

Sustainable Bioenergy: A Review of Biomass Conversion Technologies and Their Environmental Impacts

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Abstract

As the world moves toward sustainable energy systems, bioenergy has become a key component, presenting both benefits and difficulties in the quest for carbon neutrality. The global switch to renewable energy depends heavily on modern bioenergy, which provides dispatchable electricity and adaptability to supplement intermittent sources like solar and wind. Heat, electricity, and fuels can be produced from biomass by thermochemical, biochemical, and chemical routes. This includes biomass from lignocellulosic wastes and energy crops to municipal garbage and algae. The present state of knowledge about biomass resources, conversion methods, environmental consequences, and the socioeconomic aspects of bioenergy is summarized in this paper. By combining knowledge from environmental science, engineering, and policy, the study seeks to offer a fair evaluation of how bioenergy contributes to the attainment of global decarbonization objectives. Additionally, the study outlines future research goals, such as the potential of bioenergy with carbon capture and storage (BECCS) as a long-term climate solution, enhanced pretreatment techniques, biorefinery integration, and hybridization with other renewable energy sources. In order to balance the advantages and disadvantages of deploying sustainable bioenergy, this thorough review attempts to educate researchers, legislators, and industry stakeholders. Ultimately, the deployment of sustainable bioenergy is a complex issue for the twenty-first century as well as a crucial potential since it depends on balancing energy demands with ecological and societal limitations.

Keywords: Bioenergy, Biomass conversion, Environmental impacts, Life Cycle Assessment, Dispatchable energy and Sustainable policy.

INTRODUCTION

Global energy consumption has increased at an unprecedented rate in the twenty-first century due to growing urbanization, population growth, and industrialization. The International Energy Agency estimates that under current practices, the world's energy demand will increase by roughly 25–30% by 2040. According to predictions of population growth and the

growth of energy-dissipative economic activity in the upcoming decades, the world's energy demand is rising and is only anticipated to rise further (Chaturvedi *et al.*, 2013; Benti *et al.*, 2021).

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Fossil fuels, which are directly related to greenhouse gas (GHG) emissions and climate change, continue to dominate the energy industry despite notable advancements in renewable energy technologies (Adams, Klobodu, and Apio, 2018; Benti *et al.*, 2021). Fossil fuels still provide the majority of energy, particularly electricity, today.

Modern renewables like solar, wind, and biomass only contribute a small percentage of the world's electricity, while nuclear and hydropower each provide less than 10%.

But according to the primary energy sources trend, renewable energy will expand at the fastest rate over the next 20 years (Bahadori, 2021; Benti *et al.*, 2021). For about one-third of primary energy, biomass is used. Bioenergy can take the role of fossil fuels in hard-to-decarbonize sectors (transport, heat, and electricity) in climate mitigation scenarios (Reid, Ali, and Field, 2020). But widespread bioenergy raises sustainability issues: land-intensive bioenergy can risk food production and biodiversity and create "carbon debt" through changes in land use (DeCicco and Schlesinger, 2018; European Academies Science Advisory Council, 2019; Searchinger, Wiersenius, Beringer and Dumas, 2018). In this regard, renewable energy technologies such as hydropower, wind, solar, and bioenergy have become essential means of guaranteeing energy security and minimizing environmental harm. Bioenergy stands out among these because of its adaptability, energy storage capability, and potential for integration into current energy infrastructures.

About 10% of the world's primary energy supply and about 55% of all renewable energy use come from biomass, making it the greatest renewable energy source in the world (REN21, 2023). Its versatility can be integrated into current energy infrastructures and transformed into heat, power, and biofuels for transportation makes it significant. Biomass energy can offer a steady baseload supply, guaranteeing energy system dependability in contrast to intermittent sources like solar and wind (Scarlat *et al.*, 2015). Utilizing a variety of feedstocks, such as algae, forestry byproducts, municipal solid waste, agricultural residues, and energy crops, is a key benefit of biomass. Regional adaptability is ensured by this diversity, particularly in rural areas where the deployment of other renewable technologies may provide difficulties.

Furthermore, because biomass systems reduce environmental burdens by converting waste streams into energy and value-added goods, they are frequently linked to models of the circular economy. Since CO₂ emitted during combustion is theoretically offset by CO₂ absorbed during

plant development, biomass has long been seen as carbon neutral from a climatic standpoint. However, because lifecycle emissions are highly dependent on supply chain logistics, conversion technologies, and land-use change, the carbon neutrality discussion is still controversial (Searchinger *et al.*, 2018). However, under sustainable management, biomass can help mitigate greenhouse gas emissions and be a key factor in decarbonizing hard-to-abate businesses including heavy industries, shipping, and aviation (IRENA, 2024).

This review aims to contribute to the conversation on the deployment of sustainable bioenergy by offering a thorough examination of biomass conversion technologies and their effects on the environment. Evaluation of conversion technologies, including thermochemical, biochemical, and chemical processes; classification and analysis of the different biomass resources available for energy production, such as lignocellulosic residues, energy crops, municipal solid waste, and algae; and a critical assessment of the environmental impacts of bioenergy systems, with a focus on GHG emissions, air quality, water use, land use, and biodiversity. To assess the overall sustainability of biomass-based energy systems, the evaluation also incorporates results from life cycle assessment (LCA) research. Given their importance to the regional and worldwide adoption of bioenergy, socioeconomic and policy aspects are also examined, including rural development, energy security, and the food versus fuel controversy. The study concludes by outlining research gaps and prospective avenues for future study, such as developments in feedstock pretreatment, the incorporation of bioenergy into biorefineries, and its possible contribution to the implementation of deep decarbonization plans. This evaluation attempts to give policymakers, researchers, and industry stakeholders a fair assessment of the role of bioenergy in the global shift to sustainable energy systems by combining existing knowledge and pointing out both potential and obstacles.

BIOMASS RESOURCES FOR BIOENERGY

The largest and most adaptable renewable energy source is biomass, which accounts for over 10% of global primary energy consumption and nearly 60% of renewable energy worldwide (REN21, 2023). It includes a broad variety of organic feedstocks made from garbage, plants, and animals that can be used to produce fuel, electricity, and heat. Land-use practices, socioeconomic considerations, and regional agro-ecological conditions all have a significant impact on the availability, composition, and sustainability of biomass resources (Scarlat *et al.*, 2019). A vast variety of organic materials are used as biomass feedstocks.

Key categories include:

Lignocellulosic biomass: Woody crops, grasses, and crop and forest wastes are examples of non-food plant matter made up of cellulose, hemicellulose, and lignin. Biofuels derived from lignocellulose may lower greenhouse gas emissions, boost the economy, and improve energy security. A plentiful source of this type of second-generation biomass is derived from forestry or agricultural waste. Over 1.3×10^9 t/yr of lignocellulose, for instance, has been anticipated to be available globally for biofuel production without interfering with food supply (El-Araby, 2024). Biotechnology techniques are being used by the US and the EU to produce 1.3 billion tons a year without sacrificing food security (Mat Aron *et al.*, 2020; El-Araby, 2024).

Energy crops: To reduce competition with food, fast-growing, specialized crops (such as switchgrass, miscanthus, poplar, and willow) are planted in marginal or degraded areas. Food and fuel sources may compete as a result of the first-generation biofuels' frequent use of edible feedstocks such corn, soybeans, wheat, sunflower oil, and palm oil (Saladini *et al.*, 2016; Wang *et al.*, 2024).

These perennials are frequently developed for their high cellulose or sugar content and can produce a lot of biomass per hectare.

Municipal Solid Waste (MSW): Both biological and thermochemical methods can be used to treat the organic components of home and industrial waste, such as food scraps, yard debris, and paper. In biogas plants or waste-to-energy facilities, MSW (food/yard waste) is being used more and more to produce electricity while lowering methane emissions from landfills. Since the discovery of fire, these plants have changed from wood to biochar, forest products, and other renewable resources (Murthy *et al.*, 2021; El-Araby, 2024).

Algae: Second-generation bioenergy feedstocks are microalgae and macroalgae (seaweeds). With saline or wastewater, they can be grown on non-arable land (ponds, photobioreactors, etc.) and give incredibly high growth rates and biomass productivity. First- and second-generation biofuels are produced from algae, which photosynthesise more quickly than land plants (El-Araby, 2024). Unlike conventional crops, algae do not compete with them and can amass large amounts of oil or

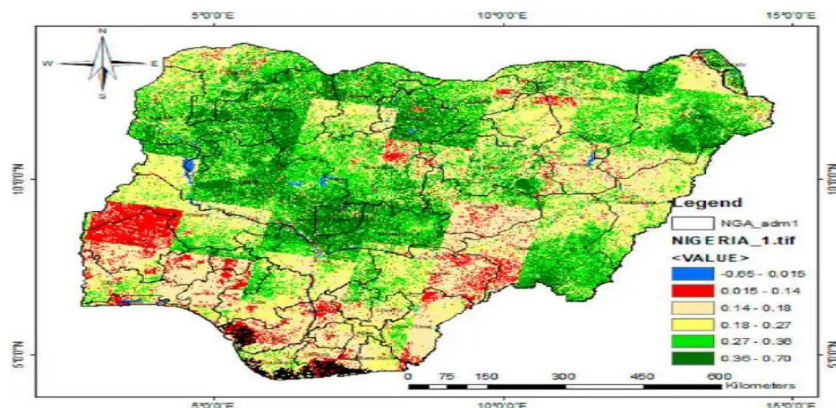


Fig1. Nigerian biomass distribution

Source: Ukoba *et al* (2024)

carbohydrates for biodiesel or bioethanol.

Other wastes and residues: Other resources include industrial off-gases, fats and oils (tallow, spent cooking oil), and animal dung. By turning these wastes into biogas or biofuels, a circular economy can close material loops (El-Araby, 2024).

Every feedstock has different sustainability factors to take into account (land use, water consumption, nutrient cycles). In order to reduce waste streams and avoid competition with food, it is generally preferred to use non-food residues and wastes. Because of differences in temperature, land-use patterns, and agricultural techniques, biomass resources are widely distributed

around the world, yet their availability varies greatly by region. In Asia, for example, lignocellulosic residues like crop stalks, husks, and bagasse are common since nations like China and India produce enormous amounts of agricultural byproducts (Scarlat *et al.*, 2019). There are also substantial amounts of agricultural wastes in Sub-Saharan Africa, but a large portion of them go unused because of inadequate infrastructure and a lack of bioenergy regulations (IEA, 2022).

The EU's Renewable Energy Directive and sustainable forest management have made energy crops and forest residues the primary sources of biomass in Europe (Thrän *et al.*, 2020). The United States leads the world in the

production of second-generation bioethanol, and North America benefits from a combination of woody biomass, corn stover, and municipal solid waste (MSW). The availability of marine resources and rising investment in microalgae-based biorefineries have led to an increased exploration of algal biomass in coastal regions of Asia and Europe (Khan *et al.*, 2018). But regional differences still exist: Africa and parts of South America frequently struggle to mobilize biomass because of poor storage, transportation, and policy frameworks, whereas North America and Europe have established biomass supply chains.

It is crucial to ensure the sustainability of biomass resources since extensive use could put food production in competition, harm ecosystems, and worsen water stress. In developing nations where land resources are already limited, energy crops like corn, sugarcane, and oil palm, for instance, intensify the struggle between food and fuel (Tilman *et al.*, 2009). Focus is now being placed on non-food lignocellulosic wastes and waste streams in order to combat this, as they reduce direct rivalry with the food supply (Cherubini, 2010). The regional water footprint of biomass production is another sustainability concern.

Table 1. Global biomass resource availability and potential

Biomass Source	Global Potential (EJ/year)	Key Region	Notes on Availability & Sustainability	References
Agricultural residues (straw, husks, stalks)	20–50	Asia, Africa, Latin America	High availability, avoids food vs. fuel debate	Scarlat <i>et al.</i> , 2015; IEA, 2021)
Forestry residues	10–30	North America, Europe, Russia	Linked to sustainable forest management	Berndes <i>et al.</i> (2003)
Municipal solid waste (MSW)	10–15	Urban centers worldwide	Waste-to-energy reduces landfill pressure	Moya <i>et al.</i> (2017)
Energy crops (switchgrass, miscanthus, jatropha)	30–70	US, EU, Brazil, Sub-Saharan Africa	High yield but land-use conflict	Tilman <i>et al.</i> , 2009
Algal biomass	20–80	Coastal regions, ponds, photobioreactors	High productivity, still costly	Chisti (2007)

Water scarcity may be made worse by the need for heavy irrigation for crops like maize and sugarcane in arid areas (Gerbens-Leenes *et al.*, 2009). In the meanwhile, algae-based bioenergy is thought to be more sustainable because it can grow in salty water and non-arable terrain, which lessens the strain on freshwater resources.

BIOMASS CONVERSION TECHNOLOGIES

Technologies for converting raw biomass feedstocks into useable energy sources including heat, electricity,

and liquid fuels are the foundation of the bioenergy industry. With respect to operating conditions, feedstock appropriateness, and principles, these technologies can be roughly categorized into three categories: thermochemical, biochemical, and chemical pathways (Demirbas, 2011). The type of biomass resource, the desired energy product, technological maturity, cost-effectiveness, and environmental performance are some of the factors that influence the conversion pathway selection. Each of these approaches has its own advantages and disadvantages,

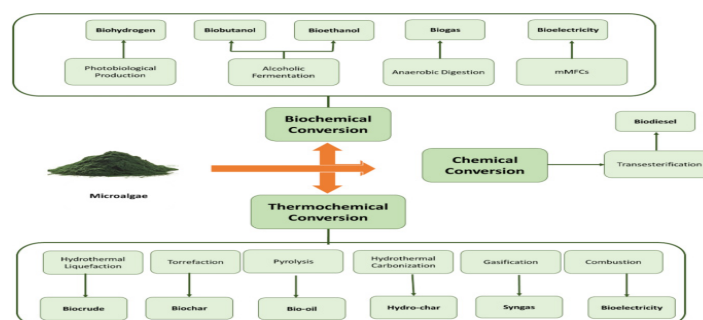


Figure 1. Different types of algal biofuels and conversion technologies

Source: Ali *et al.* (2024; El-Araby (2024)

but taken as a whole, they offer a variety of choices for incorporating biomass into the global energy mix.

An in-depth understanding of these conversion technologies is critical for evaluating their efficiency, scalability, and environmental impacts.

Each pathway encompasses specific technologies as discussed below:

THERMOCHEMICAL PROCESSES

Thermochemical processes convert biomass into energy-carrying gases, liquids, and solids by applying heat, pressure, and regulated oxygen conditions. The oldest and most used method for producing heat and electricity is combustion, which is followed by pyrolysis, gasification, and combustion. These techniques provide quick conversion rates with comparatively high energy efficiency, and they work especially well with dry, lignocellulosic feedstocks (McKendry, 2002).

- i. **Combustion:** Burning biomass at 800–1000 degrees Celsius in the air to produce steam or heat. One of the oldest and most fundamental methods of biomass conversion is the burning of organic materials to produce energy and heat. Burning biomass in the air and transforming its chemical energy into heat, mechanical power, or electrical energy is known as combustion. Simmers, boilers, steam turbines, boilers, furnaces, and turbo-generators are some of the process equipment used in the combustion process (Escalante *et al.*, 2022; El-Araby, 2024). Heat, electricity, or combined heat and power (CHP) from burning biomass are the main combustion products. CHP is a successful method that uses subsequent heterogeneous and homogeneous processes to use both heat and power (Correa *et al.*, 2019).
- ii. **Pyrolysis:** Biomass is thermally decomposed at temperatures between 400 and 700 degrees Celsius without the presence of oxygen, producing syngas, charcoal, and liquid bio-oil. While slow pyrolysis or torrefaction generates char for solid fuel or soil amendment, fast pyrolysis produces bio-oil appropriate for fuel (El-Araby, 2024).
- iii. **Gasification:** High temperatures (600–1500 °C) cause biomass to partially oxidize, producing combustible syngas (CO, H₂, CH₄). After tar is cleaned, gasification provides a clean “fuel” gas that can be burned to generate electricity or converted into fuels (by Fischer-Tropsch) (El-Araby, 2024; Balopi *et al.*, 2025).
- iv. **Hydrothermal liquefaction (HTL):** Hydrochar and biocrude oil are produced by processing wet biomass in water at high pressure and moderate temperature (El-Araby, 2024). HTL produces a crude oil that may be refined into fuels by handling wet wastes without drying them out, unlike pyrolysis.

BIOCHEMICAL PROCESSES

Biochemical conversion is the process of breaking down biomass into fuels like biogas, bioethanol, or biobutanol using microbes or enzymes. Anaerobic digestion of organic waste and fermentation of feedstocks high in sugar or starch are common techniques. High-moisture materials such as crop residues, sewage sludge, and food waste are particularly well-suited for this approach. According to Sun and Cheng (2002), biochemical processes fit well with models of the circular bioeconomy, are somewhat tolerant, and are environmentally benign.

- i. **Fermentation:** Sugars (from hydrolyzed cellulose or starch) are converted by microbes to bioethanol. Common feedstocks are lignocellulosic biomass (after pretreatment and enzymatic hydrolysis), maize, and sugarcane. Ethanol and CO₂ are produced when bacteria or yeasts break down hexose or carbon substrates (El-Araby, 2024).
- ii. **Anaerobic digestion:** Microbes break down organic materials biologically without oxygen, creating biogas that is high in methane. This method produces a nutrient-rich digestate fertilizer and biogas for use as fuel, heat, or power. It is commonly applied to wet feedstocks like as manure, food waste, and sewage (El-Araby, 2024).

CHEMICAL PROCESSES

Chemical processes, such as transesterification, which turns vegetable or animal fats into biodiesel, use catalysis or chemical reactions to turn biomass into fuels. This pathway is especially pertinent to feedstocks that are high in lipids, such as algae. Although there are still issues with feedstock costs and catalyst performance, chemical conversion technologies are becoming more and more significant in the field of renewable transportation fuels and are compatible with current fuel infrastructure (Atabani *et al.*, 2012).

- i. **Transesterification:** Using a catalyst, triglyceride oils (vegetable, animal, and algae oils) combine chemically with alcohol (often methanol) to create glycerol and biodiesel (fatty acid methyl esters). This is the conventional process for turning waste or plant oils into biodiesel (El-Araby, 2024).
- ii. **Other catalytic processes:** Hydrogenation or catalytic upgrading of intermediates obtained from biomass (e.g., hydrodeoxygenation of bio-oil to biojet fuels, or catalytic rapid pyrolysis) are examples of emerging chemical pathways. Fischer-Tropsch synthesis of biofuels from syngas is one example of a process that uses solid catalysts to selectively transform biomass

Table 2. Comparison of biomass conversion pathways

Conversion Route	Examples	Advantages	Limitations	References
Thermochemical (pyrolysis, gasification, combustion)	Bio-oil, syngas, heat/power	High efficiency, versatile	Emissions, costly gas cleaning	(Demirbas, 2011)
Biochemical (fermentation, anaerobic digestion)	Bioethanol, biogas	Environmentally friendly, waste valorization	Lower efficiency, pretreatment needed	Cherubini (2010)
Chemical (transesterification, catalytic upgrading)	Biodiesel, biochemical	Mature technology, liquid fuels	Feedstock competition, land use	Gaurav <i>et al.</i> (2017)

molecules into high-value chemicals and fuels.

Every conversion technology has trade-offs between product distribution, feedstock flexibility, and efficiency. Major products from each pathway are depicted in the above image (e.g., pyrolysis producing bio-oil, gasification producing syngas, fermentation producing ethanol, digestion producing biogas, and transesterification producing biodiesel).

ENVIRONMENTAL IMPACTS OF BIOMASS CONVERSION

When it comes to discussions concerning the sustainability of biomass-based energy sources, the environmental effects are still at hand. The kind of feedstock, conversion method, and supply chain logistics all affect biomass's environmental impact, despite the fact that it is frequently marketed as a carbon-neutral substitute for fossil fuels. One of the main issues is the balance of greenhouse gases (GHGs). However, emissions from land-use change, feedstock transportation, and processing have called into question the carbon neutrality assumption, even though the carbon dioxide released by burning biomass is typically offset by carbon uptake during plant growth (Searchinger *et al.*, 2009; Haberl *et al.*, 2012). Depending on the feedstock and technology, bioenergy systems have varying environmental profiles. Principal effects include:

Greenhouse Gas Emissions

Bioenergy is theoretically "carbon-neutral" since CO₂ released during biomass burning and conversion is ideally offset by CO₂ sequestered during growth (El-Araby, 2024). But life-cycle GHG savings differ widely. Carbon emissions from land-use changes, including deforestation, can result in a "carbon debt" that could be greater than any fossil fuel offset. GHG reductions from modern second- and third-generation systems (such as algae and straw ethanol) are typically greater than those from first-generation biofuels

(Reid *et al.*, 2020). Additionally, indirect emissions are increased by the transportation and processing of biomass feedstocks, especially when fossil fuels are utilized for drying or logistics (Cherubini, 2010). When combined with carbon capture and storage (CCS) or when biogas takes the place of more carbon-intensive fossil fuels, anaerobic digestion and gasification are two conversion methods that can provide reduced emissions profiles. Inefficient biomass combustion in small-scale stoves, on the other hand, produces methane (CH₄) and nitrous oxide (N₂O), two powerful greenhouse gases, in addition to CO₂ emissions.

Air Pollutants

Particulates (PM), NO_x, CO, and organic compounds are released during biomass burning, frequently at levels that are comparable to those from coal or wood stoves if left unchecked. Particulates and ashes are released as a result of it (El-Araby, 2024). Air quality can be significantly deteriorated by burning agricultural leftovers outside. Emission controls and advanced combustion/gasification are required to reduce the release of NO_x and particulates. Millions of premature deaths are caused by indoor air pollution from traditional biomass cooking stoves each year, which is still a serious public health concern in poor nations (WHO, 2018). Notwithstanding these obstacles, biomass has the ability to enhance air quality with the implementation of contemporary, effective solutions. For example, using biogas and pelletized biomass produces fewer particles than burning raw wood. However, stringent regulation and the incorporation of emission control technology are essential to guaranteeing that biomass energy serves public health and energy objectives.

Water Footprint

Although water-related effects are crucial to sustainability, they are frequently disregarded in discussions of biomass. Significant amounts of water may be needed to grow

energy crops, particularly if they are irrigated. The water footprint of producing biofuel is higher (m^3 per GJ) than that of producing fossil fuels. It takes thousands of liters of water to produce one liter of ethanol from sorghum or maize, for example. Because bioelectricity uses all biomass, not only sugars and oils, lifecycle evaluations indicate that it has a water impact that is about half that of biofuels. Depending on the crop, climate, and practice, water use varies greatly (Gerbens-Leenesa, Hoekstra, and van der Meer, 2009). Water is used in the biomass conversion processes themselves. For instance, the fermentation and chilling processes in the synthesis of bioethanol from corn require significant amounts of water (Chiu and Wu, 2012). Anaerobic digestion and fermentation wastewater frequently contains significant levels of organic matter and needs to be treated before being released. Localized water pollution brought on by poor management might further erode the environmental credentials of bioenergy systems. Conversely, some routes can lessen water loads.

Land Use and Biodiversity

Table 3. Environmental trade-offs of biomass conversion pathways

Technology	GHG Reduction Potential (%)	Land-use Impacts	Water footprint	Air Emissions	References
Combustion	40–60	Moderate (depending on source)	Medium	High (NO _x , PM)	Cherubini and Strømman (2011)
Pyrolysis/Gasification	50–70	Low to moderate	Medium	Medium (tar, particulates)	Demirbas (2011)
Fermentation	60–80	Higher (if food crops used)	High (corn, sugarcane)	Low	Jeswani <i>et al.</i> (2020)
Anaerobic digestion	70–90	Very low (uses waste)	Low	Very low	Poeschl <i>et al.</i> (2012)
Biodiesel (transesterification)	40–65	High (if palm/soy used)	Very high	Medium	Gaurav <i>et al.</i> (2017)

in carbon that can benefit soils; fermentation provides waste solids rich in lignin; anaerobic digestion produces a digestate fertilizer rich in nutrients; and biomass combustion produces ash, which is frequently recycled as a soil supplement. If correctly handled, these byproducts can be advantageous. Pollution, however, can result from poor management (such as open burning of char or nitrogen runoff from digestate). In general, bioenergy can decrease waste disposal methods such as open burning or landfilling by valuing wastes and residues (Iaquaniello *et al.*, 2018; El-Araby, 2024).

LIFE CYCLE ASSESSMENT (LCA) OF BIOMASS BIOENERGY

Food production and natural ecosystems may be lost when land is converted to bioenergy crops. It may take “hundreds of millions of hectares” to produce bioenergy on a large scale, endangering ecosystems and the food supply. Research indicates that the substitution of monoculture energy crops for natural ecosystems tends to decrease biodiversity. However, compared to annual monocultures like maize, planting a variety of perennial bioenergy systems (agroforestry, mixed-grass prairies) can support increased species richness (Haan *et al.*, 2023). To prevent unfavorable land-use change, careful land management is essential (e.g., using degraded land). Crop rotation, agroforestry-based bioenergy systems, and cooperation with conservation initiatives are examples of biodiversity-friendly tactics. To guarantee widespread adoption, these strategies need financial incentives and legislative backing.

Waste and Byproducts

Processes that produce bioenergy produce leftovers. For instance, pyrolysis creates biochar, a stable solid rich

One of the most important methodological tools for assessing the overall sustainability of biomass-based energy systems is life cycle assessment, or LCA. LCA takes a “cradle-to-grave” approach, looking at environmental effects along the whole value chain, from feedstock cultivation and harvesting to processing and conversion to final use and waste management, in contrast to traditional performance assessments that only concentrate on energy efficiency or emissions at the point of combustion (Cherubini and Strømman, 2011). Finding trade-offs, synergies, and possible areas for technical or legislative intervention is made possible by this holistic viewpoint. Boundaries may or may not include indirect effects (such as changes in land usage), and functional units vary (per

MJ fuel, per hectare land). Numerous LCA approaches have been created, each with unique system boundaries and scopes. The ISO 14040/44 standards are frequently used frameworks that provide guidance for goal definition, inventory analysis, impact assessment, and interpretation. Global warming potential (GWP), energy return on investment (EROI), cumulative energy demand (CED), eutrophication potential, acidification potential, and water use intensity are important environmental indicators evaluated in bioenergy life cycle assessments (LCAs) (Sadhukhan et al., 2014).

Additionally, life cycle sustainability assessment (LCSA), a social and economic extension of life cycle assessment (LCA), is being used more and more to incorporate multifaceted consequences. Under ideal circumstances, advanced biofuels and bioelectricity lower net GHG emissions relative to fossil fuels (often by 40–90% CO₂-eq), according to numerous life cycle assessment (LCA) studies. For instance, compared to coal with an equivalent output, burning biomass for heat or power often has a lower GWP (Wang et al., 2025). The environmental performance of various biomass conversion processes varies significantly, according to comparative life cycle assessments. For example, because it requires less acreage and effectively valorizes waste, anaerobic digestion biogas typically outperforms first-generation bioethanol in terms

of reducing greenhouse gas emissions. Compared to biological mechanisms, thermochemical pathways such as gasification and pyrolysis frequently exhibit higher energy efficiency but may also include larger emissions of air pollutants (Parajuli et al., 2015).

However, assumptions have an impact on the results. The allocation of co-products and the system boundary (such as whether to incorporate indirect land-use change or fertilizer supply) are important concerns. While newer crops might avoid these constraints, first-generation biofuels frequently face LUC carbon penalties in LCA. There are significant differences between studies as a result of methodological decisions (functional unit, time horizon, and pollutant measurements) (Wang et al., 2025). GWP (climate), acidification, eutrophication (from fertilizer runoff), and land occupation are among the impact categories that are frequently evaluated. Notwithstanding its resilience, LCA has a number of drawbacks and unknowns. The quality and comparability of many bioenergy LCAs are reduced by their reliance on out-of-date or regionally specific statistics. Choices regarding waste treatment, co-products, and indirect land-use change (ILUC) can have a big impact on results.

Global LCAs frequently oversimplify the effects of regional farming practices, climate, and energy mixes on biomass

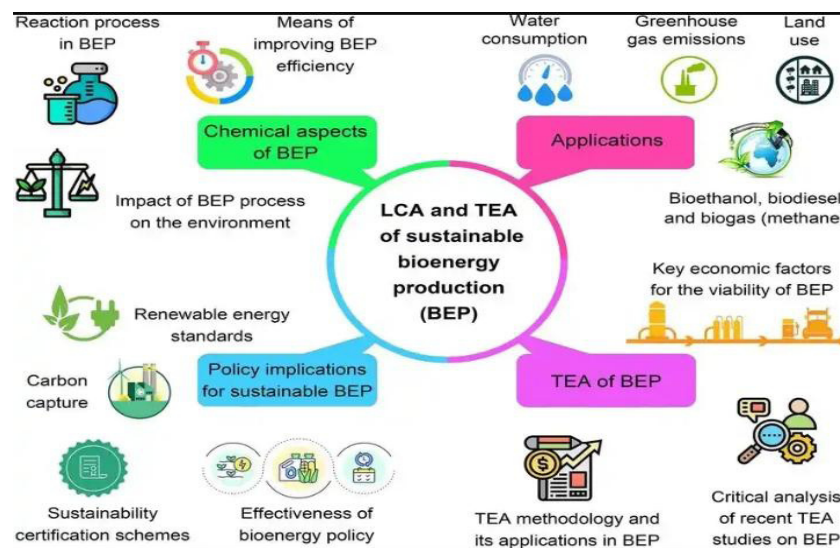


Fig3.Life cycle assessment (LCA) framework for biomass energy

Source: Osman et al. (2024)

systems. especially for soil health, water shortage, and biodiversity loss—all of which are still underrepresented in traditional LCA models. Dynamic LCAs that take time-dependent variables into account, the incorporation of geospatial data for region-specific evaluations, and coupling with techno-economic analyses (TEA) to produce more policy-relevant results are all being promoted by

researchers as ways to increase reliability (Jeswani et al., 2020). Developments in hybrid modeling techniques that integrate LCA with input-output analysis and predictive models based on machine learning also have the potential to improve decision-making and lower uncertainty in the deployment of sustainable bioenergy.

FUTURE PROSPECTS AND RESEARCH NEEDS

Research and innovation are advancing bioenergy. Key trends include:

Advanced feedstock pretreatment: Enhancing lignocellulose breakdown (for example, by using ionic liquids, new enzymes, or genetically modified microorganisms) can boost fermentation sugar output. Two current strategies to reduce the cost of cellulosic biofuels include biological pretreatments and highly effective enzymatic hydrolysis (El-Araby, 2024).

Integrated biorefineries: Biorefineries go beyond single fuels by using a single feedstock to co-produce high-value chemicals, power, and fuels. A lignocellulosic biorefinery, for instance, might generate bioplastics, ethanol, and biodiesel precursors. Efficiency and economies are increased when processes are co-located and all biomass fractions are valorized. Co-products (animal feed, lignin-based materials) are essential for viability, according to techno-economic assessments (El-Araby, 2024).

Hybrid and co-firing technologies: As a bridging method, biomass can be blended with other fuels. To reduce coal use, biomass is co-fired in several coal plants (Balopi *et al.*, 2025). Hybrid systems can balance variable renewables, such as solar-thermal with biomass boilers. Blending biofuels (such as ethanol or biodiesel) with current fuel sources is already commonplace in the transportation industry. Additionally, hybrid gasification-Fischer-Tropsch plants which co-process natural gas and biomass are being investigated.

Role in decarbonization: Bioenergy is one of the few alternatives for net-negative emissions, particularly when paired with carbon capture (BECCS). According to international roadmaps (such as the IEA and UNEP), achieving the “well below 2°C” targets will need a significant rise in the usage of biofuel and BECCS. Sustainable bioenergy will supplement solar and wind power in future energy systems by supplying materials for a bioeconomy, renewable fuels for ships and airplanes, and dispatchable power.

Table 4. Summary of key findings

Aspect	Key Findings
Biomass Resources	Biomass is globally available with regional variations in resource distribution; agricultural residues, forestry by-products, and organic waste streams represent the most sustainable feedstocks (Scarlat <i>et al.</i> , 2015).
Thermochemical Processes	Pyrolysis and gasification provide high energy yields and versatile fuel products but require emission controls and optimized process integration (Demirbas, 2011).
Biochemical Processes	Fermentation and anaerobic digestion enable waste valorization and lower GHG emissions but are limited by pretreatment requirements and lower efficiency (Cherubini, 2010).

Research is still being done to guarantee bioenergy's place in a sustainable energy future and to maximize biomass conversion (e.g., novel catalysts, hybrid processes). How well bioenergy supports climate goals and rural development will depend on advancements in pretreatment, integrated processes, and policy design as the demand for clean energy rises globally (El-Araby, 2024).

CONCLUSION

Biomass conversion technologies have a great deal of promise to help solve the world's energy problems and promote sustainable growth. As the review shows, biomass is a renewable and widely accessible resource that can be crucial in lowering greenhouse gas emissions, increasing energy security, and decreasing dependency on fossil fuels. Conversion pathways that are thermochemical, biochemical, or chemical each have their own advantages and disadvantages. Although thermochemical processes like gasification and pyrolysis offer substantial energy yields, they have difficulties controlling emissions and optimizing their operations.

Anaerobic digestion and fermentation are two examples of biochemical processes that are more efficient and environmentally benign in valorizing organic waste streams; nevertheless, they frequently need pretreatment and have lower conversion efficiencies. Chemical techniques, especially transesterification for the generation of biodiesel, are still commercially feasible but are limited by the supply of feedstock and conflicting land uses.

According to feedstock type, conversion method, and geographic circumstances, sustainability outcomes might vary, as demonstrated by Life Cycle Assessment (LCA) research. Bioenergy produced from agricultural wastes and waste streams frequently performs better environmentally than energy crops, which could lead to indirect land-use change. In order to guarantee a fair and sustainable transition, biomass integration into the renewable energy mix must also carefully take socioeconomic effects, environmental trade-offs, and long-term policy frameworks into account.

Chemical Processes	Transesterification remains effective for biodiesel production but faces feedstock sustainability issues and land-use competition (Gaurav <i>et al.</i> , 2017).
Life Cycle Assessment	Environmental performance varies across feedstocks and technologies; residues and waste-based bioenergy outperform crop-based biofuels in sustainability (Cherubini and Strømman, 2011).
Environmental Impacts	Bioenergy reduces fossil fuel dependence but may cause land-use change, biodiversity loss, and water stress if not managed sustainably (Cherubini <i>et al.</i> , 2009).

In the end, the development of effective conversion technologies, the implementation of resource management strategies tailored to a given location, and the inclusion of strong legislative support mechanisms will determine the survival of biomass energy. A diversified, robust, and low-carbon global energy system can benefit greatly from the combination of biomass with other renewable energy sources like solar and wind. To fully realize biomass's potential in the global energy transition, more research is necessary on new feedstocks, carbon-negative technologies like bioenergy with carbon capture and storage (BECCS), and integrated biorefineries.

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Conflict of Interest

The authors declared that there are no conflicts of interest.

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REFERENCES

1. Chaturvedi, V., Hejazi, M., Edmonds J, et al. (2013). Climate mitigation policy implications for global irrigation water demand. *Mitig Adapt Strateg Glob Chang.* 20:389–407.
2. Adams, S., Klobodu, E.K.M. and Apio, A. (2018). Renewable and non-renewable energy, regime type and economic growth. *Renew Energy.* 125:755–67. <https://doi.org/10.1016/j.renene.2018.02.135>.
3. Bahadori, A.D. (2021). *Energy, architecture, and sustainability.* Amsterdam: Elsevier Imprint by Academic Press; 2021.
4. Berndes, G., Hoogwijk, M., & van den Broek, R. (2003). The contribution of biomass in the future global energy supply: A review of 17 studies. *Biomass and Bioenergy*, 25(1), 1–28. [https://doi.org/10.1016/S0961-9534\(02\)00185-X](https://doi.org/10.1016/S0961-9534(02)00185-X)
5. Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology Advances*, 25(3), 294–306. <https://doi.org/10.1016/j.biotechadv.2007.02.001>
6. Moya, D., Aldás, C., López, G., & Kaparaju, P. (2017). Municipal solid waste as a valuable renewable energy resource: A worldwide opportunity of energy recovery by using waste-to-energy technologies. *Energy Procedia*, 134, 286–295. <https://doi.org/10.1016/j.egypro.2017.09.618>
7. Poeschl, M., Ward, S. and Owende, P. (2012). Environmental impacts of biogas deployment – Part II: Life cycle assessment of multiple production and utilization pathways. *Bioresource Technology. Journal of Cleaner Production.* 24;184-201. DOI: 10.1016/j.jclepro.2011.10.030
8. 10.1016/j.jclepro.2011.10.030
9. Ukoba, M. O., Diemuodeke, O., Tobinson A. Briggs, T. A. (2024). Multicriteria GIS-based assessment of biomass energy potentials in Nigeria. *Frontiers in Bioengineering and Biotechnology.* DOI:10.3389/fbioe.2024.1329878
10. Osman, A. I., Fang, B., Zhang, Y., Liu, Y. et al., (2024). Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review. *Environmental Chemistry Letters.* DOI:10.1007/s10311-023-01694-z
11. Benti, N.E., Gurmesa, G.S., Argaw, T. et al. (2021). The current status, challenges and prospects of using biomass energy in Ethiopia. *Biotechnol Biofuels.* 14, 209. <https://doi.org/10.1186/s13068-021-02060-3>
12. Reid, W. V., Ali, M. K. and Field, C. B. (2020). The future of bioenergy. *Global change biology.* 26(1);274–286. <https://doi.org/10.1111/gcb.14883>
13. DeCicco, J. M. and Schlesinger, W. H. (2018). Opinion: Reconsidering bioenergy given the urgency of climate protection. *Proceedings of the National Academy of Sciences of the United States of America.* 115(39);9642–9645. 10.1073/pnas.1814120115
14. European Academies Science Advisory Council.

- (2019). Forest bioenergy, carbon capture and storage, and carbon dioxide removal: An update. Retrieved from https://easac.eu/fileadmin/PDF_s/reports_statements/Negative_Carbon/EASAC_Commentary_Forest_Bioenergy.
15. Searchinger, T., Waite, R., Hanson, C. and Ranganathan, J. (2018). Creating a sustainable food future. Retrieved from <https://www.wri.org/publication/creating-sustainable-food-future>
 16. REN21. (2023). Renewables 2023 Global Status Report. REN21 Secretariat. Retrieved August 31, 2025, from <https://www.ren21.net/gsr-2023>.
 17. Scarlat, N., Dallemand, J. F., Monforti-Ferrario, F. and Banja, M. (2015). The role of biomass and bioenergy in a future bioeconomy: Policies and facts. *Environmental Development*. 15, 3–34. <https://doi.org/10.1016/j.envdev.2015.03.006>
 18. International Renewable Energy Agency. (2024). World Energy Transitions Outlook: 1.5 °C Pathway. IRENA. Retrieved August 31, 2025, from <https://www.irena.org/publications/2022/Mar/World-Energy-Transitions-Outlook-2022>
 19. El-Araby, R. (2024). Biofuel production: exploring renewable energy solutions for a greener future. *Biotechnol Biofuels*. 17;129 <https://doi.org/10.1186/s13068-024-02571-9>
 20. Mat Aron, N.S., Khoo, K.S., Chew, K.W., Show, P.L., Chen, W.H. and Nguyen, T.H.P. (2020). Sustainability of the four generations of biofuels—a review. *Int J Energy Res*. 44(12):9266–82.
 21. Saladini, F., Patrizi, N., Pulselli, F.M., Marchettini, N. and Bastianoni, S. (2016). Guidelines for emergy evaluation of first, second and third generation biofuels. *Renew Sustain Energy Rev*. 66:221–7.
 22. Wang, M., Ye, X., Bi, H. et al. (2024). Microalgae biofuels: illuminating the path to a sustainable future amidst challenges and opportunities. *Biotechnol Biofuels*. 17; 10. <https://doi.org/10.1186/s13068-024-02461-0>
 23. Murthy, G.S., Gnansounou, E., Khanal, S.K. and Pandey, A. (2021). Biomass, biofuels, biochemicals: green-economy: systems analysis for sustainability. Amsterdam: Elsevier; 2021.
 24. IEA. (2022). Renewables 2022: Analysis and forecast to 2027. International Energy Agency. <https://www.iea.org/reports/renewables-2022>
 25. Thrän, D., Schaubach, K., Majer, S. and Horschig, T. (2020). Governance of sustainability in the German biogas sector—Adaptive management of the Renewable Energy Act between agriculture and the energy sector. *Energy, Sustainability and Society*. 10(3);1–16. <https://doi.org/10.1186/s13705-020-00257-7>
 26. Khan, M. I., Shin, J. H. and Kim, J. D. (2018). The promising future of microalgae: Current status, challenges, and optimization of a sustainable and renewable industry for biofuels, feed, and other products. *Microbial Cell Factories*. 17(1); 36. <https://doi.org/10.1186/s12934-018-0879-x>
 27. Tilman, D., Socolow, R., Foley, J. A., Hill, J., Larson, E., Lynd, L. and Williams, R. (2009). Beneficial biofuels—The food, energy, and environment trilemma. *Science*. 325(5938); 270–271. <https://doi.org/10.1126/science.1177970>
 28. Cherubini, F. (2010). The biorefinery concept: Using biomass instead of oil for producing energy and chemicals. *Energy Conversion and Management*. 51(7);1412–1421. <https://doi.org/10.1016/j.enconman.2010.01.015>
 29. Gerbens-Leenes, W., Hoekstra, A. Y. and van der Meer, T. H. (2009). The water footprint of bioenergy. *Proceedings of the National Academy of Sciences of the United States of America*. 106(25); 10219–10223. <https://doi.org/10.1073/pnas.0812619106>
 30. Demirbas, A. (2011). Competitive liquid biofuels from biomass. *Applied Energy*. 88(1); 17–28. <https://doi.org/10.1016/j.apenergy.2010.07.016>
 31. McKendry, P. (2002). Energy production from biomass (part 1): Overview of biomass. *Bioresource Technology*. 83(1); 37–46. [https://doi.org/10.1016/S0960-8524\(01\)00118-3](https://doi.org/10.1016/S0960-8524(01)00118-3)
 32. Sun, Y. and Cheng, J. (2002). Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresource Technology*. 83(1);1–11. [https://doi.org/10.1016/S0960-8524\(01\)00212-7](https://doi.org/10.1016/S0960-8524(01)00212-7)
 33. Atabani, A. E., Silitonga, A. S., Badruddin, I. A., Mahlia, T. M. I., Masjuki, H. H. and Mekhilef, S. (2012). A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and Sustainable Energy Reviews*. 16(4);2070–2093. <https://doi.org/10.1016/j.rser.2012.01.003>
 34. Correa, D.F., Beyer, H.L., Fargione, J.E., Hill, J.D., Possingham, H.P., Thomas-Hall, S.R. and Schenk, P.M. (2019). Toward the implementation of sustainable biofuel production systems. *Renew Sustain Energy Rev*. 107:250–63.
 35. Escalante, J., Chen, W.H., Tabatabaei, M., Hoang, A.T., Kwon, E.E., Lin, K.Y.A. and Saravanakumar, A. (2022). Pyrolysis of lignocellulosic, algal, plastic, and other biomass wastes for biofuel production and

- circular bioeconomy: a review of thermogravimetric analysis (TGA) approach. *Renew Sustain Energy Rev.* 169:112914.
36. Balopi, B., Moyo, M., Gorimbo, J. et al. (2025). Biomass-to-electricity conversion technologies: a review. *Waste Dispos. Sustain. Energy.* 7; 323–351. <https://doi.org/10.1007/s42768-025-00226-5>
 37. Ali, H.E.A., El-fayoumy, E.A., Soliman, R.M., Elkhatat, A., Al-Meer, S., Elsaid, K. and Abdullah, M.A. (2024). Nanoparticle applications in Algal-biorefinery for biofuel production. *Renew Sustain Energy Rev.* 192:114267.
 38. Reid, W. V., Ali, M. K. and Field, C. B. (2020). The future of bioenergy. *Global change biology.* 26(1);274–286. <https://doi.org/10.1111/gcb.14883>
 39. Gerbens-Leenesa, W., Hoekstra, A. Y. and van der Meer, T. H. (2009). The water footprint of bioenergy. *PNAS* 106 (25); 10219 –10223. www.pnas.org/cgi/doi/10.1073/pnas.0812619106 PNA
 40. Haan, N. L., Benucci, G. N. M., Fiser, C. M., Bonito, G. and Landis, D. A. (2023). Contrasting effects of bioenergy crops on biodiversity. *Science advances.* 9(38); eadh7960. <https://doi.org/10.1126/sciadv.adh7960>
 41. Iaquaniello, G., Centi, G., Salladini, A. and Palo E. (2018). Waste as a source of carbon for methanol production. In: *Methanol*. Amsterdam: Elsevier. 95–111.
 42. Chiu, Y. W. and Wu, M. (2012). Assessing county-level water footprints of different cellulosic-biofuel feedstock pathways. *Environmental science & technology.* 46(16); 9155–9162. <https://doi.org/10.1021/es3002162>
 43. WHO. (2018). Household air pollution and health. World Health Organization. Retrieved from <https://www.who.int>
 44. Wang, K., Tong, R., Zhai, Q., Lyu, G. and Li, Y. (2025). A Critical Review of Life Cycle Assessments on Bioenergy Technologies: Methodological Choices, Limitations, and Suggestions for Future Studies. *Sustainability.* 17(8):3415. <https://doi.org/10.3390/su17083415>
 45. Cherubini, F. and Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: state of the art and future challenges. *Bioresource technology.* 102(2); 437–451. <https://doi.org/10.1016/j.biortech.2010.08.010>
 46. Sadhukhan, J., Ng, K. S. and Hernandez, E. M. (2014). Biorefineries and chemical processes: Design, integration and sustainability analysis. DOI:10.1002/9781118698129.ch15
 47. Jeswani, H. K., Chilvers, A. and Azapagic, A. (2020). Environmental sustainability of biofuels: a review. *Proceedings. Mathematical, physical, and engineering sciences.* 476(2243);20200351. <https://doi.org/10.1098/rspa.2020.0351>
 48. Balopi, B., Moyo, M., Gorimbo, J. et al. (2025). Biomass-to-electricity conversion technologies: a review. *Waste Dispos. Sustain. Energy* 7, 323–351. <https://doi.org/10.1007/s42768-025-00226-5>
 49. Gaurav, N., Sivasankari, S., Kiran, G. S., Ninawe, A. and Selvin, J. (2017). Utilization of bioresources for sustainable biofuels: A review. *Renewable and Sustainable Energy Reviews.* 73; 205–214. <https://doi.org/10.1016/j.rser.2017.01.070>
 50. Cherubini, F., Bird, N. D., Cowie, A., Jungmeier, G. and Schlamadinger, B. (2009). Energy- and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations. *Resources, Conservation and Recycling.* 53(8);434–447. <https://doi.org/10.1016/j.resconrec.2009.03.013>

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