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REVIEW ARTICLE

Life cycle assessment and techno-economic analysis of sustainable bioenergy production: a review

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Abstract

The global expansion of the bioenergy industry raises concerns, emphasizing the need for careful evaluation and sustainable management. To facilitate this, life cycle assessments beyond greenhouse gas emissions and energy balance are essential, along with the standardization of assessment methodologies to enable meaningful comparisons. Here, we review life cycle assessment, chemical aspects, and policy implication of bioenergy production. We discuss life cycle assessment in terms of concepts, methods, impacts, greenhouse gases, land use, water consumption, bioethanol, biodiesel, biogas, and techno-economic analysis. Chemical aspects comprise reaction processes and means to improve efficiency. Concerning policies, tools, and frameworks that encourage sustainable energy production are presented. We found that carbon dioxide removal ranges from 45 to 99% in various bioenergy processes. The review also emphasizes the importance of chemistry in advancing sustainable bioenergy production for a more sustainable and secure energy future.

Keywords Life cycle assessment · Techno-economic analysis · Sustainable bioenergy production · Bioenergy chemical aspect · Policy implication

Introduction

Sustainable bioenergy production stands at the intersection of profound global challenges, signaling a transition to low-carbon, renewable energy sources that can combat climate change, reinforce energy security, and foster environmental sustainability. Thus, the exploration of life cycle assessment (LCA), techno-economic analysis (TEA), and their associated policy implications in the context of sustainable bioenergy production are crucial (Osman et al. 2021). The urgency of addressing climate change has never been more apparent; increasing global temperatures, extreme weather events, and the irrevocable transformation of ecosystems demand a re-evaluation of our energy landscape (Chen et al. 2023; Rashwan et al. 2023). Fossil fuels, with their accompanying emissions of greenhouse gases, are a principal cause behind these shifts. To counter this extreme trajectory, the world is shifting to renewable and low-carbon energy sources, and bioenergy plays a pivotal role in this transformation (Osman et al. 2023b; Tawfik et al. 2023). Particularly when produced from organic matter of agricultural residues, fast dedicated energy crops, and algae, this offers a potential pathway to a

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substantial reduction in net greenhouse gas emissions compared to fossil fuels when managed sustainably.

Furthermore, bioenergy strengthens the pillars of energy security by diversifying energy sources, diminishing dependence on finite fossil fuel resources, and enhancing supply risks and price volatility (Duarah et al. 2022). It contributes to local and regional energy self-sufficiency, thus enhancing resilience in the face of external energy shocks (Bouoiyour et al. 2023). Beyond its contribution to mitigating climate change and securing energy supply, bioenergy aligns with broader sustainability goals. It fosters rural development, facilitates job creation, and bolsters sustainable land use and biodiversity preservation. Bioenergy pathways encompass a variety of chemical transformations, from fermentation to gasification, pyrolysis, and catalytic conversion, which are mainly thermochemical or biological routes into energy or energy carriers (Jha et al. 2022). A profound understanding of these reactions and processes is essential for optimizing efficiency and sustainability in bioenergy production (Sharma et al. 2022a). Developing innovative materials and technologies, including catalysts and reactor designs, can substantially enhance bioenergy conversion rates while mitigating environmental impacts. These chemical advancements are pivotal in making bioenergy production both economically viable and environmentally sustainable.

The novelty of this review is to explore and integrate the analytical tools and methodologies, such as life cycle assessment and techno-economic analysis, to assess and elevate the sustainability and viability of bioenergy production, as shown in Fig. 1. Furthermore, we thoroughly investigate the policy instruments and frameworks that frame the landscape of sustainable bioenergy production.

Life cycle assessment of bioenergy production

Life cycle assessment concept

The feasibility of a bioenergy project is contingent upon a precise evaluation of the biomass resource, cost-efficient logistical planning, and a thorough consideration of potential

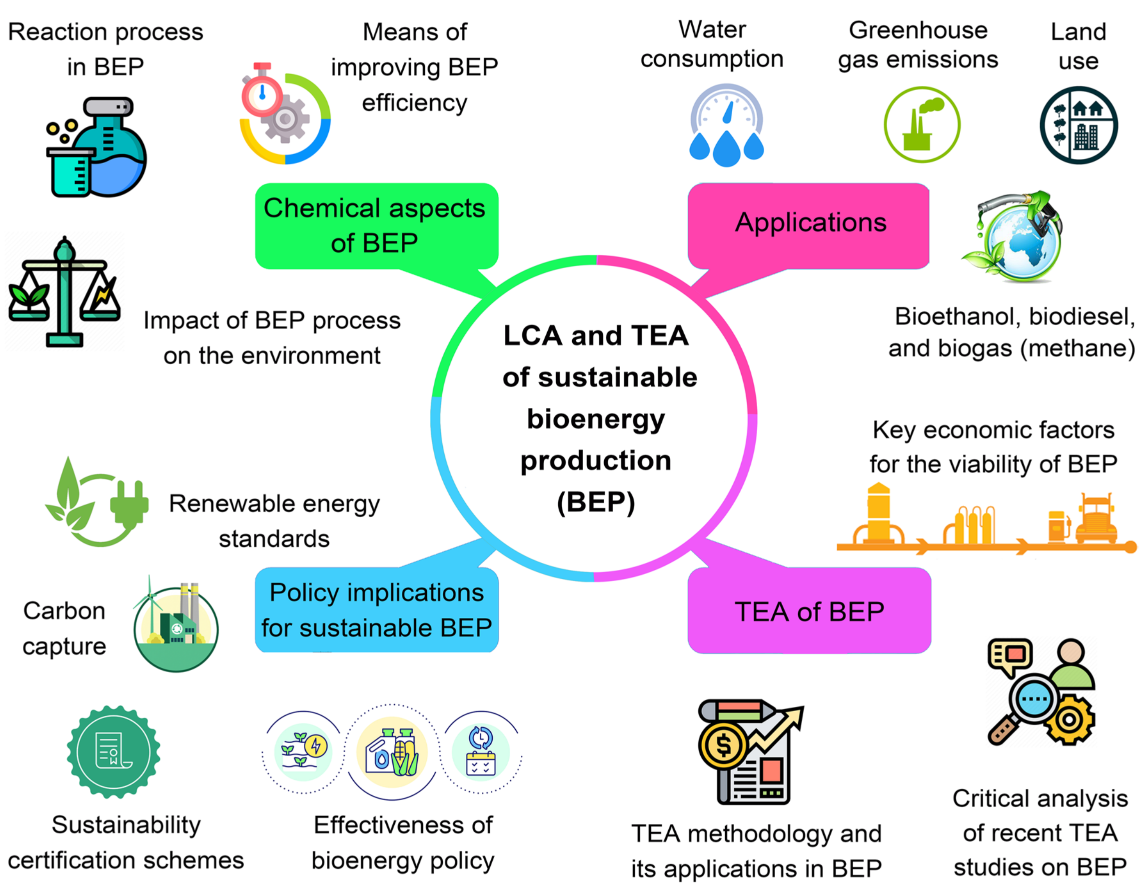

Fig. 1 Life cycle assessment (LCA) and techno-economic analysis (TEA) of bioenergy production (BEP). The review started with life cycle assessment techniques, methods, and applications in bioenergy production. The review also investigates various policy implications for sustainable bioenergy production. Finally, it delves into detailed techno-economic assessment methodology and application in bioenergy production

environmental impacts (Hiloidhari et al. 2017). It is vital to analyze the advantages and disadvantages of bioenergy production, considering the environmental uncertainties involved. The assessment should be conducted from the perspective of life cycle assessment. Life cycle assessment is a methodology used to quantify and evaluate the environmental burdens associated with the use of energy, materials, and waste emissions throughout the entire lifecycle of a product, process, or activity. (Hiloidhari et al. 2017). The life cycle of biofuels and bioproducts, from cradle to grave, encompasses a series of interconnected stages that reflect their environmental and societal impact. It begins with the cultivation and harvesting of biomass, such as crops, algae, or forestry residues, which serve as the primary raw materials. Once harvested, these feedstocks undergo conversion processes, such as fermentation, pyrolysis, or enzymatic digestion, to transform them into biofuels, bioenergy, or bioproducts. These products then enter the utilization phase, where they are consumed for energy production or incorporated into various applications, such as transportation fuels, electricity generation, or biodegradable plastics. As biofuels and bioproducts are used, their environmental and social performance is monitored and assessed, considering factors like greenhouse gas emissions, resource consumption, and economic benefits. Finally, at the end of their life cycle, biofuels and bioproducts are either recycled, repurposed, or disposed of in an environmentally responsible manner. This holistic approach to evaluating their life cycle helps us understand the broader implications of these renewable alternatives and make informed decisions to promote sustainability and reduce the environmental footprint. Figure 2 shows the life cycle of biofuels and bioproducts from cradle to grave, illustrating the byproducts and environmental burden at the processing stage.

The deployment of energy-intensive agricultural machinery for tasks such as irrigation, land preparation, planting, harvesting, collection, and feedstock transportation results in significant greenhouse gas emissions and various environmental consequences within any bioenergy production system (Jeswani et al. 2020). The synthesis, application, and utilization of synthetic pesticides and fertilizers lead to emissions and have a profound impact on soil and water quality, as previously highlighted (Harun et al. 2021). Reports indicated that within the realm of sugarcane-based bioenergy production, the agricultural phase exerted the most detrimental environmental effects. This is primarily due to land usage, fuel consumption, and the application of agrochemicals. However, it's worth noting that bagasse derived from sugarcane holds the potential for the production of bioethanol and bioelectricity, offering a more sustainable outcome.

In contrast to using bagasse for co-generation-based power, either compared to bagasse bioethanol or fossil energy systems, it has been suggested that the former may lead to lower energy-related emissions (Khatri and Pandit 2022). Furthermore, there are claims that producing bagasse bioethanol through a combination of first and second-generation processes is more environmentally sustainable than the traditional first-generation production method (Ayodele et al. 2020). Tsiropoulos et al. (2014) found that Indian bioethanol generally results in lower or comparable greenhouse gas emissions, non-renewable energy consumption, human health impacts, and ecological damage when compared to Brazilian bioethanol in a cradle-to-gate life cycle assessment. India's bioethanol program predominantly relies on sugarcane molasses, a byproduct of sugar production. Consequently, the environmental impacts are distributed between the main product (sugar) and the byproduct (molasses), potentially accounting for the lower emissions

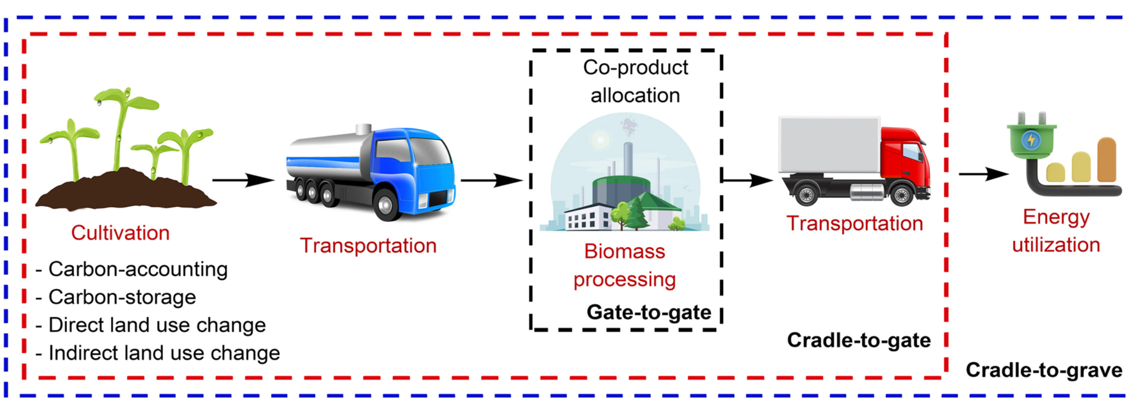

Fig. 2 Methodological challenges in life cycle assessment of biofuels and bioproducts. Cradle-to-grave assessments often adopt functional units based on energy content or driving distance, while cradle-to-gate studies typically utilize mass or volume. In scenarios emphasizing raw material usage, functional units based on land area may be employed. A critical challenge in these assessments is the allocation of environmental burdens, particularly in cases where biomass systems are intricately linked with by-products throughout the cultivation and processing stages

observed. It is essential to distinguish between cradle-to-gate and cradle-to-grave life cycle assessments, with the former covering the evaluation from resource extraction to the factory gate and the latter encompassing the entire life cycle assessment process, from resource extraction to waste disposal (Theuerl et al. 2019).

Life cycle assessment method overview

In line with ISO 14042 standards, the choice of impact categories should encompass comprehensive environmental considerations relevant to the product system under study, considering its objectives and scope. The selection of impact categories, indicators, and characterization modeling should adhere to internationally recognized standards, often based on international conventions or endorsed by authoritative international bodies. Impact assessment methods fall into two categories: midpoint and endpoint methods. Midpoint methods within environmental impact assessment aim to categorize and characterize the outcomes of inventory analysis, yielding various environmental impact indicators (Cano-Londoño et al. 2023). Well-known midpoint methods include Center for Environmental Studies Leiden (CML), Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI)—2005, Building for Environmental and Economic Sustainability (BEES), Environmental Design of Industrial Products (EDIP)—1997, and Environmental Design of Industrial Products (EDIP)—2005 (Reyes et al. 2020). On the other hand, endpoint environmental impact indicators offer a more intuitive comprehension of the environmental harm caused by products. In endpoint environmental impact assessment methods, characterization factors, also referred to as damage factors, convert the results of inventory analysis into damage-centric indicators. Common endpoint analysis methods encompass EPS 2000, Impact 2002, and Eco-indicator 99 (Carvalho et al. 2019).

The assessment of life cycle impacts involves the compilation of impacts generated by various potential methods using SimaPro 8.5.0.0 software. These impacts are then cross-referenced in an Excel spreadsheet to select prospective impacts for comparative analysis among methods, taking into consideration the units and categories of these impacts. The primary effects associated with these approaches encompass eutrophication, land usage, global warming, acidification, and toxicity, as previously noted (Carvalho et al. 2019).

Employing diverse available methods for impact assessment enables the quantification of emissions, including carbon dioxide, nitrogen oxide, and sulfur dioxide released into the atmosphere, as well as nitrogen and phosphate emissions into water, along with land use considerations, as presented in Table 1. Emissions to the atmosphere are primarily linked to categories such as global warming, photochemical smog, and acidification, while nitrogen and phosphorus emissions into water pertain to the eutrophication category (Jeswani et al. 2020).

Table 1 Comparison of life cycle assessment methods for eutrophication, acidification, photochemical smog, and global warming

Method	Land use	Global warming (GWP 100)	Acidification	Eutrophication		Reference
	m^2/year	Kg carbon dioxide equivalent	Kg sulfur dioxide equivalent	Kg nitrogen equivalent	Kg phosphate equivalent	
BEES	-	6.65	-	-	1.52×10^{-3}	Zhuo et al. (2013)
CML 2	-	6.65	7.84×10^{-3}	-	3.00×10^{-3}	Cortes et al. (2020); Hosseini et al. (2022)
CML 2001	5.46×10^{-1}	6.65	7.93×10^{-3}	6.66×10^{-3}	3.00×10^{-3}	Hosseini et al. (2022)
EDIP 2003	-	6.67	-	7.41×10^{-4}	5.58×10^{-4}	Carvalho et al. (2019)
EPD 2008	-	6.65	6.98×10^{-3}	-	3.04×10^{-3}	Brandão et al. (2022)
TRACI 2	-	6.66	-	5.85×10^{-3}	-	Carvalho et al. (2019)
Ecoindicator 99	5.31×10^{-1}	-	-	-	-	Pavlovic et al. (2019)
Impact 2002	2.77×10^{-1}	-	8.07×10^{-3}	-	8.00×10^{-4}	Bulle et al. (2019)
ReCiPe	5.33×10^{-1}	6.76	7.03×10^{-3}	8.67×10^{-4}	6.37×10^{-4}	Huijbregts et al. (2017)
Average	4.70×10^{-1}	6.67	7.57×10^{-3}	3.53×10^{-3}	1.794×10^{-3}	-
Standard deviation (%)	27.41	0.60	6.90	89.70	65.90	-

Multiple life cycle assessment methods are applied to conduct environmental impact assessments for a wide range of activities. The following table details the references and values associated with each life cycle assessment approach that was used

Life cycle assessment impacts

Recent academic and environmental policy discussions have increasingly emphasized resource efficiency and the concept of a circular economy. The circular economy introduces a specific geographic dimension where the value of waste takes center stage and can act as a catalyst for productive restoration (Sariatli 2017). This concept is underpinned by a commitment to reducing waste, energy consumption, and water use. Moreover, it demands that associated environmental pressures meet specified targets or constraints (Vlachokostas et al. 2020). The bioeconomy's primary objectives revolve around the efficient use of biomass and bio-waste, with a strong focus on adding substantial value to raw materials in fundamental production processes, spanning various sectors such as agriculture, forestry, and fisheries. Notably, the bioeconomy aims to harness the enormous potential of biomass to support the European Union in achieving its renewable energy objectives (Vlachokostas et al. 2020). This transition toward a circular bioeconomy not only promotes waste reduction but also contributes to resource efficiency and sustainability, playing a crucial role in environmental conservation and the attainment of renewable energy targets.

Greenhouse gas emissions

Global warming potential (GWP) primarily centers around the assessment of greenhouse gas emissions, including carbon dioxide, nitrous oxide, and methane. It quantifies the contribution of various emission factors to global warming using coefficients expressed in terms of carbon dioxide equivalents. These coefficients are based on the recommended global warming potential factors by the Intergovernmental Panel on Climate Change (IPCC), as illustrated in Table 2. The IPCC defines global warming potential as a metric designed to measure the impact of different greenhouse gas emissions on global warming. It signifies the cumulative effect of a unit mass of emitted gas on global warming over a specified time horizon. The evaluation of climate change potential has long been a central focus of research in life cycle assessment (Jungbluth and Meili 2019; Jones et al. 2023).

The concept of global warming potential centers on understanding the combined impact of greenhouse gases in the atmosphere and the strength of their infrared radiation outward. This assessment model for global warming potential utilizes characterization factors that align with IPCC recommendations, typically considering a time horizon of 100 years (Pacheco and Silva 2019). For instance, during the cultivation process, corn straw absorbs 0.71–2 kg of carbon dioxide, and the production of solid biomass fuel is effective in reducing greenhouse gas emissions, as shown in Table 2.

In 2016, bioenergy ranked fourth among global energy sources, after coal, oil, and natural gas, contributing to 9.5% of the world's primary energy supply and a substantial 69.5% of the world's renewable energy supply (Kang et al. 2020). Projections from the International Energy Agency suggest that the worldwide biomass resource potential may reach between 100 and 600 exajoule by 2050, representing 15% to 65% of the world's primary energy consumption (Kang et al. 2020). Bioenergy is increasingly recognized as the most promising alternative to fossil fuels due to its potential to reduce greenhouse gas emissions. It stands out as the only renewable energy source that relies on a carbon supply, making it an integral part of the renewable energy mix. Typically, the carbon in bioenergy is sourced from atmospheric carbon dioxide absorbed during the biomass's photosynthesis (Staples et al. 2017). Consequently, if combined with

Table 2 Carbon emission reduction efficiency of various straw utilization techniques

Utilization methods	Type of straw	Calculation baselines	Method	Calculation boundaries	Carbon reduction efficiency (kg carbon dioxide equivalent per kg)	Reference
Straw to produce fuel ethanol	Corn straw	Burning in field	Life cycle assessment model; GREET (Greenhouse Gases, Regulated Emissions and Energy in Transportation) model	From agriculture sowing to the usage of ethanol in automobile gasoline	0.71	Yang et al. (2019b)
Straw direct combustion power generation	Crop straw	Field burning and coal-fired power generation	Life cycle assessment model	From the planting of crops to the usage of electricity	1.24	Yang et al. (2019c)

This table provides an analysis of the impact of straw utilization on carbon emission reduction, including two case studies, calculation baselines, methodologies, calculation boundaries, and specific carbon reduction efficiencies (expressed in kg of carbon dioxide equivalent per kg) carbon capture and storage, bioenergy could render carbon emissions neutral or even negative. The development of bioenergy chains centers on assessments of biomass resource availability and their associated greenhouse gas reduction potential, crucial steps as we transition to a low-carbon future.

In conclusion, the escalating issue of increased energy consumption is certainly linked to greenhouse gas emissions. Nevertheless, careful management and cultivation of energy crops on unused or marginal lands offer a substantial opportunity to curtail emissions from other sources by sequestering atmospheric carbon. Although quantifying this offsetting effect poses certain challenges at the present stage, it remains an endeavor of utmost importance. Energy crops, when cautiously grown on marginal lands, have the unique capacity to transform atmospheric carbon dioxide into biomass without disrupting regular agricultural output. Consequently, harnessing marginal land for energy crop cultivation necessitates a comprehensive assessment, encompassing the net impact of soil carbon removal and greenhouse gas emissions from the bioenergy cropping system. Indeed, the cultivation of energy crops presents a viable avenue to reduce atmospheric carbon dioxide levels and mitigate the consequences of increased energy consumption (Kumar et al. 2023a).

Land use

The future of sustainable bioenergy feedstock production is expected to rely heavily on energy crops, which may necessitate additional land and water resources to meet the growing demand for plant biomass bioenergy (Guzman et al. 2019). Traditional grain-based feedstocks like corn and sugarcane are challenged to provide bioenergy without risking food security and soil quality, given the increasing demand (Guzman et al. 2019). Evidently, the substantial increase in the production of ethanol from corn in the USA since the mid-2000s has established the USA as the foremost producer of fuel ethanol globally. However, these biofuel initiatives have instigated and are projected to bring about alterations in land utilization patterns in other nations. Studies show that the growth of corn ethanol production in the USA could lead to the extensive transformation of native forests and grasslands into bioenergy crops on a worldwide level, particularly in countries such as Brazil, where established crops like soybeans may be displaced (Miyake et al. 2012).

To address concerns regarding limited land and water resources, particularly where bioenergy crops compete with food production, a strategy that combines arable land for both food and feed production with the cultivation of low-input perennial vegetation on marginal soils has emerged (Mehmood et al. 2017). Marginal lands are typically characterized by low soil fertility, soil quality, and limited economic returns, rendering food production unsustainable. In addition to biomass production and climate change mitigation via carbon sequestration, energy crops grown on marginal lands also contribute significantly to the restoration of these areas (Mehmood et al. 2017). It is noteworthy that the impacts of land-use changes associated with bioenergy production can vary, resulting in either positive or negative effects on natural resources, contingent on specific contextual factors at each location.

Humpenöder et al. (2018) employed the global multi-region land-use optimization model MAgPIE (Model of Agricultural Production and its Impact on the Environment) to demonstrate that negative environmental externalities gradually rise with the increasing yields of bioenergy crops over the twenty-first century. The projection for 2100 suggests that the global bioenergy crop cultivation area will expand to 636 hundred million hectares, leading to issues related to carbon dioxide emissions from land use and land-use change, nitrogen losses, and unsustainable water resource use (Humpenöder et al. 2018). To accommodate the additional production of food, feed, and bioenergy crops, global cropland expansion is inevitable, with an expected absolute increment of 441 hundred million hectares between 2010 and 2030, equivalent to 27% of the relative increase in cropland (Humpenöder et al. 2018).

In conclusion, a multitude of variables shape the impacts of bioenergy land-use transformations, including deployment levels, prior land usage, the choice of bioenergy crops, soil quality, local climate, and management practices (Cherubin et al. 2021). For instance, confining bioenergy development to marginal or degraded lands, such as Brazil's extensive and inefficient pastures, may offer environmental benefits (Bordonal et al. 2018; Oliveira et al. 2019). Additionally, when land conversion for bioenergy production is combined with best management practices through appropriate scale and implementation, it can have positive effects (Werling et al. 2014; Romeu-Dalmau et al. 2018; Cherubin et al. 2019). Consequently, solutions for land-use transformations with minimal impacts and the adoption of best management practices are essential to maintain the sustainability of the overall production system.

Water consumption

The concept of the water footprint serves as a measure to quantify the freshwater utilized, polluted, and consumed along a product's entire production chain (Gerbens-Leenes et al. 2021). This measurement is further categorized into different types. The "green" water footprint denotes rainwater consumption or evaporation. The "blue" water footprint reflects the net extraction of blue water and represents the consumption, or evaporation, of surface and groundwater. The "gray" water footprint, on the other hand, signifies the volume of freshwater necessary to absorb a pollution load, according to environmental water quality regulations. This classification aids in the analysis of water consumption within supply chains, enabling the identification of areas with water-related issues and highlighting priorities. Water footprint assessments can be conducted for various entities, including individuals, entire countries' consumption, or specific products such as food or energy. Studies examining water footprint data for particular crops and agricultural products are available (Mekonnen and Hoekstra 2011). It is also possible to evaluate the water footprint of heat and electricity generated by biomass combustion, assuming a 100% efficiency, based on the higher heating value of the feedstock (Gerbens-Leenes et al. 2009). While electricity can be produced using alternative conversion processes, such as gasification, prior research on the water footprint of biomass power generation has predominantly concentrated on combustion (Mathioudakis et al. 2017).

Table 3 offers several examples of water usage in the context of bioenergy. Cheroennet and Suwanmanee (2017) employed a life cycle assessment approach to calculate the overall water footprint of a corn-based ethanol production chain, yielding a result of 3.67 m^3 per L of ethanol. Using a hybrid life cycle assessment technique, Yang et al. (2018) found that China's biomass pyrolysis system consumes 3.89 L per MJ of water. Direct combustion of corn stover had the lowest water demand coefficient (260 L per kWh for consumption and 260–387 for outflows) in a life cycle assessment (Ali and Kumar 2017). Mathioudakis et al. (2017) examined combustion, gasification, bioethanol fermentation, and bio-oil pyrolysis using a water footprint assessment approach and found that agricultural leftovers were water-efficient and better for oil than ethanol. Nogueira Junior et al. (2018) observed that producing 1 kg of algae in ponds needed 1564 L of water, whereas utilizing ponds and photobioreactors required just 372 L. The boundary of the whole life cycle model of the nitrogen-doped catalytic process is shown in Fig. 3.

In conclusion, the global expansion of the bioenergy production industry has sparked concerns regarding its wide-ranging impacts. The production and utilization of biomass for bioenergy can result in a complex interplay of positive synergies, negative side effects, and potential risks. These include implications for sustainable development goals, issues related to land degradation, concerns about water scarcity, impacts on food security, and considerations about greenhouse gas emissions (Cherubin et al. 2021). This complex web of interactions necessitates careful evaluation and sustainable management to ensure that bioenergy contributes positively to global energy needs while minimizing adverse effects.

Recent life cycle assessment studies of bioenergy products

Bioenergy encompasses various products, including bioethanol, biodiesel, advanced alcohols, bio-liquid fuels, biomethane, biohydrogen, and bioelectricity. When compared to fossil fuels, synthetic bioenergy offers several notable advantages. It primarily relies on renewable biomass resources for feedstock, making it a sustainable alternative. When these bioenergy sources are combusted, they are carbon neutral in terms of carbon dioxide emissions, and if properly managed, could be even negative carbon emission technology. This has made the development of synthetic bioenergy a strategic choice for many major economies worldwide, aimed at ensuring energy security, environmental quality, and economic development. Table 4 provides an overview of published literature on life cycle environmental impacts, highlighting a significant reduction in carbon dioxide emissions in almost every study.

Bioethanol

The development of biofuels, particularly bioethanol, has played a significant role in renewable energy strategies. After biodiesel, bioethanol is the primary renewable energy source in Europe and is made from a range of biomass feedstock, such as lignocellulosic biomass and energy crops. The USA is the world's largest bioethanol producer, followed by the European Union and Brazil (Singh et al. 2022). While Brazil primarily uses sugarcane and Europe focuses on maize for bioethanol production, corn is the predominant crop for bioethanol production in the USA (Soleymani Angili et al. 2021). The first generation of bioethanol, produced from food crops containing starch or sugar, marked the initial shift away from fossil fuels. However, this raised concerns about global food security (Vohra et al. 2014). As a result, research and development efforts have been directed toward the second generation of bioethanol, which is based on non-food sources like lignocellulose.

Environmental assessments of bioethanol production methods vary depending on the feedstock. When corn is used as the substrate for acetone-butanol-ethanol fermentation, it results in the highest associated environmental damages at the midpoint or endpoint assessment level. In contrast, when wheat starch replaces corn, the environmental impact is lower. This suggests that producing acetone-butanol-ethanol from wheat starch is a more ecologically sustainable approach for producing 1-butanol. The distribution of environmental burdens associated with oxidative synthesis in this scenario is split between the two acetone-butanol-ethanol fermentation solutions, depending on whether a mass-based or value-based allocation method is employed (Ingrao et al. 2021). According to Brito and

Table 3 Assessment of water use in some bioenergy systems, including their technologies, methodologies, and key findings

Bioenergy system	Year	Country	Technology	Method	Main findings	Reference
Biodiesel production	2017	Thailand	Corn ethanol	Life cycle assessment	The total water footprint of the corn-based ethanol manufacturing chain is 3.67 m^3 per L ethanol	Cheroennet and Suwanmanee (2017)
Pyrolysis polygeneration	2018	China	Pyrolysis polygeneration	Hybrid life cycle assessment	A Chinese biomass pyrolysis system's life cycle water consumption intensity is 3.89 L per MJ	Yang et al. (2018)
Power generation	2017	-	Direct or bio-oil combustion for power generation	Life cycle assessment	Among all biomass routes, direct burning of maize stover has the lowest water demand coefficient (about 260 L per kWh for consumption and 260–387 L per kWh for outflows)	Ali and Kumar (2017)
-	2017	-	Heat or electricity is produced by combustion and gasification, bioethanol is produced by fermentation, and oil is produced by pyrolysis	Water footprint assessment	Crop residue application is relatively water efficient. Crop wastes are better converted to oil than to ethanol	Mathioudakis et al. (2017)
-	2018	Canada	Thermochemical conversion of algal biomass to produce fuels and chemicals	Life cycle assessment	1564 L of water is needed to create 1 kg of algae in ponds. When ponds and photobioreactors are used, just 372 L of water are needed	Nogueira Junior et al. (2018)

The table highlights the water-related aspects of bioenergy systems, including ethanol production, pyrolysis polygeneration, power generation, crop residue utilization, and algal biomass conversion, providing insights into their water footprints and efficiencies

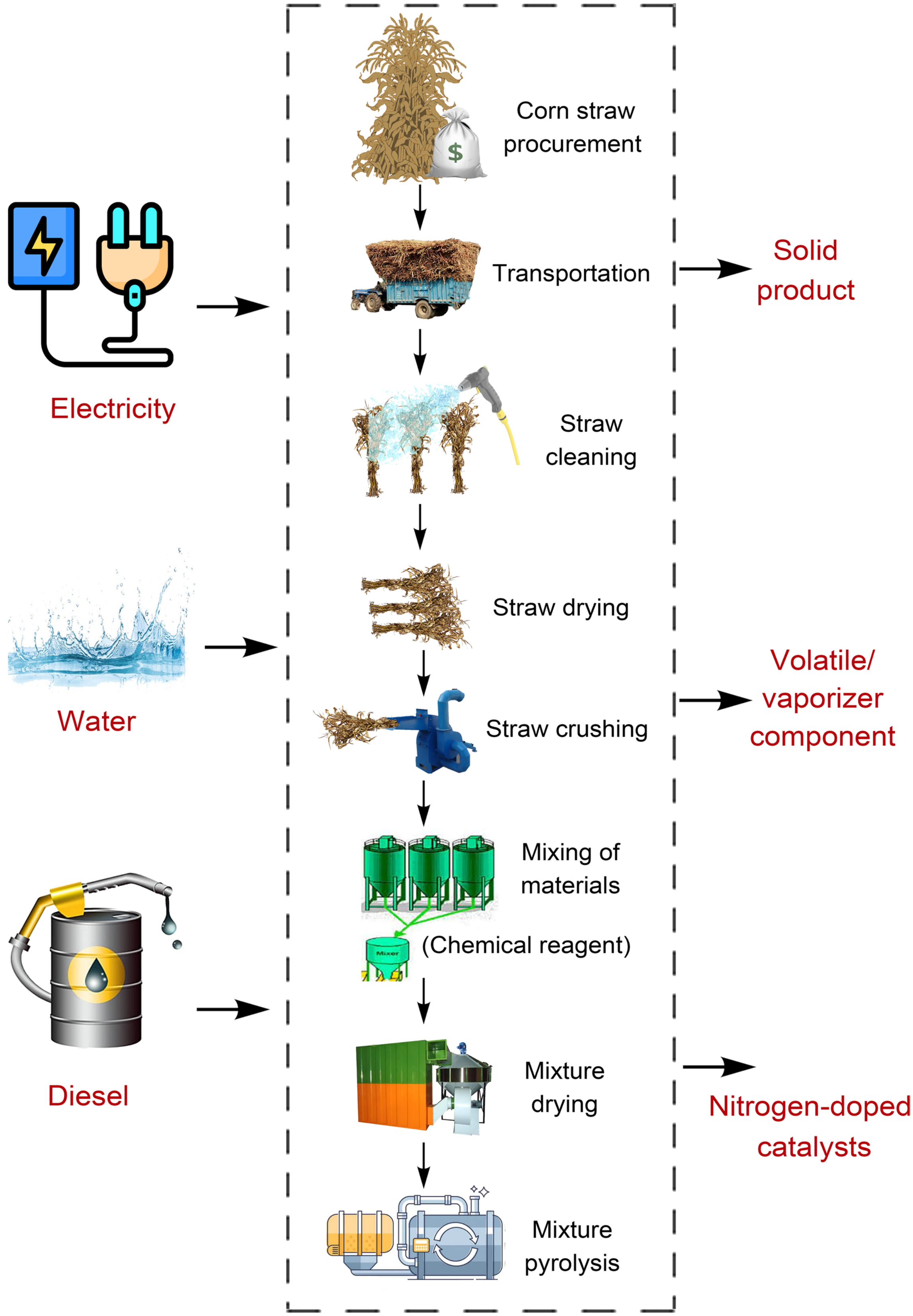

Fig. 3 System boundary diagram for a catalytic experiment. The model predominantly encompasses seven-unit processes related to material transport: cleaning of corn straw, drying of straw, crushing of straw, mixing of the mixture, drying of the mixture, and pyrolysis

Table 4 Environmental impacts of bioenergy processes based on life cycle analysis

Bioenergy	Dominant species	Process description	Life cycle analysis			Acidification potential (kg of sulfur dioxide equivalent)	Reference
			Carbon dioxide removal (%)	Water (m)	Land footprints (m)		
Biomethane	*Methanosercina-bankeri*	Bio electrochemical system	82.97	-	-	-	Bai et al. (2020)
	Methanobacterium	Bio electrochemical system	50	-	-	-	Charles et al. (2021)
	Methanogenic archaea	Anaerobic digestion	95.2	-	-	-	Díaz et al. (2020)
	Methanobacterium fexile	Dark fermentation	99	-	-	-	Muñoz-Páez and Buitrón (2022)
Bioethanol	Corn stalk	Fermentation to produce ethanol, pyrolysis to produce bio-oil, and gasification to produce aviation fuel	54.5	-	-	-	Sun et al. (2021a)
	Microalgae	Saccharification (fermentable sugar conversion) and fermentation (bioethanol production)	45	2	2	-	Hossain et al. (2019)
Biodiesel	*Jatropha*	Transesterification	69%	-	-	33%	Khang et al. (2017)
	Waste cooking oil	Transesterification	96	-	-	-	Khounani et al. (2020)

This table presents a review of various bioenergy processes, such as biomethane, bioethanol, and biodiesel, showcasing their different percentages of carbon dioxide removal, water footprints, land footprints, and acidification potential

Martins (2017), the global environmental impacts related to acetone-butanol-ethanol fermentation processes (corn versus wheat starch) significantly increase in this scenario due to the reduced economic value of the gases generated during fermentation. This scenario considers carbonyl synthesis as a more environmentally friendly approach for producing 1-butanol.

Biodiesel

Biodiesel is a long-chain fatty acid methyl / ethyl ester produced through the esterification of plant, animal, or microbial oils / fats with short-chain alcohols (methanol and ethanol). When conducting life cycle assessment studies to evaluate the environmental impact of biodiesel, one of the primary focuses is estimating and assessing carbon dioxide emissions. Zhao et al. (2021) and others found that the esterification step is responsible for a significant portion of biodiesel production emissions. In the case of biodiesel produced from waste cooking oil, it was calculated to have emissions of 1383 kg of carbon dioxide equivalent per ton (from "cradle to gate"). Based on a "well-to-wheels" method, Dufour and Iribarren (2012) determined that each ton of waste cooking oil biodiesel emits approximately 652.16 kg of carbon dioxide equivalent into the atmosphere. This assessment indicated that the esterification phase significantly contributes to carbon dioxide equivalent emissions.

Incorporating enzymatic catalysis into the biodiesel production process, as noted by Peñarrubia Fernandez et al. (2017), led to the generation of 388 kg of carbon dioxide equivalent per ton of waste cooking oil biodiesel. Mendecka et al. (2020) compared standard esterification processes utilizing sodium hydroxide, potassium hydroxide, and sulfuric acid catalysts to a non-catalytic supercritical methanol method in terms of carbon dioxide equivalent emissions in another research. Sulfuric acid had the greatest carbon dioxide equivalent (813 kg/ton waste cooking oil), while sodium hydroxide had the lowest (234 kg/ton waste cooking oil). Another research assessed the overall carbon footprint for one ton of waste cooking oil biodiesel at 553 kg carbon dioxide equivalent (Foteinis et al. 2020). According to de Pontes Souza et al. (2012), each ton of waste cooking oil biodiesel produced 2323.35 kg of carbon dioxide equivalent. The esterification process accounted for 54% of the total carbon dioxide equivalent, followed by the combustion step (46%).

In addition to the esterification processes, the utilization of biomass as a source of energy that may be converted into solid or liquid fuels is an exciting new development. Biofuels, when employed as substitutes for fossil fuels, have the potential to significantly reduce human-induced greenhouse gas emissions. However, making decisions about biofuel policies should be based on evidence that the production of biofuels can be carried out sustainably (Balajii and Niju 2019). Research has indicated that tracking the origins of biofuels, such as biodiesel and biochar, can help mitigate the negative environmental impacts associated with the use of fossil fuels (Peng et al. 2020). In other words, the use of biofuels can help counteract the increasing demand for fossil fuels and reduce the pressure on non-renewable resources. Nevertheless, it is crucial to assess the actual benefits of utilizing biofuels compared to traditional energy sources through rigorous, scientific, and applicable methods (Chamkalani et al. 2020). Life cycle assessment is a recognized comprehensive approach for quantifying the environmental consequences of the entire biofuel production chain (Collotta et al. 2019).

Biogas

Low-quality organic waste, encompassing materials like agricultural, forestry, and food processing waste, livestock manure, and kitchen waste, which is rich in carbohydrates, proteins, fats, and other components, can be anaerobically fermented and converted into biogas (methane) and other biofuels. In the production of biogas, life cycle assessment can also be used to analyze the environmental impacts related to products, processes, or services by identifying the energy requirements, materials used, and emissions released into the environment. Environmental impacts can be measured at the endpoint of the life cycle assessment cause-and-effect chain. Therefore, life cycle assessment techniques can be used to identify possibilities for enhancing the environmental performance of the system. On the other hand, life cycle-based environmental assessments are comprehensive approaches that can demonstrate biogas power generation as a clean and safe technology. Consideration should be given to composting the digestate generated from biogas production and using natural coagulants for the treatment of wastewater from bioprocessing to ensure process sustainability (Amin et al. 2022). Therefore, as a holistic approach, life cycle assessment is a fundamental tool that should be applied to biogas plants to assess the environmental performance of the biogas produced.

To unlock the future potential of biogas utilization, aligning with the principles of the circular economy is imperative. Implementing an intelligent strategy to minimize process waste and integrate it into the biodigester system can be achieved through an organizational competitive advantage. This approach not only has the potential to reduce environmental impacts but also enhance economic benefits by effectively closing the materials and energy loop within the organization.

In conclusion, conducting a comprehensive life cycle assessment is essential for the reliable evaluation of bioenergy systems. Effective life cycle assessment studies should encompass various indicators of environmental sustainability, going beyond greenhouse gas emissions and energy balance. Standard requirements should cover functional units, system boundaries, allocation mechanisms, and environmental indicators. Currently, differing standards in various research areas hinder comparisons across bioenergy life cycle assessment studies. Adopting a unified methodology would enable such comparisons. It is essential for both the academic and business communities to engage in detailed life cycle assessments and to have access to streamlined and cost-effective versions of this tool. While potent, life cycle assessment should remain adaptable and continuously improved as scientific knowledge evolves.

Bioenergy sustainability evaluation using life cycle assessment

The assessment of environmental impacts associated with converting biomass into biofuels (e.g., hydrogen and methane) or bioproducts (e.g., cellulase and hydrolysate) can be effectively conducted using life cycle assessment. Life cycle assessment results play a crucial role in pinpointing opportunities for advancing biorefineries. In this context, life cycle assessment serves as a macro-level decision support tool capable of influencing significant policy changes and infrastructure developments, such as the establishment of biorefineries. Research indicates that life cycle assessment is a valuable tool for comparing emerging biorefining concepts with conventional waste disposal methods, such as landfilling (Escamilla-Alvarado et al. 2017). Nonetheless, there remains potential for applying similar studies to novel processes to identify areas for further research and development. To bolster the findings presented in this study, it is essential to gather operational data similar to the hexamethyldisilazane process. Additionally, comparing hexamethyldisilazane biorefineries with alternative waste treatment and disposal methods like anaerobic digestion, composting, and vermicomposting can establish benchmarks for researchers, practitioners, and decision-makers to select and implement environmentally sound technologies for urban solid waste management in specific geographical regions.

Life cycle assessment procedures, according to ISO 14040:2006, measure environmental elements and possible environmental consequences connected with goods, processes, or services. Life cycle evaluation encompasses extraction and refinement of raw materials, transportation, manufacture, usage, and end-of-life disposal, depending on the system boundaries. Life cycle assessment accuracy is heavily dependent on the quality and accuracy of the underlying data and assumptions utilized to conduct the study (Velasquez-Orta et al. 2018; Torkayesh et al. 2022). Despite the interest in bioenergy life cycle evaluation, there is a distinct shortage of research employing real-world primary data from manufacturing plants. In fact, most bioenergy life cycle assessment studies are based on hypothetical industrial facilities then extrapolated or theoretically estimated. Data sources vary, stemming from small-scale laboratory studies and scholarly literature.

In addition to data gaps, life cycle assessment in bioenergy production encounters several challenges. A significant issue inherent to life cycle assessment, in general, is the lack of comparability among seemingly similar assessments. While ISO 14040 and 14,044 provide an overarching framework and standards for conducting standardized LCA, they do not prescribe methodologies for making distinct choices within a life cycle assessment. Practitioners have discretion in defining functional units, boundary conditions, and impact categories, leading to considerable disparities in assumptions, methodologies, and data quality among ostensibly similar LCA, rendering them non-comparable (Valente et al. 2019; Sills et al. 2020). Moreover, certain elements of ISO 14040 and 14,044, like the scope of effect categories to be evaluated, are frequently disregarded.

Molina-Besch (2022) performed a detailed critical examination of 40 LCA papers published between 2019 and 2021, including techniques and study results, to understand the most recent improvements in environmental impact assessments of biofuel production. Only eight studies were found to cover all three phases of biofuel production, including biomass cultivation, biofuel manufacturing techniques, biofuel usage, and end-of-life management. This incompleteness limits the comprehensive assessment of the overall sustainability of bioenergy production.

In conclusion, sustainability tools depend on environmental assessments such as life cycle assessments to mitigate pollution and negative impacts on ecosystems. Conducting LCA for newly developed materials or technologies remain.

Techno-economic analysis of bioenergy production

Techno-economic analysis methodology and its applications in bioenergy production

Fossil fuels are used to produce energy for the generation of heat and electricity as well as for transportation, which are responsible for around 80% of the world's greenhouse gas emissions. The consumption of fossil fuels is rising along with the population and is anticipated to reach 90% by 2050 (Antar et al. 2021). Biomass, a natural, non-fossil organic material rich in chemical energy, has emerged as a promising alternative to fossil fuels, offering the potential to mitigate their emissions (Rozzi et al. 2020). Biomass energy sources include materials from forestry, agriculture, and urban waste, such as wood, sawdust, straw, manure, paper waste, and household waste. Biomass is considered an alternative energy source with a heat value of approximately 3×10^6 kcal/mg (Brosowski et al. 2019). Assume that the ratio of fossil fuels is around 33% diesel and 50% coal. In that situation, the need for developing and implementing sustainable biomass production techniques to establish a thriving and sustainable bioeconomy should expand. The best ways to combat global warming and greenhouse gas emissions while meeting our energy needs are green technologies, such as biofuels and bioproducts.

The techno-economic analysis is a methodology used to calculate, compare, and evaluate various technical plans and strategies to find the optimal combination of technology and economic feasibility. The techno-economic analysis involves comparing the costs of different technological approaches with the revenues generated by the most cost-effective and economically viable schemes. This analysis considers both the costs incurred and the income generated by a program (Beaucamp et al. 2022). In practical applications, techno-economic analysis helps measure both tangible and intangible benefits (Pan et al. 2023).

The techno-economic analysis offers a multifaceted evaluation, taking into account various aspects of technology, economics, and market dynamics, thus providing a comprehensive assessment (Salimbeni et al. 2023). Moreover, it has the capability to embed sustainability considerations into its evaluation framework. The bioenergy sector faces extreme competition from fossil fuels, with bioenergy feedstock transitioning from primary food crops to agricultural residues and non-food crops to mitigate competition in the food markets. Techno-economic analysis harnesses the concept of agro-economy and sustainability, which can help bioenergy make more informed choices regarding raw materials and, in turn, garner support from governing bodies, potentially securing economic subsidies to drive down costs (Deep Singh et al. 2022).

The techno-economic analysis is instrumental in assessing the economic viability of biomass production methods, determining the minimum selling price of biofuels, and identifying the primary cost drivers for each process. Common applications of techno-economic analysis in bioenergy production include cash flow analysis, sensitivity analysis, technology assessment, environmental cost evaluation, and market analysis, as shown in Fig. 4.

Techno-economic analysis plays a crucial role in assessing the economic viability of bioenergy production. It

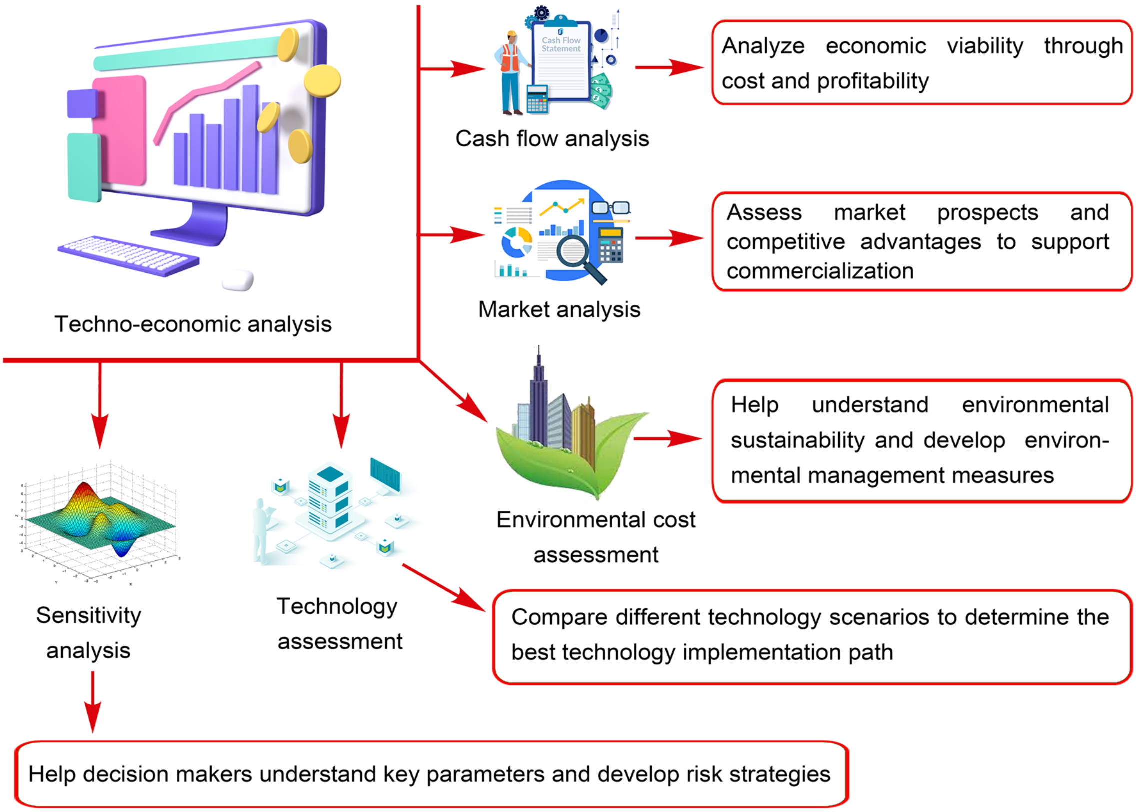

Fig. 4 Five prevalent areas of focus within techno-economic analysis. These components encompass cash flow analysis, sensitivity analysis, technology assessment, environmental cost evaluation, and market analysis. This figure depicts how the integration of technical and economic assessments offers valuable decision-making insights for bioenergy producers. The diagram outlines the distinct types of analyses and the situations in which they are relevant. Technical and economic analysis serves to appraise projects by parameterizing key indicators, aiding in the evaluation and optimization of bioenergy production strategies

involves calculating essential financial metrics like net present value, internal return, and return period, considering various factors such as investment costs, operating costs, energy output, and related income (Martínez et al. 2022). Several factors within the bioenergy production process influence the project's economic feasibility, including raw material prices, energy costs, and operating expenditures. Furthermore, the pre-treatment of raw materials and the associated chemical transformations affect product efficiency, yield, reliability, and environmental impacts (Meenakshisundaram et al. 2021).

The insights derived from techno-economic analysis aid bioenergy producers in selecting the most profitable technology options. For instance, Li et al. (2023) suggested the utilization of microalgae from urban sewage through anaerobic fermentation to produce fuel. The techno-economic analysis divided biomass dehydration treatment into closed and open systems. The cost of producing dehydrated, dry substances in both scenarios were 5.54 and 4.65 US dollars/kg, respectively. At the same time, the productivity was 0.8 kg/m^3 per day and 0.6 kg/m^3 per day, respectively (Somers et al. 2021). As a result, the production costs of open systems were lower than those of closed systems for bioenergy producers. From a sensitivity analysis point of view, the most significant cost for bioenergy production was the depreciation of labor, which represented 39% to 42% of all the total operating costs (Ighalo et al. 2022).

Additionally, techno-economic analysis helps in evaluating different raw materials and treatment methods. Take alkaline treatment as an example; compared to untreated straw, sodium hydroxide pre-treatment of corn straw led to a significant increase in methane production by 73.4% (Zdeb et al. 2023). However, it also revealed that for low lignin biomass, the costs of wastewater treatment could outweigh the profit gained from higher methane production, suggesting that alkaline treatment is more suitable for raw materials with higher lignin content.

Furthermore, cash flow analysis and market analysis provide valuable insights for companies' development strategies. For instance, biogas, a key component of bioenergy, can be a cost-effective alternative to natural gas, typically produced from domestic and agricultural waste (Keerthana Devi et al. 2022). While the process is relatively simple, the collection, transport, and storage of raw materials can incur high costs. From a cash flow and market analysis perspective, constructing biogas reactors within community units was proposed as a means to minimize production expenses and supply biogas directly to the community (Ali et al. 2021a). Thus, techno-economic analysis can significantly influence the layout and strategy of biorefinery projects.

In conclusion, techno-economic analysis is a critical tool for evaluating the feasibility and profitability of bioenergy production. With the various methods of bioenergy production having distinct cost structures, profitability, and environmental implications, techno-economic analysis systematically combines these parameters to assist producers in making informed decisions regarding key financial metrics such as net present value, internal return, and return on investment. It serves as an essential guide for sustainable bioenergy development in the transition from fossil fuels (Hosseinzadeh et al. 2022).

Key economic factors for the viability of bioenergy production

Bioenergy holds substantial economic promise by efficiently utilizing abundant waste resources. It offers a sustainable alternative to the traditional disposal methods of incineration or landfilling for agricultural waste, effectively transforming this waste into a valuable substitute for fossil fuels. Not only does bioenergy contribute to the carbon cycle, but it also enriches the energy matrix, making it a highly attractive prospect (Cavalcanti et al. 2020). One of the primary concerns for businesses engaged in bioenergy production is ensuring profitability. To address this concern, techno-economic analysis plays a critical role. It involves the assessment of various bioenergy methods, considering aspects like design, process description, process simulation models, and cost estimation (Sarker et al. 2023). The feasibility of biofuel production is determined through modeling, and sensitivity analysis identifies the most expensive and environmentally detrimental steps within the production process. By optimizing these steps, costs can be reduced, and the overall feasibility of bioenergy production can be enhanced. This approach contributes to making bioenergy a more economically viable and sustainable option in the energy landscape.

In bioenergy production, understanding the raw materials required and the methods for bioenergy generation is crucial. As suggested by Ahn et al. (2023), there are several pathways to transform biomass into biofuels and other valuable byproducts. These pathways include enzymatic conversion, heat conversion, and catalytic conversion, with catalytic conversion being particularly promising. This is due to the ability to control production rates using chemical reagents, resulting in lower operational costs (Kim et al. 2020). To assess the economic viability of these processes, techno-economic analysis is often employed. Specialized software like Aspen Plus v12 and SuperPro Designer v9.0 is used for simulating the entire experimental process (Sarker et al. 2022). This software allows for the creation of a comprehensive list of components involved in the process and the application of a thermodynamic model. By defining the relevant production parameters and simulating the reaction processes, techno-economic analysis can evaluate the feasibility of bioenergy production. This analysis considers critical economic factors that impact the overall viability of bioenergy production.

The economic factors that significantly impact bioenergy production can be categorized into three key areas: capital costs, operating costs, and market demand. These factors play a pivotal role in determining the overall cost of bioenergy production and the expected profitability in the future. Capital expenditure in bioenergy production revolves around the distinction between plant and production pipeline costs, often referred to as total fixed costs. As indicated by Sarker et al. (2023), total fixed capital can be further subdivided into direct and indirect fixed costs. Plant direct fixed costs encompass expenses associated with plant equipment, processing facilities, piping, and other infrastructure. In contrast, indirect fixed costs comprise expenditures related to engineering and construction (Manouchehrinejad et al. 2021). To assist in estimating capital expenditure parameters and assumptions, a valuable resource is Table 5, which has been compiled based on the work of Sarker et al. (2022) and Parkinson et al. (2017). This table offers a means of pre-budgeting capital expenses by building upon equipment costs, enabling better financial planning.

Operating costs are a crucial component of bioenergy production, encompassing the expenses incurred in the process, particularly the costs related to materials and processing. Bioenergy production typically relies on agricultural waste as raw materials, which are relatively cost-effective, ranging from approximately 27.90 to 232.48 US dollars per ton of dry biomass (Clauser et al. 2021). However, these raw materials come with inherent challenges as follows:

- Collection, transportation, and storage costs: raw materials for bioenergy, such as straw and bagasse, are subject to various processing steps, including collection, transportation, and storage. These steps add to the operational costs of biorefineries, as they involve expenses and logistics. Additionally, materials like straw and bagasse can be challenging due to issues like scattering, low density, and perishability, which further increase the complexity and cost of bioenergy production (Sun et al. 2021b).
- Conversion and processing costs: bioenergy production involves the conversion of raw materials into useful biofuels and products. Traditional processing methods may suffer from low efficiency. For example, the theoretical production of biological hydrogen and

Table 5 Cost forecast for bioenergy production

Total fixed cost	Cost category	Related parameters for estimation
Factory direct fixed costs	Purchase price of all equipments	Equipment acquisition costs
	Installation costs	50% of equipment acquisition costs
	Instrument costs	30% of equipment acquisition costs
	Piping costs	60% of equipment acquisition costs
	Electrical installations	20% of equipment acquisition costs
	Building-related maintenance	20% of equipment acquisition costs
	Material yard improvement	5% of equipment acquisition costs
	Support facilities	40% of equipment acquisition costs
Factory indirect fixed costs	Engineering costs	12% of factory direct fixed costs
	Construction costs	10% of factory direct fixed costs

Total fixed capital, an essential consideration for project planning, is divided into two key categories: plant direct fixed costs and plant indirect fixed costs. Each of these categories includes specific cost items and related parameters for estimation. This table shows what direct fixed costs typically mean for equipment and associated facilities, while indirect fixed costs relate to plant building construction and construction costs. In addition, this table is based on the cost of equipment acquisition and estimates the cost of the associated facilities by parameters. This approach helps investors to estimate the total fixed cost of the project

biomethane from bagasse is estimated at 336 L/kg of dry bagasse and 440 L/kg of dry bagasse, but actual production often falls short, yielding 150 and 200–300 L/kg of dried sugarcane bagasse (Pan et al. 2022). This indicates a substantial profit potential if the efficiency of raw material utilization can be improved through pre-treatment.

- Pre-treatment costs: enhancing the efficiency of raw material utilization often involves pre-treatment. Conventional heat treatment methods can be energy-intensive and environmentally unfriendly. To mitigate these issues, cheaper acids and alkali reagents, such as sodium hydroxide, are commonly employed for biomass pre-treatment (Baral et al. 2021). For instance, pre-treatment of sugarcane bagasse with sodium hydroxide has been shown to reduce fermentation costs by 41.3%.
- Water use and wastewater management: lignocellulosic materials from agricultural waste are not water-soluble. Consequently, the production process, which includes pre-treatment, saccharification, and fermentation, requires a substantial amount of water to cleanse pollutants and manage wastewater (Yuan et al. 2021). As a result, water usage constitutes a significant cost component in biofuel production, accounting for approximately 2% of the total direct cost. Efficient wastewater management and measures to reduce water usage are essential to control these operational costs.

Operational costs are a substantial part of the total cost of bioenergy production. Efficient management of these costs, particularly through the optimization of raw material collection and processing, can greatly influence the economic feasibility of bioenergy production. In addition to operational costs, market demand for bioenergy significantly impacts the profitability of bioenergy producers:

- Market demand for bioenergy: the demand for bioenergy is closely connected to market conditions, especially the pricing of fossil fuels. During periods when fossil fuels are relatively expensive, there is an increased shift in energy demand toward biofuels. This shift allows bioenergy producers to achieve higher profits (Sajid 2021). According to Wu et al. (2022), the average production cost per gallon of cellulose biofuel for low, medium, and high conversion rates is 3.72–3.86 US dollars per gallon, 3.23–3.26 US dollars per gallon, and 2.85–2.92 US dollars per gallon, respectively. The current cost of gasoline is 3.70–4.10 US dollars per gallon (Bautista-Herrera et al. 2021). In cases where the price of gasoline decreases significantly (2–3 US dollars), large biorefineries may remain economical, while small and medium-sized biorefineries might require tax incentives and subsidies to maintain profitability and competitiveness. Producers can enhance market demand by optimizing production processes and increasing conversion efficiency, thereby reducing prices.

Furthermore, biorefineries can enhance their resilience to market volatility by adopting multi-product revenue strategies. When the demand for bioenergy decreases due to falling fuel prices, biorefineries can shift production to alternative products, providing a buffer against market fluctuations (Katakojwala and Mohan 2020).

In conclusion, the operational costs in bioenergy production significantly impact the feasibility of the production process. Key components of these costs include raw material collection, transportation and processing, pre-treatment expenses, and water use and wastewater management. Efficient management of these costs is essential for the economic viability of bioenergy production. Moreover, market demand, which is closely related to the pricing of fossil fuels, plays a critical role in determining the profitability of bioenergy producers (Shah et al. 2022). Policies, such as government subsidies, can further support bioenergy production, and ongoing optimization of production processes is essential to reduce costs and attract more energy companies to the bioenergy sector (Akindipe et al. 2022).

Critical analysis of recent techno-economic analysis studies on bioenergy feedstocks and production technologies

Recent studies have investigated various bioenergy feedstocks and production technologies, analyzing their economic feasibility and sustainability with a critical analysis of some of the key findings in these studies reported herein. Studies highlight that biorefineries using starch-based feedstocks, such as sugar and starch fermentation, have well-established technologies that are proven to be profitable (Tena et al. 2022). However, the excessive use of this raw material by biorefineries that use food as a feedstock for cash crops, such as maize, increases the price of the raw material market due to competition. Therefore, although the technology of producing bioenergy using starch as a raw material is well-established, prices always fluctuate due to competition (Yang et al. 2020).

Lignocellulose is considered a more sustainable and accessible feedstock for bioenergy production. It does not compete with food sources, making it an attractive option (Rajesh Banu et al. 2021). Various treatment methods, such as fermentation and anaerobic digestion, can be applied to lignocellulose to produce bioethanol efficiently (Okolie et al. 2021). The mechanical treatment of lignocellulose can result in high-density biomass fuel that can be used in power generation alongside coal. However, a major challenge in using lignocellulose as a feedstock is the collection, transportation, and preservation of this material. Due to its low density and susceptibility to decay, the collection process is complex. Efficient preprocessing during collection can address these issues and make the use of lignocellulose more viable (Anand et al. 2022). It is important to note that different raw materials, such as starch-based and lignocellulosic feedstocks, require distinct treatments. These variations can lead to different outputs in terms of energy or biofuel production. The choice of treatment methods has economic implications, as certain treatments may be more cost-effective and yield higher returns, as shown in Table 6.

In conclusion, the choice of bioenergy feedstocks and production technologies is influenced by various economic and sustainability factors. While starch-based feedstocks have established profitable technologies, the competition for these resources can lead to price fluctuations. Lignocellulose, on the other hand, offers a more sustainable option, but its efficient collection and preprocessing are significant challenges. Additionally, different treatments of raw materials can result in varying outputs. These studies emphasize the importance of considering the entire supply chain, from feedstock collection to the end product, when assessing the economic feasibility of bioenergy production. Such analysis is crucial for making informed decisions in the transition to sustainable and economically viable bioenergy production.

The techno-economic analysis employs specific economic indicators, such as net present value, internal rates of return, and return on investment periods. These metrics enable decision-makers to gage the feasibility of bioenergy projects. It allows for a quantitative assessment of different feedstocks; for example, it can reveal that bioethanol production from mango residues is not financially viable, while bioethanol derived from algae proves to be a highly competitive option (Stewart et al. 2023). By conducting sensitivity analysis, techno-economic analysis identifies and evaluates risk factors and pivotal elements in bioenergy projects. For instance, in the case of ethanol refineries, it reveals that the cost of producing ethanol for transportation comprises around 2% to 4% of the total expenditure. An additional insight it provides is that if ethanol refineries are situated close to the location where ethanol is needed, it can reduce costs (Kumar et al. 2023b). In essence, techno-economic analysis empowers decision-makers with comprehensive insights by integrating the economic merits of the project with the applicable technologies involved.

While techno-economic analysis is invaluable in supplying bioenergy producers with essential data for informed decision-making, it does have limitations. A significant constraint is the reliability of the data it relies on. The precision and trustworthiness of the technical and economic analysis are heavily reliant on the quality of the data available, which can often be challenging to obtain with certainty in bioenergy production (Deivayanai et al. 2022). For example, the transport of raw materials faced restrictions due to the impact of the Coronavirus disease 2019 (COVID-19), while equipment depreciation and labor costs persisted. This unforeseen challenge was further compounded by a 10% to 30% increase in raw material prices due to transportation disruptions, introducing unpredictability into the profitability of biorefineries and associated uncertainties (Duc Bui et al. 2023). Moreover, techno-economic analysis demands a wealth of data that is not always universal and is influenced by regional policies (Deivayanai et al. 2022). In regions where financial constraints are high, governments may be less inclined to favor biofuels, thus reducing the demand for bioenergy.

Table 6 Output of different raw materials in the bioenergy production process and their economic value

Raw material	Origin	Processing method	Output	Economic value	Characteristics of techno-economic analysis	Reference
Guayule	Southwest United States	The guayule bagasse was bio-refined successfully after the latex extraction using the exhaust gas reaction pyrolysis, then the table distillation and hydrogenation deoxygenation	Biofuel	Biofuels produced are similar to local fossil fuel prices	From a technical assessment point of view, the cost is reduced by 26% when the capacity of the facility reaches 2000 tons	Moreno et al. (2022)
Seaweed	Indonesia	Enzymes digest the carbohydrates in the algae to produce sugar and then ferment to produce ethanol	Bio-ethanol	1.38 US dollars/gallon bioethanol, lower than the lowest price for ethanol in 2019	From a technology assessment point of view, this bioenergy production method is only suitable for coastal cities with high electricity demand	Sadhukhan et al. (2019); Fasahati et al. (2022)
Forestry residues (sawdust and shavings)	Quebec, Canada	Biochemical processes include fermentation and anaerobic digestion	Biodiesel	Per gallon of gasoline-equivalent dollar 4–5, bioenergy consumption accounts for 17% of final energy consumption	The technical and economic analysis puts forward some suggestions on the scale of production. When total bioenergy increases by 20%, forest feedstock costs 35%	Durocher et al. (2019); Kouchaki-Penchah et al. (2022)
Compressed wood chip particles	The USA	Pyrolysis formation synthesizer under pressure and heating gasification under oxygen enrichment	Synthesis gas	Electricity costs 86.85 US dollars/MWh, while normal electricity costs 61.41 US dollars/MWh	Processing biomass with the same properties reduces the cost of electricity from 87.13 US dollars/MW to 62.9 MWh	Ghiami et al. (2021)
Mango waste	South Africa	Fermentation with cellulase and yeast	Bio-ethanol	Not profitable, not self-sufficient in most cases	From sensitivity analysis, fluctuations of 10 percent of raw material prices affect 4% of net present value	Manhongo et al. (2021)
Olive residue	Morocco	Anaerobic fermentation using microorganisms in confined biogas pools	Methane	Electricity costs 15.49 cents/kWh, compared to the cost of a cogeneration plant, 28 cents/kWh bringing significant profit	From sensitivity analysis, temperature has a large effect on yield, and a 10% change in temperature results in a 1% change in energy production efficiency	Mana et al. (2021)

Table 6 (continued)

Raw material	Origin	Processing method	Output	Economic value	Characteristics of techno-economic analysis	Reference
Poultry waste (bones, powder, and feathers)	The United Kingdom	Pyrolysis by high-temperature	Syngas, bioils	The production cost of poultry waste is much lower than the purchase price of conventional polymer fillers if the whole United Kingdom poultry waste is synthesized. Saving 29 tons of oil equivalent per day	From the point of view of environmental assessment, it saves 5 times more crude oil as a polymerization additive than direct combustion	McGauran et al. (2021)

As it is shown, raw materials from various regions are different, which necessitates different processing methods. The table also shows how different products can be obtained due to different treatment methods; different products have different economic values, some can be considered alternatives to gasoline, and some products are used directly for power generation. The output of different raw materials through different treatment methods has different economic values

In conclusion, the viability of bioenergy production is contingent on various factors, including the choice of raw materials and their distinct processing requirements. For this reason, bioenergy producers need to conduct thorough assessments of their environments when establishing biorefineries to optimize collection and transportation costs (Ranjbari et al. 2022). Techno-economic analysis, through quantitative evaluation, offers predictions regarding the competitiveness of biorefineries relative to fossil fuels and provides policymakers with the quantitative insights necessary for sustainable bioenergy production. Nonetheless, it is crucial to acknowledge the constraints of techno-economic analysis to prevent analysis errors that could pose risks to investors.

Chemical aspects of bioenergy production

Reaction process in bioenergy production

As shown in Fig. 5, thermochemical and biochemical conversion are the two main routes of biomass conversion in the production process of bioenergy (Gnanasekaran et al. 2023). The former approach entails the application of heat or oxidation to biomass, leading to the generation of syngas. Subsequently, this syngas can be further transformed into high-value products. Various technologies are employed in this process, including direct combustion, torrefaction, hydrothermal liquefaction, pyrolysis, and gasification (Osman et al. 2021). Through chemical or thermal conversion processes, organic waste can be converted into bioenergy for reuse (Wang et al. 2020). Thermal conversion has two methods: advanced thermal conversion and conventional incineration (Dong et al. 2018). The advanced thermal method includes gasification and pyrolysis methods. Gasification involves the conversion of solid biomass into syngas, a versatile gas mixture used in various applications. Pyrolysis is particularly well-suited for breaking down carbonaceous biomass components, making it a common choice in bioenergy production (Dhanya et al. 2020). Pyrolysis is considered to be one of the most commonly used thermochemical schemes for the degradation of carbonaceous biomass, such as cellulose, hemicellulose, and lignin (Aravind et al. 2020).

Biofuels can be classified based on their different production materials. Edible biomass such as sugars, starch, and vegetable oil are classified as the first generation of biofuels (Luiza Astolfi et al. 2020). The residues of agricultural and forestry raw materials, such as sugarcane leaves, are the main components of second-generation biofuels (Jutakridsada et al. 2019). The second generation of biofuels, mainly based on agricultural raw materials, is mainly composed of lignocellulosic biomass (Westensee et al. 2018). Microalgae have excellent capabilities in manufacturing important

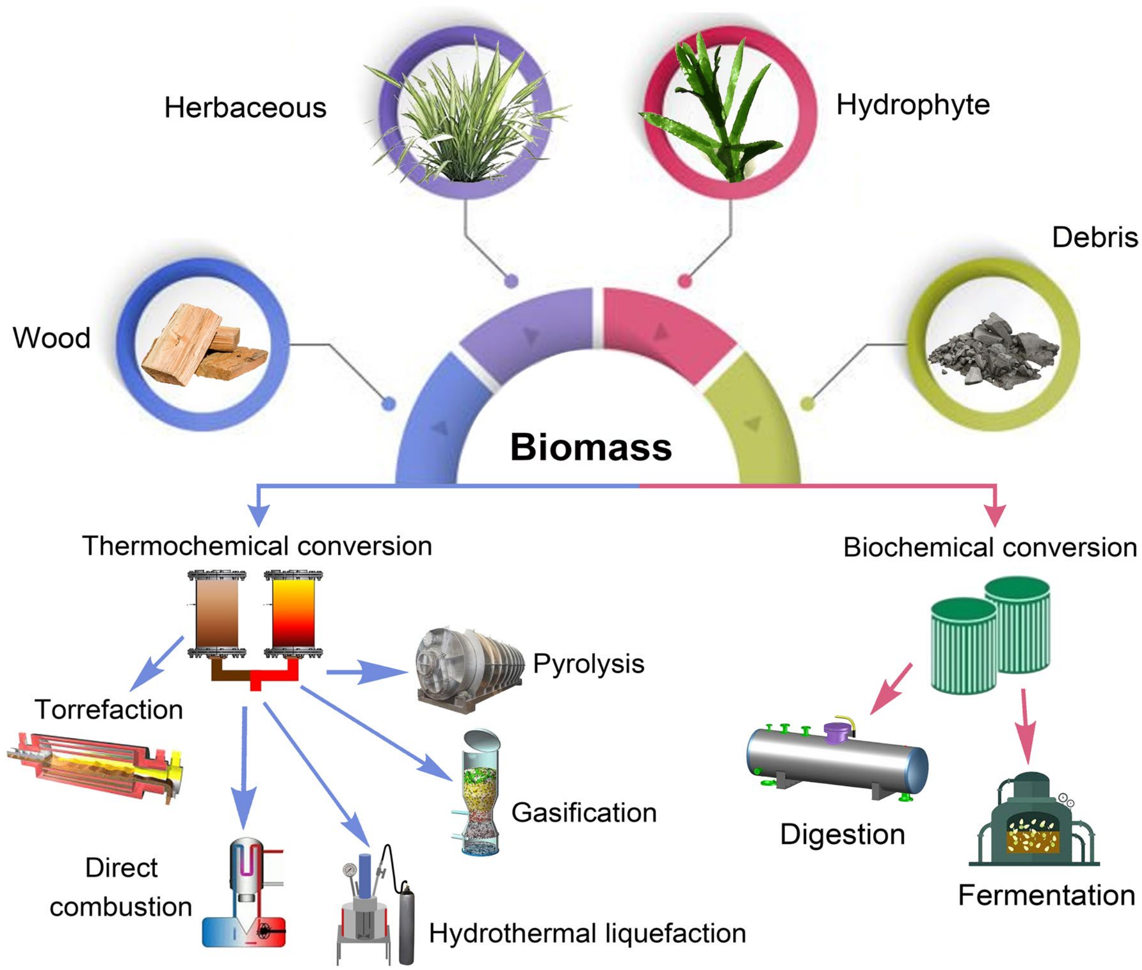

Fig. 5 Techniques of biomass conversion to bioenergy. In the bioenergy production process, the two primary techniques of biomass conversion are thermochemical and biochemical conversion, which include hydrothermal liquefaction, pyrolysis, gasification, and direct combustion processes. Fermentation and anaerobic digestion are two biochemical methods for converting biomass into biofuel. There are two types of digestion: aerobic digestion, which produces carbon dioxide and fertilizer, and anaerobic digestion, which produces biogas, which, when mixed with hydrogen, can be converted into liquid fuel. Another approach is the fermentation process. First, biomass is pre-treated, then enzymatic hydrolysis and fermentation are performed, and finally, liquid biofuel is produced

chemical and nutritional products and are an important component of third-generation biofuels (Kumar et al. 2018). High oil content, high carbon dioxide fixation efficiency, growth potential in limited space, and environmentally friendly characteristics make microalgae become one of the popular biomass energy sources. The fourth generation of biofuels is mainly obtained through bioengineering. Algae, fungi, and crops are all potential raw materials for fourth-generation biofuels, which are still in the development process (Sikarwar et al. 2017).

Algae, particularly microalgae, have been considered as one of the potential biomass reagents for pyrolysis due to their high biological yield (Aravind et al. 2020). Table 7 lists the conversion of different algae into biofuels using different technologies. Based on temperature, algae thermal degradation can be separated into three processes. Algae undergo dehydration at temperatures below 200 °C and devolatilization at temperatures between 200 °C and 500 °C. This is the main process of pyrolysis, and solid decomposition occurs at temperatures above 550 °C (Das et al. 2021). As the temperature changes, the biochemical components in algae also change accordingly. During the pyrolysis process of algae, the decomposition of proteins and carbohydrates usually occurs at temperatures below 400 °C. When the temperature rises to 550 °C, lipids begin to decompose. When the temperature increases to 600 °C, larger molecular weight hydrocarbons in biomass will decompose into smaller hydrocarbons (Pourkarimi et al. 2019). The transformation of algal biomass into bioenergy is mainly through three transformation technologies: biochemical, thermochemical, and chemical processes, each with its unique characteristics and applications (Chew et al. 2017).

Table 7 Bioenergy production from different algae using various conversion technologies

Algal type	Transformation	Bioenergy	Reaction temperature	Reference
Chlamydomonas reinhardtii, *Thiomonas intermedia*	Biochemical	Hydrogen	25 ± 1 °C	Ge et al. (2019)
Microalga *Chlamydomonas reinhardtii*, olive mill solid waste	Anaerobic co-digestion	Methane	35 °C	Lu et al. (2019)
Chlorella vulgaris, microalgae	Photosynthetic microalgae microbial fuel cell	Electricity	25 ± 2 ℃	Bazdar et al. (2018)
*Chlorella vulgari*s, sewage sludge	Hydrothermal liquefaction	Biological oil	340 ℃	Xu et al. (2018)
*Chlorella vulgari*s	Chemical looping gasification	Biological oil	500 ℃	Zainan et al. (2018)
Microalgal biomass	Hydrothermal carbonization	Water carbon	210 ℃	Lee et al. (2019)
Sewage sludge, *Chlorella vulgari*s	Hydrothermal carbonization	Water carbon	210 ℃	Chauhan et al. (2020)
Microalga Chlorella sp. FC2 IITG	Biodiesel via supercritical methanol transesterification	Biological oil	255 ℃	Chauhan et al. (2020)

Algae, a renewable and sustainable biomass source, can be converted into different forms of bioenergy through chemical, biochemical, and thermochemical processes. Thermochemical methods such as torrefaction, pyrolysis, and gasification are commonly used for algae biomass conversion

Hydrothermal carbonization is a method used to simulate the natural formation of coal to achieve a balanced approach to generating, storing, and producing sustainable clean energy materials through innovative technology (Nicolae et al. 2020). Lignocellulosic biomass primarily consists of three key components: cellulose, hemicellulose, and lignin. Lignin, under hydrothermal conditions, stands out as the most stable and least susceptible to hydrolysis, typically necessitating temperatures exceeding 250 °C for decomposition to commence (Wikberg et al. 2015). Nevertheless, biomass often contains a significant lignin component, which can impede the hydrolysis of long sugar chains under hydrothermal conditions, thereby diminishing the conversion rates of soluble and insoluble products (Dinjus et al. 2011). The degradation of cellulosic materials under hydrothermal conditions can be described into several fundamental steps: cellulose and hemicellulose chains are hydrolyzed, yielding glucose and other hexoses and pentoses. Hexoses dehydrate into 5-hydroxymethyl furfural, pentoses dehydrate into furfural, and further breakdown into lower molecular weight compounds occurs, alongside condensation and aromatization reactions, leading to the production of hydrothermal carbon (Steinbach et al. 2017). Buendia-Kandia et al. (2018) explored the decomposition of microcrystalline cellulose at temperatures of 180 °C, 220 °C, and 260 °C, revealing that extended cellulose chains were initially hydrolyzed into smaller glucose oligomers or monomers.

Biochemical transformation involves the generation of fermentable carbohydrates using specific microbial populations, converting them into liquid fuels like ethanol and butanol, or into gaseous molecules such as methane (Gautam et al. 2020). Biochemical conversion is a vital and cost-effective method for producing fuels, chemicals, and materials derived from biomass (Wang et al. 2019). The most common form of biochemical conversion centers on the hydrolysis of lignocellulosic polysaccharides, such as cellulose and hemicellulose, into monosaccharides, subsequently fermenting them into fuels like ethanol. This process is crucial for the commercial utilization of lignocellulose as a raw material, given its compact and rigid structure, which resists degradation by bacteria and other microorganisms (Rastogi and Shrivastava 2017). Due to this inherent hardness, cost-effective conversion of lignocellulosic biomass into sugars and, ultimately, biofuels presents a challenge. Ethanol and biohydrogen are derived from fermentable biomass through ethanol fermentation and dark fermentation/photobiology, respectively, while biogas is produced via anaerobic digestion (Osman et al. 2023a).

Anaerobic digestion, ethanol fermentation, and photobiological hydrogen production are all part of the biochemical conversion process, which is the process of converting biomass into biofuel for energy conversion (Gnanasekaran et al. 2023). Anaerobic digestion facilitates the transformation of organic waste into biogas, with algal biogas holding a high energy value and recovery rate comparable to cellular lipids (Ayala-Parra et al. 2017). Fermentation, be it aerobic fermentation in the presence of air or anaerobic fermentation in the absence of air, is a biologically-driven process (Karimi et al. 2021). In ethanol fermentation, microorganisms' enzymatic activity leads to the metabolic transformation of organic substrates. Yeast, for instance, converts biomass resources containing sugars, cellulose, or starch into ethanol (Gumisiriza et al. 2017).

Different fermentation modes include photo fermentation, wherein various photosynthetic bacteria drive the fermentation and conversion of organic substrates to produce biogenic hydrogen (Wang and Yin 2019). These processes occur through a series of metabolic activities categorized into three stages of anaerobic conversion. The distinction between light and dark fermentation is based on whether they operate under illuminated or dark conditions, respectively. Another type of fermentation driven by yeast is ethanol fermentation. Fermentation entails the conversion of sugars into cellular energy, resulting in the production of ethanol and carbon dioxide. This process is classified as anaerobic integration since it transpires in the absence of oxygen. Heterotrophic algae and yeast can convert sugars into lipids within cells, and suitable solvents are employed to rupture the cells (Łukajtis et al. 2018).

Photobiological hydrogen production, harnessing algae, entails the conversion of water into hydrogen and oxygen. Algae undergo photosynthetic growth and are cultivated under anaerobic conditions to stimulate hydrogen gas production. Photosynthesis leads to the generation of both hydrogen and oxygen (Iqbal et al. 2022). Ester exchange, involving the formation of fatty acid chains and glycerol between triglycerides and alcohols in the presence of a catalyst (Sulaiman et al. 2020), can produce fatty acid methyl ester from methanol and ethanol. The production of biodiesel via alkali-catalyzed transesterification is an economical process, as the low-temperature reactions involved in the process enable high conversion rates. Notably, alkali-catalyzed transesterification typically proceeds faster than acid-catalyzed transesterification (Melero et al. 2015). However, the presence of oil impurities and catalyst properties may restrict the transesterification process. Factors such as temperature and reaction time, which define the reaction conditions, can also influence the ester exchange process (Guan et al. 2017; Xie and Wang 2020). Moreover, the supercritical state of transesterification can weaken the hydrogen bonding of alcohol, accelerating chemical kinetics and ensuring the complete conversion of triglycerides into esters (Deshpande et al. 2017).

Means of improving bioenergy production efficiency

Enhancing bioenergy production efficiency is a crucial objective in bioenergy processes, and one highly effective approach is pre-treatment. Conventional pre-treatment methods include physical, chemical, and biological approaches (Zhao et al. 2022). Pre-treatment plays a pivotal role in the conversion of lignocellulose into energy, rendering lignocellulose more flexible for subsequent utilization. The current view offers a multitude of pre-treatment techniques tailored for diverse lignocellulosic feedstocks. As shown in Table 8, different pre-treatment technologies have different advantages and disadvantages, as well as different energy production efficiency. While biological pre-treatment may pose challenges like prolonged treatment duration and reduced efficiency, when combined with chemical pre-treatment, it can, to some extent, mitigate these limitations. Emerging pre-treatment technologies, for instance, deep eutectic solvents, offer the potential to not only attain high bioenergy yields but also ensure minimal environmental impact, positioning themselves as promising pre-treatment methods (Sharma et al. 2022b).

Physical pre-treatment is a conventional method involving physical methods, encompassing techniques such as grinding, shearing, and stirring. It is commonly used for biomass with low lignin content, like wheat straw, and involves procedures like extrusion grinding, cutting, and ball milling. These methods effectively reduce the size and degree of biomass polymerization (Bai et al. 2018). Dahunsi (2019) explored methane production from six types of lignin subjected to mechanical pre-treatment in two stages, revealing a 22% increase in methane production compared to untreated biomass, demonstrating the effectiveness of pre-treatment. Ultrasonic pre-treatment, known for its high energy and penetration, is often combined with chemical pre-treatment to enhance biomass delignification (Mankar et al. 2021). Subhedar et al. (2018) found that after ultrasonic pre-treatment, the degree of delignification of peanut shells, coconut shells, and open-heart fruit shells increased to 71.1%, 89.5%, and 78.9% compared to 41.8%, 45.9%, and 38% of conventional alkali treatment, almost achieving an 80–100% increase.

Heat pre-treatment enhances the enzymatic hydrolysis of cellulose and hemicellulose, improving the solubility of substances like xylan, arabinose, and mannan (Wang et al. 2018). For the thermochemical processing of lignocellulosic biomass into biofuels, methods like pyrolysis and gasification are common, while the latter is considered a cost-effective and efficient technology for bioenergy production (Sikarwar et al. 2017). Ahorsu et al. (2019) found that the conversion efficiency of cellulose from walnut shells treated with microwave radiation can reach 96.4%. Mazzoni et al. (2017) applied the plasma co-gasification method, which is regarded as an effective energy recovery method for urban solid waste and carbon-containing waste. By using plasma co-gasification to process 1338 tons of mixed waste consisting of 90% urban solid waste and 10% petroleum hydrocarbon waste per day, 81 megawatts of electricity are generated, with an efficiency of 33.63%, surpassing traditional waste incineration technologies. Perna et al. (2018) applied plasma gasification technology to advanced power plants, studying trash power generation and energy storage generated by litter power generation. In the second factory equipped with comprehensive hydrogen plasma gasification fuel cells, the efficiency of solid fuel cells reached 53.2%, and the efficiency of power plants was 44.9%, exceeding the 33% of traditional waste power plants and the 29% of the second factory integrated with air plasma gasification fuel cells.

Chemical pre-treatment involves the use of different chemical substances to disrupt lignocellulose's rigid

Table 8 Pre-treatment is essential when converting lignocellulosic fibers into bioenergy, various pre-treatment methods have distinct benefits and drawbacks, impacting energy efficiency

Raw material	Pre-treatment	Energy	Yield	Efficiency	Reference
Grass, grass clippings, wheat straw, digested bio-fibers	Mechanical	Methane	524.2 mL/g	Improved the biodegradability of biomass by 20% and methane production by 27%	Tsapekos et al. (2018)
Rice straw	Chemistry	Ethanol	23.6 g/100 g	Compared with the scientific control, the sugar yield increased by 5 times to 92.38%, and the ethanol yield increased by 6 times to 87.13%	Zahoor et al. (2021)
Corn straw	Biological	Biogas	270.8 mL/g	The maximum methane production of the pre-treated sample was 17.35% higher than that of the untreated group	Xu et al. (2018)
Wood dust	Oxidize	Methane	287 mL/g	Substrate oxidation improved methane production and digestion efficiency by up to 25%, facilitating the metabolization rate of the treated substrate, resulting in 23–30%	Almomani et al. (2019)
Rice straw, corn straw	Alkali-heat	Biogas	480 mL/g	After pre-treatment, the biogas production of the sample increased by 62% and 66%, respectively, compared to untreated rice straw and corn straw	Patowary and Baruah (2018)
Bamboo	Steam explosion	Ethanol	20.3 g/100 g	Compared with the raw materials, the pretreated samples showed 67.2–68.2% Hemicellulose and 37.5–43.5% lignin co-extracts, with 2.0–7.6% cellulose loss	Gao et al. (2021)
Sugarcane	Ammonia fiber expansion	Methane	299 mL/g	The ammonia fiber expansion pre-treatment of sugarcane bagasse and sugarcane leaves resulted in the highest specific methane production under anaerobic single digestion, which increased methane production by 8% and 26%, respectively, compared to the untreated control under single digestion	Mokomele et al. (2019)
Wheat straw	Ionic liquid	Ethanol	46.2 g/100 g	The ethanol yield and yield of biomass pretreated for 3 h reached 43.1 g/L, reaching 84.34% of the maximum theoretical yield. However, the yield of untreated biomass is only 10.76%	Ziaei-Rad et al. (2021)

Table 8 (continued)

Raw material	Pre-treatment	Energy	Yield	Efficiency	Reference
Sugarcane	Deep eutectic solvents	Ethanol	84.2 g/100 g	The optimal cellulose digestion rate obtained after sample pre-treatment is 88.23 ± 1.24%, which is approximately 228% higher than traditional methods	Liu et al. (2021)
Cotton stalk	Supercritical carbon dioxide	Methane	177 mL/g	Compared with the untreated sample, the methane yield of the sample pretreated with steam or organic solvent plus Supercritical carbon dioxide increased by 20%	Al Afif et al. (2020)
Sugarcane bagasse, waste jute caddies	Torrefaction	Ethanol	199.62 mg/g, 234.77 mg/g	Compared with the ethanol yield of untreated biomass fermented under anaerobic conditions and added with cysteine hydrochloride, the ethanol yield of sugarcane bagasse after pre-treatment increased by 19.34%, and that of waste just caddies increased by 20.28%	Chaluvadi et al. (2019)

Traditional approaches encompass physical, chemical, and biological pre-treatments. While these methods enhance lignocellulose utilization, they often entail high costs and energy consumption. Emerging pre-treatment technologies promise higher energy yields and environmental friendliness, fostering their development

structure. Acid reagents, like sulfuric acid, acetic acid, and phosphoric acid, can dissolve cellulose, hemicellulose, and some lignin, promoting fermentable sugar release (Lorenci Woiciechowski et al. 2020). Sulfuric acid, acetic acid, and phosphoric acid are commonly used acid treatment reagents (Rezania et al. 2020). Alkaline reagents, such as sodium hydroxide, dissolve the lignin and part of hemicellulose, effectively reducing cellulose crystallinity (Lorenci Woiciechowski et al. 2020). Oxidation, too, is an effective method, where excess hydroxyl generated after hydrogen peroxide decomposition inhibits biodegradation and biotransformation of lignin (Kumar et al. 2020). Ozone can form free radicals that react with lignin to make hemicellulose (Tan et al. 2021). Advanced oxidation processes are increasingly applied in bioenergy, especially for the pre-treatment of biogas production substrates (M'Arimi et al. 2020). These processes are also used to increase biodiesel production during ester exchange. Algae cells are often disrupted through grinding and homogenization, enabling biodiesel production from algae substrates (Islam et al. 2014).

Biological pre-treatment utilizes microorganisms or enzymes to break down lignin and hemicellulose in lignocellulose. While having low operating costs and reducing byproduct formation, its efficiency is relatively lower. Ma et al. (2021b) pretreated poplar with *Peniophora incarnate* T-7, after 7 days of fermentation, the cellulose, hemicellulose, and lignin in poplar decreased by 16%, 48% and 70%, respectively. Enzymes secreted by microorganisms are effective in reducing lignocellulosic polymerization. Chen et al. (2021c) treated banana residue with *Acetobacter orientalis*, and the cellulose decomposition efficiency of the control group was 46.08%, while the cellulose decomposition efficiency increased to 76.24% after treatment. In addition to bacteria and fungi, researchers have found that termites also play an excellent role in the pre-treatment of lignocellulose. Dumond et al. (2021) performed treatment of wheat straw by intestinal microbes of termites *Nasuitermes ephratae*, *Nasuitermes lujae*, *Microcerotermes parvus,* and *Termes*. It was observed that 80% of delignification was due to the removal of lignin, and the rest was due to the removal of hydroxycinnamic acid and trioctylic acid.

Physical and chemical pre-treatments effectively remove lignin and reduce cellulose crystallinity. Steam explosion, alkali-heat pre-treatment, and ammonia fiber expansion are commonly used methods. Tanpichai et al. (2019) used steam explosion to remove over 80% of lignin from pineapple leaves within 5 minutes. Thus, steam explosion treatment is a promising alternative process for the rapid extraction of cellulose fibers (Ge et al. 2018). Alkali heat pre-treatment refers to the use of alkaline reagents such as sodium hydroxide to assist in heat treatment at 75–125 °C to dissolve lignin. Zhang et al. (2020) used different pre-treatment methods to treat corn straw and found that the corn straw pretreated with 2% sodium hydroxide had the largest cumulative hydrogen production. Ammonia fiber expansion is one of the leading pre-treatment technologies in the field of lignocellulosic biorefining. Ammonia fiber expansion mainly enhanced enzymatic hydrolysis by removing lignin/xylan, but there was no significant change in cellulose isomorphism. At the same time, anhydrous ammonia fiber expansion enhances enzymatic hydrolysis through fine physical, chemical, and ultrastructural modifications of the cell wall, including reducing the crystallinity of cellulose or modifying cellulose homomorphous structure (Zhao et al. 2020).

Extrusion pre-treatment employs thermal and mechanical performances to change the physical and chemical structure of lignocellulose. It increases temperature and pressure within closed containers through shear forces applied between biomass, screws, and machine barrels. Extrusion pre-treatment enhances corn straw's maximum sugar output by 421.77% (Yan et al. 2019). Emerging pre-treatment methods include biochemical pre-treatment, ionic liquid pre-treatment, deep eutectic solvent pre-treatment, and supercritical fluid pre-treatment. Biochemical pre-treatment combines the advantages of biological and chemical pre-treatments, partially compensating for the low effectiveness of biological pre-treatment and the inhibition of compound formation by chemical pre-treatment. The mechanism of particle liquid-lignocellulose interaction is based on the specific binding of anions and cations, which breaks the β-O-4 link and produces an ionic dipole bond (Zhang et al. 2021). As a new generation of green organic solvents, deep eutectic solvents are expected to replace ionic liquids (Ma et al. 2021a). Deep eutectic solvents, which are formed by the interaction of hydrogen bond donors and acceptors, exhibit physical and chemical properties comparable to ionic liquids. The effects of different combinations of hydrogen bond donors and acceptors on lignocellulose pre-treatment vary (Satlewal et al. 2018). Supercritical carbon dioxide is currently the most often utilized supercritical fluid, which can lower the pH of a solvent by dissolving carbon dioxide in it, improve the solubility of polar compounds in various solvents, and aid in the hydrolysis of lignocellulose (Patil et al. 2018).

Impact of the bioenergy production process on the environment

The production of bioenergy from various biomass sources has several environmental implications, both positive and negative. One of the significant environmental advantages of bioenergy is its lower carbon footprint. Biomass is considered a carbon-neutral energy source because the carbon dioxide released during combustion is roughly equal to the carbon dioxide absorbed by the plants during their growth. This can help reduce net greenhouse gas emissions and mitigate climate change, particularly when compared to fossil fuels like coal, oil, and natural gas (Chen et al. 2021b). Solid is one of the most common forms of biomass fuel, but solid biomass often has high hygroscopicity, high resistance to biodegradation, and low calorific value. Researchers discovered that torrefaction, a thermochemical conversion method, can efficiently upgrade biomass and increase the quality of solid biomass-generated fuel after years of research (Kota et al. 2022). The global warming potential index can represent the equivalent effects of a certain greenhouse gas and carbon dioxide and can be used to compare greenhouse effects (Abernethy and Jackson 2022).

Treated biomass, produced through the torrefaction process, offers some environmental advantages compared to other thermochemical processes. Torrefaction tends to have a lower global warming potential in terms of greenhouse gas emissions. However, there are both positive and negative aspects to consider. On the positive side, the global warming potential of thermally treated biomass resulting from torrefaction is relatively low, and it means a smaller impact on global warming. Additionally, during the conversion of biofuel, the process can generate surplus electricity, often due to the higher calorific value of the gas produced during torrefaction. This surplus electricity can have positive implications, especially if it is fed back into the grid or used for other applications (Thengane et al. 2022). On the downside, there is a concern that torrefaction, especially when conducted at temperatures between 200 and 350 °C, may result in the generation of persistent organic pollutants (POPs) such as polychlorinated dibenzodioxins and dibenzofuran. These pollutants can have detrimental environmental effects and should be minimized. Furthermore, torrefaction can increase the ash content in the final product, limiting its use in combustion and gasification processes (Niu et al. 2019). To mitigate these negative aspects, cleaning pre-treatment methods have been explored. These techniques aim to reduce pollutant emissions during the torrefaction process and remove excess ash from the treated biomass, making torrefaction a more environmentally friendly process overall (Chen et al. 2021a).

When considering the environmental and economic aspects of waste management, power generation from garbage using both biochemical and thermochemical processes emerges as an effective solution, especially for mixed wastes that are challenging to recycle or reuse. In the context of this waste-to-energy transformation, two fundamental approaches are employed. In biochemical processes, microorganisms play a pivotal role in breaking down municipal solid waste into smaller, more convenient molecules. However, it is essential to recognize that this biochemical transformation process is relatively slow compared to thermochemical methods and is primarily suitable for degrading and biodegradable waste (Shi et al. 2016). From an economic feasibility and environmental impact perspective, lignocellulose biorefineries have gained significant attention. These refineries are focused on producing valuable products like ethanol and electricity from lignocellulosic materials. It is noteworthy that these biological refining processes typically generate excess lignin, and the surplus electricity generated can be supplied to the grid. While these methods offer advantages, reducing net operational costs and curbing fossil fuel usage, it is essential to recognize that there are substantial capital costs associated with establishing joint production systems (Awasthi et al. 2022). In the scope of thermochemical processes for solid waste treatment, two prominent methods are combustion and gasification. Combustion is presently the most established and widely adopted method for converting waste into energy. It excels in significantly reducing the quantity and quality of waste, a critical aspect of waste management, as recently demonstrated (Felix et al. 2022).

Gasification represents the conversion of solid waste into environmentally friendly gaseous fuels, distinguished from combustion by its primary objectives. While combustion primarily aims to reduce solid waste volume through on-site power generation, gasification's focus is on transforming waste into clean gas fuels, generating inert slag, and recovering energy and valuable metals (Pressley et al. 2014). Gasification stands out as a cleaner and more eco-conscious alternative to traditional incineration. In particular, thermal plasma gasification is called one of the most successful and environmentally friendly techniques in the field of waste treatment and gasification (Ruj and Ghosh 2014). This method, distinct from conventional thermochemical processes, operates at exceptionally high temperatures exceeding 4000 °C under neutral, reducing, or oxidizing conditions. This high-temperature plasma provides the necessary heat for the efficient gasification of waste. Consequently, organic molecules are thermally fragmented into their fundamental elements, resulting in the production of materials free from tar and the vitrification of inorganic substances into dense, inert, and non-leachable products. The gas generated primarily consists of hydrogen and carbon monoxide, a valuable energy source (Perna et al. 2018). The use of thermal plasma for gasification brings notable advantages. This method is characterized by the absence of tar and ash production, a smaller installation size compared to traditional waste treatment systems for a given capacity, and the ability to process a wide range of heterogeneous and low-calorific-value materials, including hazardous waste and low-level waste, highlighting its versatility and efficiency (Materazzi et al. 2016).

Anaerobic digestion technology has proven highly effective in converting organic matter into bioenergy, primarily utilized for treating industrial wastewater and the organic fraction of urban solid waste. Notably, when compared to other bioenergy processes, anaerobic digestion stands out for its capacity to significantly reduce greenhouse gas emissions, particularly methane and carbon dioxide (Vasco-Correa et al. 2018). This process is particularly suitable for organic waste with high water content, making it highly efficient. In contrast, incineration is better suited for waste with low moisture content, necessitating the removal of moisture before the incineration process. The merits of anaerobic digestion in an environmental context become evident in its contribution to reduced energy demand, mitigation of global warming, and curbing resource consumption. From a global warming perspective, anaerobic digestion systems can positively impact the environment by minimizing methane leakage from digestion plants and digester storage, consequently reducing methane emissions and their associated global warming potential. Nevertheless, it is essential to note that in comparison to alternatives like natural gas or power grids featuring renewable energy sources, anaerobic digestion systems may not always be the primary choice (Tian et al. 2021).

In conclusion, biomass energy holds significant promise as a vital component in modern agriculture, the environmental protection industry, and resource recycling. Its potential remains substantial, especially in the domains of algae and lignin fiber conversion for biofuels. Enhancing the efficiency of bioenergy production focuses on embracing innovative pre-treatment technologies, such as biochemical and physicochemical approaches, which can overcome the limitations of conventional techniques like biological, physical, and chemical pre-treatments. Recent statistics from the International Energy Agency in 2022 indicate that bioenergy's share in the renewable energy sector stands at 55%, surpassing the combined contribution of traditional renewable sources like wind, solar, hydropower, and geothermal energy. The growth of biomass waste power generation remains robust and offers considerable global potential.

Policy implications for sustainable bioenergy production

Key policy tools and frameworks that encourage sustainable bioenergy production

Renewable energy standards

As humanity raced to meet its growing energy demands since the dawn of the Industrial Revolution, natural resources bore the brunt of exploitation. This pursuit of ceaseless novelty, coupled with the emergence of "planned obsolescence," led to the swift removal of older products from the market, fueling a consumer culture hungry for the latest offerings. In this consumption frenzy, excessive production and wastage became the norm, aggravating the rift between human society and our finite natural resources. Pressing global concerns such as environmental pollution, resource depletion, climate change, and social inequality bear testament to the consequences of this trend. The United Nations' Sustainable Development Goal 7 underscores the necessity of developing accessible, dependable, and sustainable modern energy solutions for all (Munro et al. 2017). Amid a backdrop where product lifecycles are affectedly restrained, the adoption of effective design strategies has emerged as a promising avenue to cutting waste and harnessing renewable energy, thereby mitigating our environmental footprint.

Sustainable energy systems have rapidly evolved, significantly contributing to our fight against climate change. However, the emergence of the COVID-19 pandemic negatively affected to the energy industry (Hosseini 2020). The economic recession led to the shutdown of numerous industries, causing a marked reduction in energy consumption. The pandemic-induced disruption of the global economic supply chain posed challenges to the transition to sustainable low-carbon energy systems (Tsao et al. 2021). Yet, these trying times have presented a pivotal moment to redesign energy systems with a focus on efficiency while considering carbon emissions. The investments to be made in the post-pandemic recovery phase offer a unique opportunity to steer toward green development, especially within the energy sector (Kuzemko et al. 2020). Gasoline prices bear a profound connection to electricity demand, given their significant role in the existing energy production landscape (Hoang et al. 2021). Investments in renewable energy are intrinsically influenced by the price fluctuations of oil and gas. The pandemic has underscored the cost-effectiveness and safety of renewable energy for both consumers and investors. Considering the vulnerabilities in relying on natural gas supply and the upward trajectory of natural gas costs, a surge in investments in renewable energy is a logical expectation. As a result, the pursuit of Sustainable Development Goal 7 and other energy-related objectives is ready to gain momentum (Ayyildiz 2022).

Carbon capture

The integration of bioenergy with carbon capture and storage (BECCS) offers a promising avenue for reducing carbon dioxide emissions, with the potential to offset and even reverse the upward route of global warming through net-negative emissions. Negative emission technologies (NETs) hold a pivotal role in the spectrum of strategies for achieving temperature control targets along with emission reduction technologies (Rogelj et al. 2016). Projections indicate that, by mid-century, the world will need to remove approximately 10 billion tons of carbon dioxide annually through NETs, with this figure climbing to a reduction of 20 billion tons per year by the century's end (National Academies of Sciences et al. 2018). Among the various technologies capable of attaining negative emissions are BECCS, afforestation, biochar, direct air capture, enhanced weathering, underground mineralization, ocean alkalization, and other methods (National Academies of Sciences et al. 2018). In light of feasibility and scalability, BECCS technology, along with biochar, has garnered considerable attention (Heck et al. 2018).

While the possibility of achieving the 2 °C or 1.5 °C temperature control targets through rapid and deep decarbonization measures is declining (Luderer et al. 2013), reliance on negative emission technologies, particularly BECCS, is increasingly essential for substantial emission reductions. However, the overreliance on BECCS as a means to continue fossil fuel use would render climate change action ineffective. This is due to the current immaturity of BECCS technology, coupled with various uncertainties that hinder its large-scale and sustainable deployment across environmental, economic, social, and sustainable development dimensions. Factors such as the biomass supply chain's impact on carbon intensity, water resources, and land requirements (Yang et al. 2019a), the influence of biomass conversion and carbon capture and storage retrofits in coal-fired power plants on overall economic viability (Yi et al. 2018), the effects of carbon capture and storage projects on local safety and employment (Pawar et al. 2015), and strategies for promoting the deployment of BECCS projects through policy incentives pose significant challenges. Thus, there is an urgent need for a comprehensive assessment of BECCS projects, evaluating their environmental, economic, and social aspects to facilitate large-scale and sustainable deployment. Furthermore, the lack of available indicators, data, and characterization methods for assessing economic and social impacts, despite the standardization of environmental life cycle assessment theory and methods by the International Organization for Standardization (ISO), is a focal challenge in current research.

Sustainability certification schemes

Sustainability certification schemes are widely used in agriculture to uphold eco-friendly and sustainable farming practices, ensuring the production of safer and healthier agricultural products. These certification programs encompass a range of critical aspects, including sustainable farming techniques, pesticide management, safety and health measures, and food traceability. Their primary focus is on addressing environmental concerns (Osmundsen et al. 2020). Notably, there is a growing effort to establish sustainability certification systems tailored to the production of biofuel feedstocks in tropical regions, including palm oil, sugarcane, and soybean. While tropical biofuels, such as sugarcane ethanol or palm oil biodiesel, yield greater outputs and exhibit more favorable greenhouse gas balances than temperate biofuels, they also carry a higher risk of adverse environmental consequences. Hence, the development of specific certification methods for biofuel feedstocks in tropical regions is crucial to tackle the numerous sustainability challenges they pose (Tröster and Hiete 2018).

In conclusion, vital policy tools and frameworks supporting the advancement of sustainable bioenergy encompass renewable energy standards, carbon capture technology, and sustainability certification programs. The thorough examination and exploration of environmental, economic, social, and sustainable development aspects are imperative for the effective deployment of bioenergy with carbon capture and storage. Additionally, sustainability certification schemes are of great importance, especially in tropical regions where specialized feedstocks such as palm oil and sugarcane are utilized. These certification programs contribute to the ethical production of biofuel feedstocks and aid in addressing sustainability issues. Overall, these policy frameworks and instruments are designed to facilitate the transition to sustainable bioenergy production while giving due consideration to social, environmental, and resource efficiency considerations.

Challenges and opportunities for bioenergy production policy

To foster the production of biodiesel from *Jatropha curcas*, the Indian government has passed various policies, including allocating land in four states for *Jatropha* cultivation and setting up related processing facilities, along with plans to establish biodiesel procurement centers (Kothari et al. 2020). However, the uncertain establishment of Jatropha cultivation institutions, a lack of proper zoning for cultivation, and insufficient financial support have hindered the success of India's biodiesel promotion plans (Kothari et al. 2020). In Pakistan, the government has introduced policies like tax exemptions and incentives to stimulate the development of bioenergy, especially bioenergy power generation using bagasse (Ali et al. 2021b). Nevertheless, these policies confront several challenges, including inadequate long-term planning and policy formulation, low profitability in bioenergy power generation, and underdeveloped infrastructure (Ali et al. 2021b).

In China, the government has taken measures to promote bioenergy based on crop residues. These initiatives include banning straw burning in the Air Pollution Prevention Law of 2000 and conducting public awareness campaigns to discourage straw burning (Zhang et al. 2022). The Chinese government's policy has helped to expand bioenergy based on crop residues. Nonetheless, Zhang et al. (2022) pointed out that the Chinese government's policy still faces obstacles due to financial constraints. Moreover, in 2017, multiple departments in China jointly announced the "Implementation Plan for Expanding Ethanol Production and Promotion of Transportation Fuels" to promote the production of bio-based ethanol (Yong and Wu 2022). Then, in 2018, a subsidy of 98.51 US dollars per ton was given to producing advanced cellulosic ethanol. However, from 2017 to 2020, the production of cellulosic biofuels in China dropped from 30 million liters to zero million liters (Yong and Wu 2022).

In Malaysia, the government supports bioenergy enterprises with tax exemptions, financial subsidies, and incentives to encourage bioenergy production. However, this approach is plagued by several challenges (Rashidi et al. 2022). Firstly, Malaysia lacks advanced bioenergy technologies, resulting in the need to import most of these technologies, leading to high production and maintenance costs (How et al. 2019; Nevzorova and Kutcherov 2019). Furthermore, the vast distances of bioenergy projects and distribution systems in East Malaysia led to substantial capital investments due to infrastructure limitations. Moreover, there is a shortage of local technical expertise in bioenergy. Secondly, economic challenges arise from the high capital investment and long payback periods needed for constructing bioenergy facilities, posing a burden on developers (Hamzah et al. 2019; Seetharaman et al. 2019).

In contrast, bioenergy receives lower subsidies compared to traditional energy sources in Malaysia (Rashidi et al. 2022). Indonesia promotes bioenergy through strategies such as purchasing electricity from biomass power plants, specifying the use of biofuels to replace fossil fuels, and covering the difference in the cost of raw materials for biofuels (Amelia et al. 2023). However, several challenges have surfaced in the implementation of this policy, including an unbalanced focus on biofuel over other bioenergy sectors, unattractive tariffs, unbalanced risk allocation eroding investor confidence, and regulations that create barriers to installation (Amelia et al. 2023).

In summary, India's bioenergy policy faces challenges related to Jatropha cultivation, zoning issues, and financial support. Pakistan's bioenergy policy grapples with problems like a lack of long-term planning, profitability concerns in bioenergy power generation, and infrastructure development. China's crop residue-based bioenergy policy encounters financial constraints, while bio-based ethanol production policies have witnessed a decline in production. Malaysia's bioenergy policy contends with technical and economic challenges due to the importation of advanced technologies and the lengthy payback periods. Indonesia's bioenergy policy faces issues such as an imbalance in bioenergy sector focus, unattractive tariffs, imbalanced risk allocation, and regulatory barriers. The opportunities and challenges of bioenergy policies in different countries and fields are shown in Table 9 below.

Overall, bioenergy production policies in these countries strive to encourage bioenergy development in various sectors, encompassing biodiesel, bioethanol, and bagasse-driven bioenergy power generation. However, each policy also faces its unique set of challenges, with only China's crop residue-based bioenergy policy offering opportunities.

Effectiveness of bioenergy policy

After statistical analysis of the bioenergy status, policies, and other variables in the United Kingdom and the Nordic countries, the researchers found that the renewable energy quota system, carbon tax and price floor, and feed-in tariffs are all effective in the United Kingdom's bioenergy policy. The feed-in tariff in the United Kingdom is an important factor in promoting the development of the anaerobic digestion industry (Cross et al. 2021). Carbon taxes on fuels and feed-in tariffs are also considered effective in Finland's bioenergy policy. In Sweden's bioenergy policy, the fuel carbon tax and the renewable energy quota system have also been proven to promote the bioenergy industry (Cross et al. 2021). Additionally, researchers from China developed two dynamic agricultural sector models to analyze how changes in land fertility affect bioenergy crops. The analysis results suggested that direct subsidies and tax credits can sustain the expected yields of bioenergy crops (Kung 2018). However, changes in the discount rate and

Table 9 Opportunities and challenges of bioenergy policies in different countries and fields

Country	Field	Policy	Opportunity	Challenge	Reference
India	*Jatropha cruces* produces biodiesel	1. Allotment of land 2. Establish a procurement center	-	1. The planting agency could not determine 2. Lack of planting zones 3. Lack of financial support	Kothari et al. (2020)
Pakistani	Bagasse-powered bioenergy generation	1. Tax exemption for bioenergy companies 2. Incentives for bioenergy companies	-	1. Lack of long-term planning and policy development 2. Bioenergy generation is less profitable 3. Lack of developed infrastructure	Ali et al. (2021b)
China	Bioenergy based on crop residues	1. The legislation bans straw burning 2. Strengthen publicity to ban straw burning 3. Subsidies, tax cuts for bioenergy based on crop residues	Contribute to the deployment of bioenergy based on crop residues	1. Financial constraints	Zhang et al. (2022)
China	Bio-based ethanol	1. Subsidizing advanced cellulosic ethanol	-	1. Cellulosic biofuel production declines	Yong and Wu (2022)
Malaysia	Bioenergy	1. Tax exemption for bioenergy companies 2. Financial subsidies and incentives for bioenergy companies	-	1. Lack of advanced bioenergy technologies 2. Infrastructure constraints 3. High capital investment and long payback period	Rashidi et al. (2022)
Indonesia	Bioenergy	1. Provision of biofuels to replace the supply of fossil fuels 2. Purchase electricity from bioenergy plants	-	1. Bioenergy development priorities are uneven 2. Unattractive tariffs and unbalanced risks 3. Unsupported regulations	Amelia et al. (2023)

"Country" represents countries implementing bioenergy policies. "Field" represents the areas where the bioenergy policy is implemented. "Opportunity" represents opportunities arising from bioenergy policies. "Challenge" represents challenges for bioenergy policy. "-" is not mentioned in the article. This table shows that the bioenergy production policies of all countries support the development of bioenergy, but all bioenergy production policies face challenges, and only China's bioenergy production policies based on crop residues have opportunities program scope of direct subsidies and tax credits strongly impact policy effectiveness (Kung 2018).

Furthermore, in an analysis of bioenergy policies in three Canadian communities, the researchers found that increasing direct incentives such as supplier and center incentives will not impact the amount of bioenergy generation (Vazifeh et al. 2023). On the other hand, indirect incentives such as increased supply capacity and improved bioenergy conversion capacity have significantly impacted the share of bioenergy generation (Vazifeh et al. 2023). Indirect incentives for bioenergy conversion provide or improve the necessary infrastructure. In summary, the renewable energy quota system, carbon tax and price floor, feed-in tariff are effective in the United Kingdom's bioenergy policy, carbon tax and feed-in tariff are effective in Finland's bioenergy policy, and in Sweden's bioenergy carbon taxes on fuels and renewable energy quota systems in the policy are effective. In addition, direct subsidies and tax credits have proven to be effective bioenergy policies in China. Furthermore, indirect incentives are ineffective in Canadian bioenergy policy, while indirect ones are ineffective.

The researchers used a system dynamics model to evaluate the biofuel subsidy policy in Taiwan and China and found that the subsidy policy for biofuels is effective (Kuo et al. 2019). In addition, researchers designed a two-stage stochastic programming and pursuit model for bioenergy production in China for analysis (Kung et al. 2022). Kung et al. (2022) pointed out that low-cost green bond investments in bioenergy development can improve development efficiency in the face of stringent environmental regulations and emissions management. Green bonds are an effective bioenergy policy. Moreover, to promote the use of straw for bioenergy power generation, the Chinese government has issued regulations prohibiting the burning of straw. Researchers summarizing straw disposal in rural northeastern China have found that laws banning straw burning are ineffective (Hou et al. 2019). However, subsidizing and promoting residue shredders and setting up demonstration projects to train farmers are considered to be effective policies for reducing straw burning (Kuhn et al. 2018; Hou et al. 2019).

Furthermore, after modeling and analyzing China's bioenergy policies to encourage biomass cogeneration, support biomass heating, develop biofuel technology, establish a raw material collection system, and prioritize using bio-natural gas (Wang et al. 2022). Wang et al. (2022) pointed out that the development of biofuel, the most vigorous promotion of biofuels, is the preferred policy for developing bioenergy. Prioritizing the use of bio-natural gas can better promote the development of biomass power generation (Wang et al. 2022). Additionally, after analyzing carbon pricing and subsidies for bioenergy plants in Germany through an energy system model, Meurer et al. (2023) found that higher carbon dioxide prices and policies with specific bonuses can promote the flexible operation of bioenergy plants. Overall, subsidies for biofuels, green bonds, biofuel technologies development, and biogas' priority use are effective bioenergy technologies in China. Moreover, regulations banning straw burning in Northeast China are ineffective, but subsidizing and promoting residue shredders and establishing demonstration projects to train farmers are effective bioenergy policies. Furthermore, Germany's higher carbon dioxide prices and specific bonuses are also valid bioenergy policies.

After modeling bioenergy policy and forest bioenergy installed capacity in the USA using a fixed-effects framework, the researchers found that tax incentives, especially tax credits, positively affect forest bioenergy development, so tax incentives are considered effective (Ebers Broughel 2019). Other policies, such as production incentives, project financing, and regulations, did not significantly impact installed forest bioenergy capacity (Ebers Broughel 2019). In addition, information policy has a negative impact. However, Ebers Broughel (2019) pointed out that even if individual policies did not show an identifiable impact on productivity, individual policies could still have a boosting effect when aggregated. Furthermore, Austria's biofuel policy includes reduced or exempted biofuel taxes, reduced permit fees, and tax exemptions for purchasing vehicles using biofuels. Since 2006, the production and use of ethanol in Austria have increased at a rate of 70% and 25% per year, respectively, and the production and use of biodiesel in Austria have grown at an average rate of 14% and 5% per year, respectively (Ebadian et al. 2020). Reduced or exempted biofuel taxes, reduced permit fees, and tax exemptions for purchasing vehicles that run on biofuels are considered valid in the biofuel policy (Ebadian et al. 2020).

In addition, the Danish government has adopted the policy of exempting biofuels from the carbon tax, appropriating funds to promote the production of advanced biofuels, and providing guarantees for biofuel companies (Ebadian et al. 2020). However, the Danish biofuel policy is ineffective since the annual biodiesel production in Denmark has remained unchanged since 2010, and there is no ethanol production in Denmark (Ebadian et al. 2020). In short, tax incentives, especially tax credits, are effective in United States bioenergy policy, but production incentives, project financing, regulations, and information policies are ineffective if implemented individually and are effective when multiple policies are implemented simultaneously. In addition, reduced or exempted taxes on biofuels, reduced permit fees, and tax exemptions for purchasing vehicles running on biofuels are valid in Austria's bioenergy policy. Moreover, Denmark's bioenergy policy exempts biofuels from carbon taxes, allocates funds to promote the production of advanced biofuels, and guaranteed biofuels company are invalid.

Overall, bioenergy production policies in most countries are effective. Nevertheless, some countries have ineffective bioenergy production policies, such as China's banning of straw burning, Denmark's biofuel policy, and Canada's direct incentive policy.

Conclusion

This review explores the life cycle assessment and techno-economic assessment of bioenergy. The careful cultivation of energy crops on marginal lands holds the potential to significantly mitigate emissions by sequestering atmospheric carbon. Bioenergy land-use transformations encompass a myriad of variables, including deployment scale, prior land usage, crop selection, soil quality, climate, and management practices. When combined with best management practices and thoughtful scaling, land conversion for bioenergy production can yield positive outcomes. Thus, minimizing the environmental impact while embracing best management practices is vital for the overall sustainability of the production system.

The rapid global growth of the bioenergy industry raises concerns about its complex effects, including both positive synergies and adverse impacts on sustainable development, land degradation, water scarcity, food security, and greenhouse gas emissions. The complexity of these interactions underscores the need for careful evaluation and sustainable management to ensure that bioenergy plays a constructive role in meeting global energy needs. A robust evaluation of bioenergy systems necessitates a comprehensive life cycle assessment. This assessment should encompass a diverse array of environmental sustainability indicators, moving beyond the focus on greenhouse gas emissions and energy balance. The current variability in standards across research areas inhibits meaningful comparisons of life cycle assessments. Standardizing methodology would enable such comparisons and provide valuable insights to academia and businesses, facilitating cost-effective assessments that evolve with scientific knowledge. Sustainability tools heavily rely on life cycle assessments to mitigate pollution and adverse impacts on ecosystems. Challenges, such as data limitations and future uncertainties, persist in conducting life cycle assessments for new materials or technologies. Comprehensive, standardized life cycle assessments are vital for informed decision-making and advancing the sustainability of bioenergy systems.

Techno-economic analysis proves invaluable for assessing the feasibility and profitability of bioenergy production. Given the distinct cost structures, profitability, and environmental implications associated with various bioenergy production methods, techno-economic analysis systematically amalgamates these aspects. It aids producers in making informed decisions based on critical financial metrics such as net present value, internal return, and return on investment. This analysis is indispensable in guiding the transition from fossil fuels to sustainable bioenergy. Operational costs significantly affect the feasibility of bioenergy production. Efficient management of raw material collection, transportation, processing, pre-treatment, water use, and wastewater is essential for economic viability. Market demand, influenced by fossil fuel pricing, plays a pivotal role in determining profitability. Government subsidies can provide additional support, while ongoing production process optimization remains essential to reduce costs and attract more energy companies to the bioenergy sector. Selecting bioenergy feedstocks and production technologies is influenced by both economic and sustainability factors. While starch-based feedstocks have proven profitable, competition for these resources can lead to price fluctuations. Lignocellulose presents a more sustainable option, but efficient collection and preprocessing are challenging. Varied raw material treatments result in varying outputs. Assessing the entire supply chain, from feedstock collection to the end product, is critical for informed decision-making during the transition to sustainable and economically viable bioenergy production.

Vital policy tools, including renewable energy standards, carbon capture technology, and sustainability certification programs, offer comprehensive solutions to promote sustainable bioenergy. Effective deployment of bioenergy with carbon capture and storage hinges on a detailed examination of environmental, economic, social, and sustainable development aspects. Sustainability certification schemes are particularly important in regions using specialized feedstocks. They contribute to the ethical production of biofuel feedstocks and address sustainability challenges. These policy frameworks and instruments facilitate the transition to sustainable bioenergy, considering social, environmental, and resource efficiency. Challenges exist in various countries, including India, Pakistan, China, Malaysia, and Indonesia, due to issues such as cultivation concerns, planning, profitability, infrastructure, and regulatory barriers. Subsidies, green bonds, technological development, and priority use of biogas are shown to be effective in the Chinese bioenergy landscape. Conversely, Germany's high carbon dioxide prices and specific bonuses demonstrate effectiveness as well. In conclusion, the bioenergy sector provides a substantial avenue to reduce greenhouse gas emissions, enhance sustainability, and meet global energy demands. Careful management of energy crops on marginal lands, life cycle assessments, and techno-economic analysis all contribute to the advancement of sustainable bioenergy systems. As this industry continues to evolve, a comprehensive understanding of its complexities and the adoption of effective policy tools are essential for achieving a more sustainable and greener future.

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