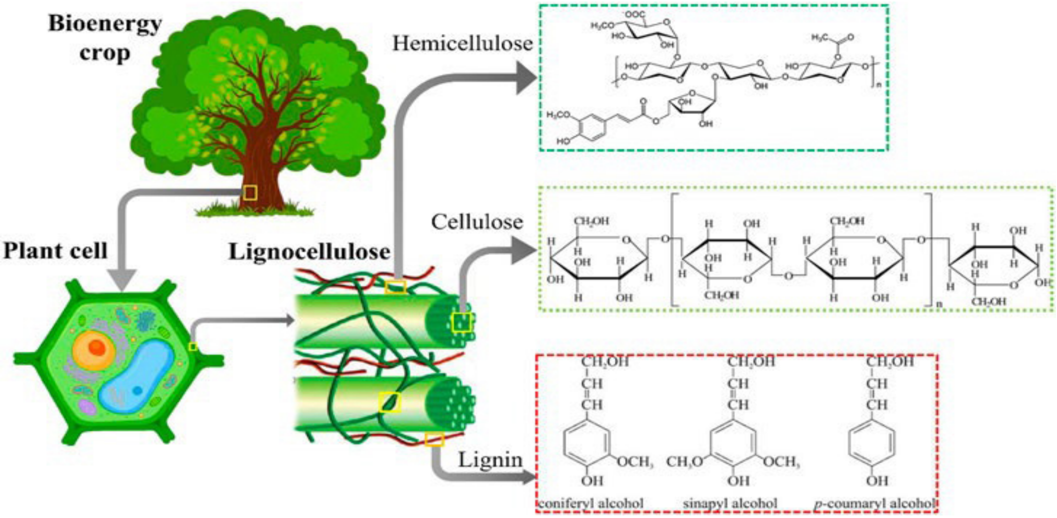


Figure 3: Schematic illustration showing lignocellulosic biomass. Reprinted with permission from Sankaran *et al.* (2021)

Biomass Conversion Technology

Modern pathways for converting biomass into energy, fuel and chemicals generally fall into three main categories: thermochemical, biochemical and chemical processes, each with its strengths and limitations (Table 1). Thermochemical technologies employ heat and chemical processes. On the other hand, biochemical processes utilise various microorganisms or enzymes to break down biomass into energy products (Choudhary *et al*., 2020). Additionally, chemical processes (e.g. transesterification and esterification) have been widely used for biodiesel production from lipid-rich biomass (Liu *et al*., 2021). The biochemical processes such as anaerobic digestion and fermentation are time-consuming and primarily limited by their low energy efficiency, high water consumption and sensitivity to biomass composition (Zhao *et al*., 2017). In recent decades, there has been an increasing focus on biomass conversion through thermochemical methods for bioenergy production. This is primarily due to their advantages, including higher conversion efficiency, a zero-waste approach, reduced resistance time, improved economic performance and compatibility with various feedstock, irrespective of whether they are wet or dry (Acharya *et al*., 2020; Ong *et al*., 2020; Solarte-Toro *et al*., 2021) pyrolysis, and gasification. Biomass analytical techniques have been developed to decrease the time and energy required for biomass conversion performance. Thermogravimetric analyser (TG). Moreover, thermochemical conversion processes play an important role in biomass-based biorefinery, which has been widely used for bioenergy production (Fan *et al*., 2020).

Pyrolysis

Thermochemical pathways play a vital role in leveraging biomass for energy use, encompassing key processes that convert biomass into valuable energy sources. Three primary methodologies (e.g., pyrolysis, gasification and hydrothermal liquefaction) stand out in this domain. Pyrolysis involves breaking down biomass through heat in the absence of oxygen, yielding solid char, liquid bio-oil and gaseous by-products. It can be categorised into slow, intermediate and fast/flash pyrolysis based on the temperature range, heating rate and vapour resistance time (Table 2) (Nanda & Berruti, 2021). However, other parameters, such as feedstock properties and reactor geometry, may also influence the product distribution. For instance, when the particle size decreases, the heat transfer rate increases, which results in decreased biochar yield and increased yield of other products (i.e. bio-oil and gas) (Sharma *et al*., 2015). For the same biomass, slow and fast/flash pyrolysis are greatly beneficial for biochar and bio-oil production, respectively, where the other products are obtained at a minimal level relative to the main products (Bulushev & Ross, 2011; Perkins *et al*., 2018; Sekar *et al*., 2021). The high temperature in the pyrolysis process leads to the decomposition of biomass, consequently producing volatile components followed by bio-oil production after the proper quenching process. The bio-oil contains organic compounds (such as heavy oil, tar, carbonyl, phenol, acids, alcohol, aldehyde, ketone, ester etc.), whereas biochar mainly contains a stable form of carbon (Azargohar *et al*., 2019; Nanda & Berruti, 2021).

Gasification

Gasification, on the other hand, transforms solid biomass into a gas mixture — comprising carbon monoxide, hydrogen and methane — in controlled reactions with oxygen or steam. This process of thermochemical conversion transforms organic compounds from the feedstock into a blend of gases, primarily composed of CO, H_2, CO_2, CH_4 and light hydrocarbons. This occurs when a gasifying agent (typically air, oxygen or steam) is present at elevated temperatures (Situmorang *et al.,* 2020). The gasification process involves four primary stages: Drying, devolatilisation, partial oxidation and reduction. These phases encompass various simultaneous endothermic and exothermic reactions, like the water-gas shift, methanisation and steam reforming (La Villetta *et al*., 2017). The drying phase involves reducing the moisture content

Table 1: Biomass conversion routes show the merits and limitations of each method

Biomass conversion route	Example	Description	Merit(s)	Limitation(s)
Thermochemical	Pyrolysis, gasification, hydrothermal, liquefaction	A thermal conversion process is carried out at high temperatures to produce different products, including bio-oil, biogas and biochar.	- Optimal efficiency - Versatility with different biomass types (both wet and dry) - Rapid conversion rate - A diverse range of processes - Reduced susceptibility to alterations in feedstock composition - Extensive utilsation - Financially feasible	- Consumes significant energy and lacks cost competitiveness. - Products contain high levels of oxygenated compounds, reducing their storage capability. - Products have lower calorific value. - Complex equipment is necessary.
Biochemical	Anaerobic digestion, fermentation	A microbial/ enzyme-assisted process for conversion of biomass to biogas or bioethanol.	- Low energy consumption and operating costs - Mild reaction conditions - Economically feasible	- Significant time is needed for conversion. - A preliminary step of biomass pretreatment is necessary to break down its structure. - Energy efficiency is low. Demands a substantial amount of water.

Chemical	Transesterification	A chemical process for biodiesel production from lipid-rich biomass.	- Quicker processing compared with biochemical conversion - A common technique to produce biodiesel - Suitable for feedstock like vegetable and waste oil, microalgae, energy crops, etc.	- First-generation biomass competes with human food production. - Complex equipment is needed. - Separating glycerol is essential to prevent the formation of dangerous gases.

Table 2: Classification of pyrolysis methods

Pyrolysis type	**Temperature range** (°C) (Nanda and Berruti, 2021)	**Heating rate** (°C/s) (Nanda and Berruti, 2021)	**Resistance time** (s) (Nanda and Berruti, 2021)	**Typical products** [a]	**Merit(s)**	**Limitation(s)**
Slow	300-700	0.1-1	600-6000	Biochar (35 %), gas (35 %), bio-oil (30 %)	-Low operation cost -Usually used for char production	-Low heat transfer -Higher input of energy
Intermediate	500-600	2-10	10-20	Bio-oil (50 %), biochar (25 %), gas (25 %)	-More moisture content for feedstock compared with fast pyrolysis	-Needs of high cooling rates
Fast	400-500	10-200	0.03-1.5	Bio-oil (75%), Biochar (13%), Gas (12%),	-Easy handling due to lower S and N content -High bio-oil yield -Relatively homogenous gas products	-Complex properties of bio-oil -Complex system

Flash	800-1000	1000	< 0.5	Bio-oil (> 75%), Gas (< 12%), Biochar (< 13%)	-Greater bio-oil yield than fast pyrolysis (high conversion rate of biomass to liquid) -Relatively homogenous gas products -High heating efficiency	-Needs very small size of particles and low moisture content -Complexity in designing -Poor thermal stability -Viscous bio-oil

of biomass to under 15% at temperatures below 200°C. Devolatilisation, occurring between 350°C and 600°C, breaks down organic materials like hemicellulose, cellulose and lignin into volatile compounds and solid residues. In the oxidation zone, with the presence of oxygen, volatile compounds and char undergo exothermic reactions at high temperatures, producing CO, CO_2 and H_2O. Conversely, in the reduction stage, characterised by endothermic reactions, devolatilisation products transform into CO, CH_4 and H_2 (Gao *et al*., 2020; Situmorang *et al*., 2020).

Biomass gasification involves a series of intricate reactions crucial in converting organic matter into valuable gases. The primary reactions include the Boudouard equilibrium, which synthesises carbon monoxide from carbon and carbon dioxide. Hydrogenating reactions generate methane from carbon and hydrogen. Partial oxidation yields carbon monoxide from carbon and oxygen, while the water-gas shift reaction transforms carbon monoxide and water into carbon dioxide and hydrogen. These fundamental reactions, alongside methanisation and reforming processes, play pivotal roles. Methane steam reforming produces hydrogen and carbon monoxide from methane and water, while carbon dioxide reforming generates carbon monoxide and hydrogen from methane and carbon dioxide. Oxidation reactions are vital, converting methane and carbon monoxide into carbon dioxide and water. Additionally, complex reactions form higher hydrocarbons like ethylene and ethane. Understanding and optimising these reactions are essential in enhancing gasification efficiency, maximising desired gas outputs and minimising undesired by-products. Table 3 depicts the main reactions to be considered during biomass gasification.

Hydrothermal Liquefaction

Biomass liquefaction is classified into direct and indirect processes for producing liquid fuels and chemicals. Indirect liquefaction refers to the Fischer–Tropsch process to liquefy the produced syngas from the gasification process. Direct liquefaction, referred to as hydrothermal liquefaction (HTL), involves the use of sub- or super-critical water/solvents at

Table 3: Main reactions in biomass gasification

No.	Chemical Equation	Name of Reaction	[a] (kJ.mol^{-1})
1	$C(s) + CO_2(g) \leftrightarrow 2CO(g)$	Boudouard equilibrium	+172.5
2	$C(s) + 2H_2(g) \leftrightarrow CH_4(g)$	Hydrogenating	-74.8
3	$C(s) + 0.5O_2(g) \rightarrow CO(g)$	Partial oxidation	-110.5
4	$C(s) + H_2O(g) \leftrightarrow CO(g) + H_2(g)$	Carbon reaction (primary steam reforming)	+131.3
5	$C(s) + 2H_2O(g) \leftrightarrow CO_2(g) + 2H_2(g)$	Carbon reaction (secondary steam reforming)	+90.1
6	$CO(g) + H_2O(g) \leftrightarrow CO_2(g) + H_2(g)$	Water-gas shift	-41.2
7	$CO(g) + 0.5O_2(g) \rightarrow CO_2(g)$	Oxidation	-283
8	$2CO(g) + 2H_2(g) \rightarrow CH_4(g) + CO_2(g)$	Methanisation	-247.3
9	$CH_4(g) + H_2O(g) \leftrightarrow CO(g) + 3H_2(g)$	Methane steam reforming	+206.1
10	$CH_4(g) + CO_2(g) \leftrightarrow 2CO(g) + 2H_2(g)$	Carbon dioxide reforming	+247.3
11	$CH_4(g) + 1.5O_2(g) \rightarrow CO(g) + 2H_2O(g)$	Oxidation	-591.3
12	$2CO(g) + 4H_2(g) \leftrightarrow C_2H_4(g) + 2H_2O(g)$	Ethylene formation	-210.3
13	$2CO(g) + 5H_2(g) \leftrightarrow C_2H_6(g) + 2H_2O(g)$	Ethane formation	-347.3

[a] Standard enthalpy (heat) of reaction

moderate temperatures (250-375°C) and elevated pressures (5-25 MPa) to generate biocrude oil as the primary output, alongside solids, gases and an aqueous phase secondary product. This innovative method shows great potential for directly converting moist biomass into liquid fuel, bypassing the expensive drying phase and reducing its energy demands. It also enhances the heat transfer rate to generate high-yield and quality biocrude oil under mild reaction conditions. Moreover, the biocrude oil obtained via this process have less moisture and oxygenated compounds and, subsequently, high energy content compared with pyrolysis bio-oil. However, HTL suffers from drawbacks in solvent recovery and biocrude oil separation because of their high viscosity, relatively low stability of biocrude oil and high operating pressure, which increases the investment cost. The mechanism of HTL includes the following pathways (Gollakota *et al*., 2018; Yang *et al*., 2019):

(i) Depolymerisation (macromolecules hydrolyse into monomer structures such as monosaccharides, amino acids, and fatty acids);

(ii) The breakdown process involves the fragmentation of substances into smaller molecules or oligomers like glucose, organic acids and phenolics. This occurs through a sequence of reactions that include dehydration, decarboxylation, deoxygenation, dehydrogenation and deamination, aimed at eliminating water, carbon dioxide, oxygen, hydrogen and amino acid components; and,

(iii) Recombination (in the absence of hydrogen compounds, the reactive fragments are repolymerised to form macromolecular compounds such as biocrude oil, char, etc. through condensation, cyclisation and polymerisation).

A schematic diagram of biomass HTL involves several steps: Feedstock pretreatment, liquefaction reactor, product separation, biocrude oil extraction and solvent recovery as shown in Figure 4. Different types of biomass, including lignocellulose, algae, sludge and manure, can be used as feedstock in HTL (Yang *et al*., 2020). Lignocellulosic biomass mainly consists of hemicellulose (15-35%), cellulose (30-50%), and lignin (20-35%) compounds. The cellulose and hemicellulose materials are mainly decomposed to monosaccharides and further to acids, aldehydes and ketones, while lignin compounds are degraded into phenolics (Song *et al.*, 2020). Additionally, the degradation of lipids and proteins, which are the major constituents of algal biomass, leads to the formation of alcohol, amines, aldehydes and acids (Gollakota *et al*., 2018). It should be noted that in the pilot scale, unlike the bench-scale plant, product separation is carried out by density difference instead of solvent extraction. Hence, the applicability of bench-scale (reactor volume up to 1 L) data to predict the behaviour of pilot-scale liquefaction plants will come into question. However, bench-scale studies have provided a solid foundation for the development and improvement of pilot-scale process designs (Watson *et al.*, 2020).

Torrefaction

Torrefaction is a thermochemical process conducted at a low-temperature range for the purpose of upgrading feedstock into energy-densified solid fuel. The benefits of torrefied biomass compared with raw biomass include higher energy yield and density, lower moisture content, lower H/C and O/C atomic ratios, higher water-resistivity (hydrophobicity), higher homogeneity and uniform properties, and better grindability (Chen *et al*., 2015). This promising method is classified into dry, wet and steam torrefaction based on its reaction medium. In this regard, dry torrefaction occurs in an inert/oxidative atmosphere, whereas wet torrefaction commonly uses water/dilute acid to improve biomass characterisations. Moreover, biomass can also be torrefied using superheated steam (high-temperature and high-pressure). In dry torrefaction, the most common carrier gases utilised for biomass pretreating are N_2/CO_2 in a non-oxidative (inert) environment, whereas it is air/flue gas for an oxidative atmosphere. Among these processes, non-oxidative torrefaction has been widely used in industry in five distinct stages (van der Stelt *et al*., 2011; Chen *et al*., 2021):

(1) *Initial heating*: Biomass is heated until reaching the drying temperature, where moisture evaporation gradually begins;

(2) *Drying*: Free water in biomass structure is evaporated at constant temperature (i.e. 100 °C);

(3) *Post-drying* (intermediate heating): Physically bound water and light organic compounds are released from the biomass by increasing the temperature to 200 °C. However, the resistance against mass and heat transfer is still within the particles;

(4) *Torrefaction*: This stage starts when the reaction temperature exceeds 200 °C and is operated under constant temperature. Moreover, it is responsible for the main mass lost in the biomass through devolatilisation; and,

(5) *Cooling*: The torrefied biomass is further cooled to the desired temperature (commonly room temperature).

The performance of the torrefaction reaction and its product characterisation are influenced by several operating parameters such as temperature, pressure, heating rate, resistance time, particle size, and carrier gas. Among them, temperature is the most important parameter that has a significant effect on product properties, especially by moisture and light volatile liberation. During torrefaction temperature, hemicellulose the most active component among lignocellulosic compounds, is thermally degraded (220-315°C), whereas cellulose (315-400°C) and lignin (160-900°C) are only hard and slightly affected, respectively (Chen *et al*., 2021). Additionally, the comparison of methods as mentioned above, including operating conditions and their advantages and disadvantages, are described in Table 4.

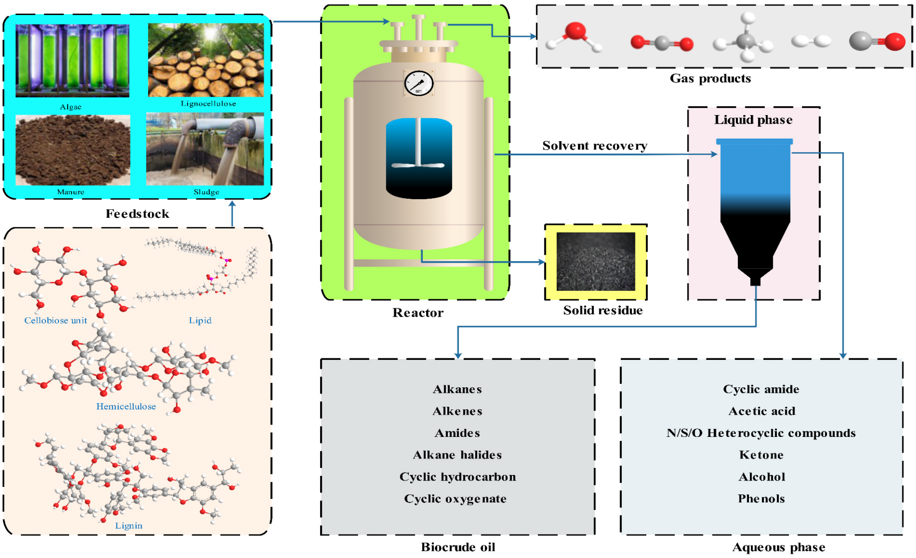


Figure 4: The schematic diagram for biomass hydrothermal liquefaction and its products

Anaerobic Digestion

Anaerobic digestion plays a central role in the realm of biomass conversion, offering an eco-friendly and effective means to extract energy from organic waste. This process relies on the activity of microorganisms that decompose biodegradable materials in an oxygen-deprived setting, resulting in the creation of biogas — mainly comprised of methane and carbon dioxide — and digestate, a nutrient-rich residue. At the heart of anaerobic digestion lies a diverse microbial community, primarily consisting of bacteria and archaea, which operate in a step-by-step sequence. Initially, hydrolysis begins the breakdown of complex organic compounds into simpler forms like sugars, amino acids and fatty acids. These compounds then undergo acidogenesis, where acid-producing bacteria further decompose them into volatile fatty acids. Subsequently, acetogenesis facilitates the conversion of these acids into acetate, hydrogen and carbon dioxide. Finally, methanogenesis occurs, where methanogenic archaea transform acetate, hydrogen and carbon dioxide into methane — the primary constituent of biogas. Anaerobic digestion typically takes place in a controlled environment, commonly within an enclosed system like an anaerobic digester. These digesters come in various designs, from batch to continuous flow systems, each tailored with specific operational conditions to optimise the digestion process. Variables such as temperature, pH levels, substrate composition and hydraulic retention time significantly impact the efficiency and stability of anaerobic digestion systems. A key advantage of anaerobic digestion lies in its versatility to handle diverse feedstock. It effectively processes organic materials like agricultural residues, food waste, sewage sludge and specialised energy crops. This not only alleviates the environmental impact of waste disposal but also generates renewable energy resources concurrently.

Transesterification

Transesterification holds a vital role in the realm of biomass conversion technology, representing the profound transformative potential embedded within sustainable bioeconomy initiatives. At its essence, transesterification is a fundamental chemical process crucial in biodiesel production, serving as a cornerstone in utilising biomass-based raw materials for generating renewable

Table 4: Characteristics of different biomass torrefaction methods

Type of Torrefaction	**Operating Conditions**			**Pros**	**Cons**
	Temperature (°C)	**Pressure** (atm)	**Resistance Time** (min)		
Dry	200-300	1	10-240	- Improving the characterisation of end-product (*i.e.,* better syngas quality in gasification, more stability in combustion, and higher bio-oil quality in fast pyrolysis) - Simple operation - Ready for industrialisation	- Higher ash content in solid products - Poor pelletability due to the low bulk density and more porous material - Low heating value of a product - Low volatile content - Feedstock with low moisture content is required
Wet	180-260	1-200	5-240	- Applicable for wet biomass and waste feedstock - Higher energy density at a much lower operating temperature - Better characterisation in grindability and hydrophobicity of torrefied biomass - Good binding properties during pelletisation - Low ash content - Enhancement of crystallinity degree	- High pressure is required - Requirement of efficient slurry pump - Corrosion behaviour in the system - Complicated design - Higher consumption of energy, which increases operational cost

Steam	200-400	1-40	5-120	-Applicable for wet biomass -Good binding properties during palletisation -Better heating value, carbon content and hydrophobicity of biomass -Improved mechanical strength and elasticity of biomass	-High pressure is required -Higher consumption of energy, which increases operational cost

energy and diversifying available resources. This chemical reaction involves the exchange of ester groups between an alcohol and a triglyceride, typically sourced from plant or animal fat. Mainly driven by alkali or acid catalysts, transesterification facilitates the conversion of triglycerides into fatty acid methyl esters or biodiesel, concurrently yielding glycerol as a by-product. The utilisation of diverse feedstock such as waste oils, algae or crop residues underscores the versatility and wide-ranging applicability of this conversion method. The significance of transesterification transcends mere biodiesel production. Its adoption epitomises the pursuit of sustainable energy sources and aims to alleviate environmental burdens associated with traditional fossil fuels. Notably, the resulting biodiesel exhibits commendable traits, including compatibility with existing diesel engines and diminished greenhouse gas emissions, offering a tangible route to mitigate the impacts of climate change.

Conclusion and Future Perspectives

The exploration of biomass within the global bioeconomy unfolds a critical narrative in the quest for sustainable energy sources. The quantitative insights from bibliometric analysis illustrate the escalating attention directed towards biomass applications, showcasing an upward trajectory in publications addressing biomass' role in fostering a global bioeconomy. Biomass, constituting approximately 70% of the global primary supply of renewable energy, emerges as a cornerstone in this landscape. The diversity of biomass, spanning from crop residues to specialised energy crops and organic waste, presents a versatile and indispensable renewable resource for various sectors. However, its current predominant use in traditional household applications in some regions calls for an expanded integration into modern bioenergy systems to augment its contribution to the global energy mix. This expansion is pivotal in addressing pressing global challenges like climate change, energy security and resource scarcity.

Technological advancements in biotechnology, bioengineering and innovative processes serve as catalysts propelling the growth of the bioeconomy. These advancements facilitate a shift away from fossil fuel and linear consumption models, aligning with global sustainability objectives. Key sectors like agriculture, forestry, fisheries, bioenergy, biotechnology and waste management drive this transition towards a bio-based economy, aiming to curtail carbon emissions, reduce waste generation and enhance resource efficiency. The comprehensive classification of biomass types — ranging from lignocellulosic materials to organic waste and algal biomass — provides a foundation for leveraging these resources across multiple industries. Modern biomass conversion technologies, namely thermochemical, biochemical and chemical processes demonstrate distinctive merits and limitations. Thermochemical pathways, such as pyrolysis, gasification, hydrothermal liquefaction and torrefaction, stand out for their higher conversion efficiency, reduced resistance time and versatility with various feedstock.

Additionally, anaerobic digestion and transesterification play pivotal roles in harnessing the potential of biomass, enabling effective energy extraction and biodiesel production, respectively. The thorough exploration of these conversion technologies, supported by quantitative figures and a comprehensive understanding of their operating principles, highlights the promise and challenges within the biomass domain. Pyrolysis, for instance, showcases distinct methods with varying temperature ranges, heating rates and resistance times, influencing the product yield and composition. Gasification and hydrothermal liquefaction demonstrate their efficacy in transforming solid biomass into valuable energy sources, offering unique pathways to produce biogas, bio-oil and biocrude oil, respectively. Torrefaction, anaerobic digestion and transesterification underscore their contributions to enhancing biomass characteristics, waste management and renewable energy production. In essence, this comprehensive review elucidates the pivotal role of biomass within the global bioeconomy. It offers a roadmap towards a sustainable future by harnessing the regenerative potential of biomass resources across diverse sectors. The convergence of technological innovation, interdisciplinary collaboration and strategic utilisation of biomass paves the way for a bio-based economy, fostering environmental sustainability, economic growth and resilience amidst evolving socio-economic and environmental landscapes.

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Conflict of Interest

All authors declare that they have no conflicts of interest.

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