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**BIOMASS ENERGY:  
A MULTIDIMENSIONAL ANALYSIS OF SUSTAINABLE ENERGY TRANSITION**

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**ЭНЕРГИЯ БИОМАССЫ:  
МНОГОМЕРНЫЙ АНАЛИЗ В КОНТЕКСТЕ ПЕРЕХОДА  
К УСТОЙЧИВОЙ ЭНЕРГЕТИКЕ**

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*Abstract.* Global energy demand is growing exponentially due to increasing population, rapid urbanization, and industrialization. Fossil fuels, which currently account for approximately 80% of the primary energy supply, are proving insufficient for a sustainable energy future due to limited reserves, geopolitical vulnerabilities, and devastating climate impacts. This study comprehensively examines biomass energy from a systematic and interdisciplinary perspective. The study covers the structural chemistry of biomass, feedstock classification, pre-treatment stages, thermochemical (combustion, pyrolysis, gasification, liquefaction) and biochemical (anaerobic digestion, fermentation, biophotolysis) conversion technologies, and final product applications within an integrated framework. The main lignocellulosic components—cellulose (35–55%), hemicellulose (15–35%), and lignin (10–30%)—possess critical feedstock characteristics for different conversion pathways. Fermentation processes employing specific microorganisms such as *Saccharomyces cerevisiae* form the basis of bioethanol production, while anaerobic digestion yields biogas with 55–75% methane content alongside organic fertilizer. Fast pyrolysis converts biomass to liquid bio-oil with 60–70% efficiency at 450–550°C with short residence times; steam gasification offers high calorific value advantages in syngas production. The global bioenergy sector currently holds a 12% share of renewable energy generation as the largest renewable source and encompasses 3.58 million jobs. Biomass emerges as a strategic resource that must be placed at the center of energy policies, providing not only energy security but also reducing greenhouse gas emissions, utilizing agricultural wastes, and supporting rural development.

*Аннотация.* Глобальный спрос на энергию неуклонно возрастает в каждом последующем десятилетии в связи с увеличением численности населения, ускоренными процессами урбанизации и индустриализации. В настоящее время ископаемые топлива, обеспечивающие около 80 % первичного энергоснабжения, оказываются недостаточными для обеспечения

устойчивого энергетического будущего вследствие ограниченности запасов, геополитической уязвимости и разрушительного воздействия на климат. Настоящая работа представляет собой систематический и междисциплинарный анализ энергии биомассы, занимающей уникальное положение среди возобновляемых источников энергии. Оригинальный вклад исследования заключается в комплексной оценке, охватывающей путь от структурной химии биомассы, классификации типов сырья, стадий предварительной обработки, термохимических (сжигание, пиролиз, газификация, ожижение) и биохимических (анаэробное сбраживание, ферментация, биофотолиз) методов конверсии до областей конечного применения получаемых продуктов. Основные компоненты лигноцеллюлозной биомассы — целлюлоза (35–55%), гемицеллюлоза (15–35%) и лигнин (10–30%) — обладают критически важными свойствами сырья для различных маршрутов конверсии. В биохимических процессах ферментация с использованием специфических микроорганизмов, таких как *Saccharomyces cerevisiae*, лежит в основе производства биоэтанола; анаэробное сбраживание позволяет получать биогаз с содержанием метана 55–75%, обеспечивая одновременно производство энергии и органических удобрений. Среди термохимических методов быстрый пиролиз позволяет превращать биомассу при 450–550°C и коротком времени пребывания в жидкую бионефть с выходом 60–70 %; паровая газификация характеризуется получением синтез-газа с высоким теплотворным значением. В настоящее время биоэнергетика занимает ведущее положение среди возобновляемых источников, обеспечивая около 12% мирового производства возобновляемой энергии и создавая рабочие места для 3,58 млн человек. В итоге биомасса выступает стратегическим ресурсом, который должен занять центральное место в энергетической политике не только благодаря обеспечению энергетической безопасности, но и в силу способности снижать выбросы парниковых газов, утилизировать сельскохозяйственные отходы и способствовать развитию сельских территорий.

*Keywords:* biomass energy; lignocellulosic biomass; thermochemical conversion; biochemical conversion.

*Ключевые слова:* энергия биомассы; лигноцеллюлозная биомасса; термохимическая конверсия; биохимическая конверсия.

In no period of human history has energy carried as much strategic significance as it does today. Since the Industrial Revolution in the 18th century, global energy consumption has increased approximately 25-fold, with fossil fuels serving as the primary driver of this growth. However, their limited reserves, price volatility, and cumulative impacts on the climate call into question the long-term sustainability of fossil fuel-based energy systems. According to IEA data, as of 2018, fossil fuels accounted for approximately 81% of the global primary energy supply. In the same year, atmospheric CO<sub>2</sub> concentration reached 407 ppm, an increase of about 45% relative to pre-industrial levels (IEA, 2019).

This trajectory is incompatible with the 1.5°C temperature limit pledged under the Paris Agreement. Among renewable energy sources, biomass occupies a unique position: unlike solar and wind energy, it is storable, dispatchable based on demand, and versatile for producing electricity, heat, and transportation fuels [8].

Biomass is defined as the aggregate of organic matter of biological origin, encompassing an extremely broad spectrum of feedstocks—from agricultural and forestry residues to municipal solid waste, dedicated energy crops, and microalgae. According to the World Bioenergy Association

(WBA), in 2018, bioenergy accounted for 12% of global renewable energy consumption, representing more than 95% of renewables in the heating and cooling sector [8].

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The academic literature on biomass energy tends to focus either on specific conversion technologies (e.g., anaerobic digestion, pyrolysis) or on particular feedstock groups (e.g., microalgae, lignocellulosic wastes) [29].

This fragmented approach leaves policymakers and engineering practice without an integrated systems perspective. Yet the biomass-to-energy system constitutes a complex chain, extending from feedstock procurement through pretreatment, conversion, and end-use stages, where the optimization of each link determines the overall system efficiency. The present study aims to address this gap by providing a comprehensive and systematic examination of biomass energy, starting from its structural chemistry, through feedstock classification, pretreatment technologies, all existing conversion methods, and the resulting fuel products. Its distinguishing feature is an integrated assessment approach that combines technical analysis with economic, environmental, and social dimensions [1].

### *Materials and methods*

This study is a comprehensive review article based on systematic literature search and descriptive analysis methods [36].

To access the relevant research literature, the Web of Science, Scopus, ScienceDirect, and Google Scholar databases were searched. The primary keyword groups used in the search included: 'biomass energy conversion', 'lignocellulosic biomass', 'thermochemical conversion', 'biochemical conversion', 'biogas production', 'pyrolysis of biomass', 'biomass gasification', 'microalgae biofuel', 'anaerobic digestion'. The search was restricted to the period 1990–2024; sources that were not openly accessible or deemed methodologically inadequate were excluded from the evaluation. Technical data assessment drew upon reports from the IEA (International Energy Agency), WBA (World Bioenergy Association), IRENA (International Renewable Energy Agency), and various national energy regulatory bodies [24].

Kinetic data related to biochemical conversion processes were compiled based on experimental studies; thermodynamic parameters for thermochemical methods were interpreted within the framework of relevant international standards.

The conversion technologies covered in the study are organized under two main categories: (1) thermochemical methods (combustion, types of pyrolysis, gasification, liquefaction) and (2) biochemical methods (anaerobic digestion, fermentation, bio-photolysis) [17].

For each method, process parameters, efficiency indicators, product compositions, and application areas are systematically compared. Pretreatment technologies are addressed in a separate section, examined in the form of physical (size reduction, densification), chemical, and biological pretreatment stages.

### *Results and discussion*

*Chemical structure and basic components of biomass.* Lignocellulosic biomass constitutes the largest portion of the biosphere's biomass and represents a natural material matrix that converts solar energy into chemical bond energy through photosynthesis [30].

This matrix is primarily composed of three structural polymers—cellulose, hemicellulose, and lignin—whose relative proportions are directly influenced by both the type and growth conditions of the biomass and significantly affect the efficiency of the conversion process. Cellulose (35–55%) is a linear polysaccharide chain composed of D-glucose monomers linked by  $\beta$ -1,4-glycosidic bonds. This structure, which contains both crystalline and amorphous regions, exhibits considerable resistance to enzymatic hydrolysis by cellulases; this recalcitrance is one of the primary factors increasing the cost of bioethanol production [4].

Hemicellulose (15–35%) is a branched heteropolysaccharide consisting of xylose, mannose, arabinose, and galactose units [26].

Compared to cellulose, it has a lower degree of polymerization and reduced thermal stability, rendering it more susceptible to a wide range of pretreatment methods. Lignin (10–30%) is a three-dimensional, amorphous, aromatic polymer formed from phenolic propan units; it provides structural rigidity to the biomass [31].

Owing to its high energy density (approximately 26 MJ/kg), lignin represents a valuable feedstock for the production of biochar and phenol-derived chemicals [17].

The composition ranges reported in the literature for different biomass types play a decisive role in the selection of appropriate conversion technologies [13].

For example, in hardwoods such as birch, cellulose accounts for approximately 41%, hemicellulose 36.2%, and lignin 18.9%; in agricultural residues such as corn stover, cellulose ranges from 35–39.6%, hemicellulose from 16.8–35%, and lignin from 7–18.4%. Rice husk, by contrast, exhibits a distinctive feedstock profile due to its high silica content (14–17% extractable matter), which complicates ash management during thermochemical conversion processes. The critical parameters for the energy conversion of biomass are not limited to polymer composition. Additional factors—including pH, carbon-to-nitrogen (C/N) ratio (optimal range 20:1–30:1 for biological conversion processes), organic loading rate, particle size, and moisture content—directly influence overall conversion efficiency [38].

Biomass feedstocks can be classified into two main categories based on their resource characteristics and economic value: (I) waste-derived biomass and (II) purpose-grown energy crops [8]. The balance between these two categories lies at the core of debates regarding whether bioenergy policies conflict with food security.

*Waste biomass resources.* Forest residues include materials left after harvesting, such as branches, bark, stumps, and processing residues from the timber industry. Utilizing these residues for bioenergy purposes provides additional benefits for forest health and wildfire risk management [14].

Agricultural residues encompass materials remaining after harvest, including straw, corn cobs, rice husks, sugarcane bagasse, and hazelnut shells. With their high lignocellulosic content, these residues serve as priority feedstocks for second-generation bioethanol production. Municipal solid waste (MSW) contributes to biogas and energy production through its organic fraction as well as biodegradable components such as paper and textiles. Animal wastes, owing to their high nitrogen content and natural bacterial populations, form highly suitable substrates for anaerobic digestion processes, yielding not only biogas but also valuable organic fertilizer.

*Purpose-grown energy biomass types.* Energy forestry relies on short-rotation cultivation of fast-growing tree species such as poplar, willow, eucalyptus, and others [25].

These systems deliver high wood biomass yields per unit area while simultaneously supporting land remediation and functioning as carbon sinks. Among energy crops, the most commonly used include starch-rich sources such as corn and sugar beet, oilseed sources such as rapeseed and sunflower, and cellulosic sources such as miscanthus and switchgrass (*Panicum virgatum*). Sugarcane stands out among these crops for achieving the highest energy yield per unit land area and currently

forms the backbone of large-scale bioethanol production, particularly in tropical and subtropical climate zones.

Microalgae are attracting increasing interest in energy biomass research. Certain species of *Chlorella* and *Nannochloropsis* can reach lipid contents of 20–50% on a dry weight basis, indicating a potential oil production per unit area that is 10–100 times higher than that of conventional oilseed crops [28, 33].

Furthermore, microalgae offer significant sustainability advantages: they can utilize saline or wastewater instead of freshwater, avoid competition with agricultural land, and perform carbon sequestration through CO<sub>2</sub> uptake. Aquatic plants (such as water hyacinth and reeds) can be integrated into wastewater treatment systems, making them valuable components of combined energy-environment systems.

*Biomass pretreatment technologies.* Raw biomass cannot be fed directly into conversion reactors; it must first undergo physical, chemical, or biological pretreatments [5].

These preparatory steps have a direct and decisive impact on conversion efficiency. Moisture removal and drying are critical to meet the requirement of moisture content below 50% for direct combustion processes. In industrial applications, belt dryers, rotary drum dryers, and atmospheric steam drying units are commonly employed. Size reduction operations—performed using grinding, chipping, and cutting equipment—are essential to ensure uniform feeding into conversion reactors. For gasification and pyrolysis systems, the optimal particle size range is typically specified as 1–10 mm. Densification (pelletizing and briquetting) involves compressing low bulk density biomass (e.g., straw with a bulk density of ~70–90 kg/m<sup>3</sup>) into pellets or briquettes with densities ranging from 350–1200 kg/m<sup>3</sup>. This process reduces transportation and storage costs while improving combustion efficiency. For lignocellulosic biomass, torrefaction—a mild oxygen-free thermal pretreatment conducted at 200–320°C—is gaining increasing importance. This treatment enhances the energy density of biomass, reduces its hygroscopicity, and improves grindability, thereby enabling the production of 'biocoal pellets'.

*Anaerobic digestion and biogas production.* Anaerobic digestion is a multi-stage biological process in which organic matter is converted into biogas and digestate through the coordinated activity of different metabolic groups of microorganisms operating in an oxygen-free environment [38].

The process is typically divided into four fundamental stages: (1) hydrolysis — breakdown of macromolecules into simple sugars, amino acids, and fatty acids; (2) acidogenesis — production of organic acids, alcohols, and H<sub>2</sub>/CO<sub>2</sub>; (3) acetogenesis — formation of acetate, H<sub>2</sub>, and CO<sub>2</sub>; (4) methanogenesis — synthesis of methane by methanogenic archaea such as *Methanosaeta* and *Methanosarcina* from acetate or H<sub>2</sub>/CO<sub>2</sub> [14].

The typical composition of the produced biogas is 55–75% CH<sub>4</sub>, 25–45% CO<sub>2</sub>, with trace amounts of H<sub>2</sub>S, N<sub>2</sub>, and water vapor. The lower heating value of biogas is approximately 5200 kcal/m<sup>3</sup> (21.8 MJ/m<sup>3</sup>). Key parameters for process optimization include: carbon-to-nitrogen (C/N) ratio (optimal range 20–30:1), temperature (mesophilic: 35–40°C; thermophilic: 50–60°C), hydraulic retention time (HRT), organic loading rate (OLR), and pH (range 6.5–8.5). Animal manure is the most widely used substrate; reported C/N ratios are approximately 18 for cattle manure, 22 for sheep/goat manure, and 14 for poultry manure. A major systemic advantage of anaerobic digestion, beyond energy recovery, is the production of a sanitized, nutrient-rich digestate (high in nitrogen and phosphorus) that serves as a valuable organic fertilizer.

*Fermentation and bioethanol production.* Bioethanol production from biomass represents one of the most extensively industrialized biomass conversion processes to date [26].

Production systems are classified according to the “generation” concept based on feedstock characteristics. First-generation bioethanol is produced directly via hydrolysis and fermentation of sugar-rich (sugarcane, sugar beet) or starch-rich (corn, wheat) crops and currently accounts for the majority of global production. Second-generation bioethanol, derived from lignocellulosic feedstocks, is considered superior from a sustainability perspective because it avoids competition with food production and utilizes a broader range of raw materials.

The main stages of lignocellulosic bioethanol production can be summarized as follows: pretreatment (acid/base hydrolysis, steam explosion, ammonia fiber expansion — AFEX), enzymatic hydrolysis (release of sugars using cellulase and hemicellulase enzymes), and fermentation (typically performed by *Saccharomyces cerevisiae* or engineered strains of *Zymomonas mobilis* or *Escherichia coli*) [2].

*S. cerevisiae* remains the industrial workhorse of fermentation biotechnology, with optimal operating conditions of 24–40°C and pH 4.5–5.0; fermentation is usually completed within 1–3 days [37].

Glucose metabolism follows the Embden–Meyerhof–Parnas (EMP) pathway, yielding 2 mol of ATP and 2 mol of ethanol per mole of glucose. The primary technological bottleneck is the high cost of cellulase enzymes; however, recent advances in enzyme production based on *Trichoderma reesei* have substantially reduced this cost [22].

*Bio-photolysis: Biohydrogen production from solar energy.* Bio-photolysis is an advanced biohydrogen production method in which microalgae and cyanobacteria use solar energy to split water molecules into H<sub>2</sub> and O<sub>2</sub> [20, 32].

Direct bio-photolysis relies on green algae such as *Chlamydomonas reinhardtii*, which produce H<sub>2</sub> under anaerobic conditions via hydrogenase enzymes [6].

The major limitation of this system is the rapid inactivation of hydrogenase in the presence of oxygen [10].

Indirect bio-photolysis was developed to circumvent this issue through a two-stage process: in the first stage, biomass (carbohydrates) is accumulated via photosynthesis; in the second stage, these carbohydrates are fermented to H<sub>2</sub> under dark anaerobic conditions [11].

Cyanobacterial species such as *Anabaena cylindrica* and *Anabaena variabilis* achieve the highest biohydrogen yields in this process through the combined action of nitrogenase and hydrogenase enzymes [23].

Bio-photolysis remains a promising carbon-neutral and renewable hydrogen production technology; however, it has not yet progressed beyond the pilot scale and continues to be an active area of research [27].

*Thermochemical conversion methods: Direct combustion, pyrolysis and its types, gasification, liquefaction.* Biomass combustion represents the oldest energy conversion process in human history [25].

In modern applications, biomass is subjected to oxidation at temperatures of 800–1000°C in fluidized bed boilers, grate combustion systems, and co-firing arrangements. Under ideal combustion conditions with stoichiometric oxygen supply, complete oxidation yields only CO<sub>2</sub> and H<sub>2</sub>O. In practice, however, factors such as excess air coefficient, particle size, and moisture content directly influence combustion efficiency. When the moisture content of biomass exceeds 50%, the lower heating value is critically reduced, jeopardizing the sustainability of the combustion process. Modern combined heat and power (CHP) systems can achieve overall energy efficiencies exceeding 80%.

Pyrolysis is the thermal decomposition of biomass in an oxygen-free atmosphere [7].

Reaction temperature and residence time fundamentally determine the product distribution: low temperature–long residence time favors biochar production; high temperature–long residence time

favors gaseous products; moderate temperature–short residence time favors liquid bio-oil. These parametric relationships correspond to the three main subcategories of pyrolysis technology. Slow (conventional) pyrolysis is carried out at 300–600°C with residence times ranging from hours to days and is primarily focused on biochar (biocoal) production [16].

Charcoal production remains the most widespread historical and contemporary application of this method. Fast pyrolysis, performed at 450–550°C with residence times on the order of seconds, provides optimal conditions for liquid bio-oil production with yields of 60–70% [9].

The resulting bio-oil—also referred to as pyrolysis liquid, biocrude, or biofuel—can be used directly in combustion furnaces or, following upgrading, as a substitute for gasoline and diesel. Flash pyrolysis occurs at approximately 500°C with residence times of less than one second and produces high yields of tar-like liquid products. Gasification is a thermochemical process in which biomass is converted into synthesis gas (syngas: a mixture of H<sub>2</sub> and CO) at temperatures above 600°C in the presence of reactants such as O<sub>2</sub>, air, steam, or CO<sub>2</sub> [5].

Comparison of the four main reactant options reveals distinct differences. Air gasification offers low-cost advantages but results in a diluted syngas with a heating value limited to 4–8 MJ/Nm<sup>3</sup> due to nitrogen dilution [12, 18].

Oxygen gasification produces a nitrogen-free syngas with a higher heating value (12–18 MJ/Nm<sup>3</sup>) and H<sub>2</sub> concentrations of 14–32%, although the high cost of oxygen production is a significant drawback. Steam gasification stands out as the most advantageous method for generating hydrogen-rich syngas; the steam-to-biomass (S/B) ratio and temperature are critical variables determining product composition [34].

Literature reports indicate that at an S/B ratio of 0.37, steam conversion rates can reach 67%, with the H<sub>2</sub> content increasing to 11% by volume [15].

Hydrothermal liquefaction (HTL) is a process in which biomass is converted into liquid hydrocarbons under high pressure (5–20 MPa) and moderate temperature (250–550°C), typically in the presence of alkali catalysts and a hydrogen atmosphere. Compared to pyrolysis, HTL requires lower temperatures and does not necessitate prior drying, representing its primary advantages. Pure cellulose can be liquefied in less than one hour at 300°C and 19.5 MPa. In catalytic liquefaction processes such as LBL and PERC, bio-oil yields of up to 50% have been achieved from poplar wood [3].

Approximately 50% of the product consists of phenolic compounds, which structurally distinguishes HTL bio-oil from crude petroleum and necessitates advanced upgrading.

*Biomass energy products and application areas.* Biomass conversion processes yield six primary energy product categories: bioethanol, biomethanol, biodiesel, biogas, synthesis gas (syngas), and biochar. This diversity positions biomass as the most versatile renewable energy source within the energy portfolio.

Bioethanol is blended with gasoline in specified proportions (E10: 10% ethanol; E85: 85% ethanol) and used as a transportation fuel. It promotes cleaner combustion of gasoline and reduces exhaust emissions. Biomethanol plays a critical role as both solvent and reactant in biodiesel transesterification processes and can also be produced via catalytic conversion of biomass-derived syngas. Biodiesel is obtained through transesterification of vegetable oils or animal fats with alcohols (predominantly methanol) and can be used directly in diesel engines or blended with petroleum diesel. The combustion quality of biodiesel is characterized by its cetane number, which in most cases equals or exceeds that of mineral diesel.

Synthesis gas (syngas), a mixture of H<sub>2</sub> and CO in varying ratios, serves as a versatile intermediate product. It can be converted via Fischer–Tropsch synthesis into liquid hydrocarbons, methanol, dimethyl ether (DME), or directly into electricity in fuel cells. Biochar, produced through

pyrolytic processes, is distinguished by its high carbon sequestration capacity and is primarily used as a soil amendment. Due to its long-term carbon storage potential in the fight against global warming, biochar is recognized as a multifunctional product that simultaneously enhances agricultural productivity and contributes to climate change mitigation.

*Global assessment of bioenergy.* According to the IEA's World Energy Outlook 2019 report, under the stated policies scenario, fossil fuels are projected to maintain their dominance in global energy supply through 2040, although renewables will experience substantial absolute growth. This projection underscores the urgent need to scale up technologies that reduce fossil fuel dependence. Bioenergy is well positioned to serve as a critical bridging technology during this transition [21].

In terms of sectoral distribution, heating and cooling represent the largest application area for bioenergy, accounting for more than 95% of global renewable heat production. In electricity generation, bioenergy ranks as the third-largest renewable source with an output of 637 TWh, trailing only hydropower and wind. In the transport sector, as of 2018, approximately 160 billion liters of liquid biofuels were produced, meeting roughly 3% of total transport energy demand. Global biogas production reached 59.3 billion m<sup>3</sup> in the same year, with 52% originating from Europe.

With respect to fuel production, wood pellets have been the fastest-growing bioenergy segment over the past decade: global wood pellet production was estimated at 39 million tonnes in 2019, while charcoal production reached 53 million tonnes, of which 65% was used for heating and cooking in Africa. In terms of employment, the global bioenergy sector provides 3.58 million direct jobs, maintaining its position as the second-largest employer among renewable energy sectors.

The world's largest biomass power plant is the Drax power station in the United Kingdom (2,595 MW installed capacity, wood pellet-fired). Other notable facilities include Russia's 300 MW Kirov plant and Finland's three major installations (Alholmens Kraft 265 MW, Toppila 210 MW, and Keljonlahti 209 MW), which rank among the global leaders. In the case of Finland, the national target of meeting 100% of energy demand from renewable sources by 2050 explains the structural drivers behind the continued growth of bioenergy in that country.

*Economics of installation and operation of biomass power plants.* The economic viability of biomass power plants is determined by the interplay of feedstock procurement costs, capital investment expenditures, operation and maintenance expenses, and revenue from energy sales. Model calculations for biogas plants (based on municipal solid waste) indicate that, under appropriate incentive mechanisms, payback periods can range from 2.5 to 4 years. For a 1 MW installed capacity, investment costs remain competitive with solar energy systems, depending on the type of biomass and the selected technology. Combined heat and power (CHP) systems significantly enhance overall energy efficiency, resulting in substantially shorter payback periods compared to electricity-only generation.

Proximity to feedstock sources constitutes a fundamental planning criterion for minimizing logistics costs [12]. The most critical variable in biomass supply is the accessibility and seasonal reliability of raw materials. Consequently, successful biomass energy projects adopt an integrated supply-chain approach based on long-term feedstock supply agreements with farmer cooperatives, forestry enterprises, and municipal waste management systems.

*Environmental and social dimensions.* The environmental assessment of bioenergy constitutes a complex and multidimensional field of debate. Among the principal advantages, the following stand out: Carbon cycle neutrality — the CO<sub>2</sub> released during biomass combustion is re-absorbed from the atmosphere through photosynthesis, thereby preserving long-term carbon cycle balance. The application of biochar further supports this process, enabling enhanced long-term carbon sequestration. Municipal waste management — energy recovery from municipal solid waste (MSW) reduces the need for landfilling, prevents groundwater contamination from leachate, and mitigates

uncontrolled methane emissions. Agricultural development — biomass production and processing increase economic returns per hectare in rural areas, provide supplementary income sources, and enable value recovery from agricultural residues.

Nevertheless, bioenergy also entails significant limitations and potential adverse impacts. Land-use and food security conflicts — the use of food crops for energy purposes (the so-called “food vs. fuel” debate) continues to occupy a prominent place on the global agenda. Second-generation biomass feedstocks substantially alleviate this issue, although they do not eliminate it entirely. Biodiversity pressure — conversion of natural habitats into energy plantations or dedicated energy crop cultivation can lead to biodiversity loss. For this reason, life cycle assessment (LCA) approaches have become an indispensable tool for determining the net environmental benefit of biomass projects. Emission management — inefficient combustion of biomass under suboptimal conditions can result in the release of particulate matter, NO<sub>x</sub>, and certain organic pollutants, thereby adversely affecting air quality.

### *Conclusion*

This review article has examined biomass energy from a broad perspective, spanning its structural chemistry to its role in global energy policy, thereby comprehensively elucidating its multidimensional significance in the transition to sustainable energy systems. The key findings are synthesized below within an integrated framework. At the feedstock level, the primary polymeric components of lignocellulosic biomass—cellulose (35–55%), hemicellulose (15–35%), and lignin (10–30%)—exhibit distinct reactivity profiles that constitute the scientific basis for selecting appropriate conversion technologies. Among biomass types, microalgae stand out as a focal point for next-generation biofuel research, offering oil production potentials 10–100 times higher per unit area than conventional energy crops. The utilization of waste biomass streams (agricultural residues, forest residues, municipal solid waste) provides an economically advantageous feedstock base that is independent of primary land-use pressures and fully aligned with circular economy principles. With respect to conversion technologies, biochemical and thermochemical pathways have been shown to be complementary. Anaerobic digestion, when optimized with respect to the C/N ratio (20–30:1), yields biogas containing 55–75% methane and delivers dual benefits through the co-production of organic fertilizer. The primary barrier to lignocellulosic fermentation—the high cost of cellulase enzymes—is being progressively overcome through advances in enzyme production based on *Trichoderma reesei*. Fast pyrolysis (450–550°C, residence times on the order of seconds) emerges as the most efficient thermochemical conversion technology, achieving liquid bio-oil yields of 60–70%.

Steam gasification produces hydrogen-rich syngas suitable as feedstock for both fuel cell systems and chemical synthesis processes. Bio-photolysis remains a forward-looking technology that promises carbon-neutral hydrogen production from solar energy, although it is still maturing at the research scale. In terms of energy products, biomass demonstrates a unique capacity to generate energy carriers in solid (biochar, pellets), liquid (bioethanol, biomethanol, biodiesel, bio-oil), and gaseous (biogas, syngas, biohydrogen) forms, offering a far broader application spectrum than any other renewable resource.

The dual functionality of biochar — as a soil amendment and a long-term carbon sink—positions biomass as a direct contributor to negative emissions technologies (NETs) in the context of climate change mitigation. Global sector analysis confirms that, as of 2018, bioenergy held the largest share (12%) of global renewable energy consumption, accounted for more than 95% of renewable heat production, and supported 3.58 million direct jobs, underscoring its substantial socio-economic development potential. The ongoing global expansion of biomass power plants—particularly evident

in Finland, the United Kingdom, and other Northern European countries—highlights the decisive role of state-supported incentive mechanisms and long-term policy commitments.

From an environmental perspective, biomass exhibits significantly lower life-cycle emissions compared to fossil fuels; however, this advantage varies considerably depending on feedstock type, supply-chain characteristics, and conversion technology. Second-generation biomass technologies substantially minimize conflicts among food, energy, water, and land systems, thereby strengthening the sustainability profile of bioenergy. Life cycle assessment (LCA) and ecosystem services analysis should be adopted as integral methodological tools in the design of biomass energy projects. From a policy standpoint, realizing the full potential of biomass energy requires inter-sectoral coordination (agriculture, forestry, energy, environment) and the establishment of stable, long-term incentive mechanisms.

Key policy instruments include programs for the valorization of agricultural residues, technical support packages for energy forestry, integration of municipal solid waste management with energy recovery systems, and access to financing for small- and medium-scale producers. Incorporating farmers and rural communities into the biomass production–conversion value chain will accelerate the energy transition while simultaneously supporting rural development and agricultural resilience. Priority research areas include: scaling up microalgae production and reducing associated biofuel costs; overcoming efficiency barriers in bio-photolysis processes; optimization of advanced pretreatment technologies such as torrefaction and hydrothermal processing; comparative LCA-based evaluation of different biomass–conversion technology combinations; and integrated system analysis of biomass-based carbon capture and storage technologies (bioenergy with carbon capture and storage – BECCS) [19].

In conclusion, biomass constitutes an indispensable component of the sustainable energy transition owing to its storability, multi-sectoral application potential, wide geographical adaptability, and versatility within the bioeconomy value chain. Given that the shift from fossil-based to renewable energy systems entails a systemic transformation encompassing not only technical but also economic, social, and ecological dimensions, a comprehensive understanding of biomass from this integrated perspective is a fundamental imperative for both scientific research and effective policy design.

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