Review Paper

A Comprehensive Review of Bioenergy Sustainability: Balancing Economic, Environmental, and Social Impacts

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Abstract: This review explores bioenergy's role in the shift from fossil fuels to renewable energy. Bioenergy, derived from biomass like plants and organic waste, promises a reliable, cost-effective, and eco-friendly energy source. However, concerns about its sustainability and feasibility require a com-prehensive assessment of environmental, economic, and social factors. The paper reviews current research on bioenergy types, technological advancements, environmental impacts, and policy frameworks. It covers biomass applications in heat, power, and fuels, and discusses benefits for rural development and waste management. Challenges such as land-use competition and economic viability are also addressed, highlighting the need for integrated approaches and strong regulatory frameworks. The review provides insights into bioenergy's potential and challenges in achieving sustainable global energy goals.

Keywords: Bioenergy; Renewable energy; Biofuels; Carbon emissions; Organic waste

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1. Introduction

In recent years, the world has seen an increased focus on transitioning to renewable and sustainable sources of energy (Osman et al. 2024). Promoting the shift from fossil fuels to renewable energy sources is a key answer for global sustainability (Abernethy and Jackson 2022). Bioenergy, which is produced from biomass materials such as plants, forestry residues, and organic waste, has emerged as a promising alternative to fossil fuels. Bioenergy has the potential to provide a reliable, affordable, and environmentally friendly source of energy (Lehtinen, Juntunen, and Juga 2020). Promoting the shift from fossil fuels to renewable energy sources is a key global solution. Bioenergy is projected to play a significant part in this transition. Bioenergy usage for power and transportation fuels has increased significantly in recent years, driven by increased legislative support (Chunark et al. 2017). However, there are concerns about the sustainability and feasibility of bioenergy production and use. A review of the literature reveals numerous studies on the sustainability of bioenergy. However, most of these are tightly focused, such as on a certain technology or region (Cambero, Sowlati, and Pavel 2016; Igos et al. 2016). Most current studies predominantly concentrate on a single aspect, such as the environmental impact or the economic influence of bioenergy.

For example, (Igos et al. 2016) conducted a case study on forest-based biorefinery supply chains for bioenergy in British Columbia and discovered that social benefits, such as job creation, are expected consequences. (Cambero et al. 2016) investigated the environmental and economic impact of rye as a bioenergy source. Similarly, (Glithero, Ramsden, and Wilson 2012) created an economic model to assess farm systems in the UK. (Vellini, Gambini, and Stilo 2020) conducted a technical and economic feasibility analysis for a cogeneration plant in the agro-food business, and (Efroymson et al. 2013) developed environmental indicators to assess biofuel sustainability. There are few studies that incorporate numerous variables when evaluating bioenergy sustainability (Fantozzi et al. 2014), which presents a difficulty for academics seeking a thorough grasp of the subject. (Robertson et al. 2008) stated that bioenergy sustainability should include environmental, economic, and social considerations. (Solomon 2010) reviewed these three characteristics of bioenergy sustainability using a variety of metrics. (Gelfand et al. 2013; Tilman et al. 2009) have also examined the relationship between bioenergy sustainability, food security, and the utilization of marginal land. Second, numerous studies, such as those conducted by (Makkonen et al. 2015), produce contradicting results, making it difficult for stakeholders, including academia and politicians, to reach an agreement on the sustainability of bioenergy. According to Jeswani et al. (Jeswani, Chilvers, and Azapagic 2020a) the carbon-saving potential of biofuels differs depending on how they are produced. Their findings imply that biofuels sourced from waste biomass or cultivated on abandoned land are more successful at reducing carbon emissions than other varieties. (Daioglou et al. 2017; Hudiburg et al. 2016) conducted an analysis of croplands in the United States and determined that bioenergy from waste biomass is much more useful than crop-based biomass. Jeswani et al. (Jeswani, Chilvers, and Azapagic 2020b) compared the environmental costs and advantages of biodiesel and bioethanol and discovered that biodiesel emits less pollutants than ethanol. Liu et al. (Liu et al. 2021) compared first and second-generation biofuels, emphasizing the policy obstacles associated in their transition. Third, many studies address sustainability challenges in specific regions of the world, such as those by (Amigun, Musango, and Stafford 2011; van Meijl et al. 2018; Mohr and Raman 2013), whereas worldwide viewpoints on bioenergy sustainability are less common. (Walmsley and Godbold 2010) focused on environmental issues, while (Simangunsong et al.

2017) assessed the social sustainability of bioenergy, and (Khan et al. 2022) investigated combined land use and environmental aspects for sustainability assessment. Currently, biomass stands as the largest global source of renewable energy and holds substantial potential for increasing the production of heat, electricity, and transport fuels. If managed effectively, the further deployment of bioenergy could significantly increase its share of the global primary energy supply, achieve notable reductions in greenhouse gas emissions, and bring potential environmental improvements (Erickson 2017). Additionally, it could enhance energy security by reducing reliance on imported fossil fuels, provide economic and social benefits for rural communities, and improve waste management through the utilization of residues and waste materials.

2. Background

Bioenergy has been used as a source of energy for centuries, with early humans using biomass materials such as wood for heating and cooking. In the modern era, bioenergy has emerged as a promising alternative to fossil fuels, offering a reliable, affordable, and environmentally friendly source of energy. Bioenergy is produced from biomass materials such as plants, forestry residues, and organic waste, and can be used in various forms, including solid, liquid, and gaseous fuels, for heating, cooling, electricity generation, and transportation (Efroymson et al. 2013).

Compared to other sources of energy, such as fossil fuels and nuclear energy, bioenergy has a number of advantages and disadvantages. One advantage of bioenergy is that it is a renewable source of energy, relying on the growth and regrowth of biomass materials. This means that bioenergy can provide a more sustainable source of energy compared to finite fossil fuels. Bioenergy can also offer significant environmental benefits, such as reduced greenhouse gas emissions and improved waste management. Additionally, bioenergy production can support rural development and improve energy access in developing countries. However, there are also a number of disadvantages associated with bioenergy production and use (Perea-Moreno, Samerón-Manzano, and Perea-Moreno 2019a). One major concern is the potential for negative environmental impacts, such as land-use change, water depletion, and increased greenhouse gas emissions from the production and transportation of biomass materials. Another concern is the potential for competition with food production and other land uses, which could drive up food prices and cause social and economic issues. Additionally, there are concerns about the economic viability of bioenergy, as well as the potential for technological limitations and supply chain issues. To address these concerns, there is a need for a comprehensive assessment of the feasibility and sustainability of bioenergy as a source of energy. This report aims to provide such an assessment, based on a review of the current state of research on bioenergy production and use.

3. Biomass

3.1. Biomass resources

Currently, forestry, agricultural, and municipal residues and **waste** are the principal feedstocks for generating power and heat from biomass, with sugar, corn, and vegetable oil crops accounting for a minor share of liquid biofuel production. Biomass presently contributes roughly 50 exajoules EJ globally, accounting for 10% of total annual primary energy consumption, primarily from traditional biomass used for cooking and heating (Perea-Moreno, Samerón-Manzano, and Perea-Moreno 2019b). There is a great opportunity to increase biomass consumption by exploiting enormous amounts of underutilized residues and garbage. Furthermore, the use of conventional crops for energy can be enhanced while taking into account land availability and food demand (Hudiburg et al. 2016). In the longer term, lignocellulosic crops, both herbaceous and woody, might be produced on marginal, degraded, and surplus agricultural lands to supply a considerable amount of biomass resources. In the long run, aquatic biomass such as algae could make a substantial contribution. Based on this varied spectrum of feedstocks, the technical potential for biomass might be up to 1500 EJ per year by 2050, however most sustainability-conscious scenarios estimate an annual potential of 200 to 500 EJ, excluding aquatic biomass (Perea-Moreno et al. 2019b). Forest and agricultural residues, combined with other organic wastes, might generate 50 to 150 EJ per year, with the remaining coming from energy crops, excess forest growth, and higher agricultural productivity. Global primary energy demand is anticipated to reach 600 to 1000 EJ by 2050, up from around 500 EJ in 2008. Scenarios for low-carbon energy sources predict that future bioenergy demand might be up to 250 EJ per year, which is consistent with sustainable supply potential estimates, implying that biomass could sustainably supply a quarter to a third of the future global energy mix. The realization of this potential will be dependent on bioenergy's cost competitiveness and future regulatory frameworks, such as greenhouse gas emission reduction targets. Various demand and supply issues will influence the growth in biomass resource use through 2030. Strong renewable energy targets at the regional and national levels, such as the European Renewable Energy Directive, are expected to drive up demand, which will be satisfied by increased usage of residues, wastes, sugar, starch, and oil crops, as well as lignocellulosic crops (Perea-Moreno, Samerón-Manzano, and Perea-Moreno 2019c; Perea-Moreno et al. 2019b). The contribution of energy crops will be determined by crop selection and planting rates, which are impacted by agricultural productivity, environmental limits, water availability, and logistical issues. Under ideal conditions, significant expansion is feasible over the next 20 years, while estimates of prospective production increases vary greatly. For example, the potential biomass from leftovers and energy crops in the EU by 2030 is expected to reach between 4.4 and 24 EJ (Perea-Moreno et al. 2019c).

3.2. Biomass conversion technologies

Bioenergy, which is obtained from forestry, agricultural, and municipal residues, as well as garbage, is currently the world's greatest source of renewable energy. It has great promises for increasing the generation of heat, power, and transportation fuels. Converting raw biomass into energy products requires a variety of technologies according to the feedstock's composition and the energy service required (Perea-Moreno, Perea-Moreno, et al. 2017). Palletization, torrefaction, and pyrolysis are examples of methods that improve the transportability and storage of biomass (Shah, Khan, and Kumar 2018). Direct biomass combustion is the most common method of producing heat around the world, with technologies ranging from basic burners to complex equipment. For power, co-combustion in coal plants and specialist biomass combustion plants are less expensive, with anaerobic digestion best suited to wet organic feedstock. Although less prevalent, gasification provides higher efficiency and reduced emissions, with significant future prospects. First-generation biofuels, such as bioethanol and biodiesel, are widely utilized but have limitations due to their dependency on food crops. Second-generation biofuels, which use non-food biomass such organic waste and energy crops, offer lower environmental impact and more sustainability (Wang et al. 2018). These technologies require further research to become commercially viable. Bioenergy technology will become more efficient, reliable, and sustainable across a wide range of applications. In the long run, bioenergy production in biorefineries might co-produce transport biofuels, power, heat, and other marketable goods, increasing resource efficiency and assisting in the transition to a sustainable energy future.

3.3. Biomass storage facilities

Effective biomass storage is crucial for ensuring a consistent supply of feedstock for energy production, particularly given the seasonal and variable nature of biomass resources. Proper storage facilities prevent degradation and loss of biomass quality, which can significantly impact the efficiency and emissions of biomass conversion technologies. One common method is dry storage (Feria et al. 2024), where biomass is kept in open or covered stacks, allowing natural drying processes to reduce moisture content. This method is widely used for forestry residues and agricultural **waste**. For example, in the Scandinavian countries, large volumes of wood chips and pellets are stored in covered facilities to maintain their low moisture content and high energy density, essential for efficient combustion and gasification processes. Another approach involves ensiling, commonly used for wet biomass like silage crops and food waste (Chen et al. 2021; Deepika et al. 2024). This method involves compacting biomass in airtight conditions to promote anaerobic fermentation, which preserves biomass for long periods and is particularly beneficial for feedstocks used in anaerobic digestion. In Germany, numerous biogas plants utilize ensiled maize and other crops, ensuring a steady year-round feedstock supply. Advanced storage technologies are also emerging, such as torrefaction (Tumuluru et al. 2021) and palletization (Wei, Cheng, and Shen 2024), which enhance the stability and energy density of biomass. Torrefaction involves heating biomass in the absence of oxygen to produce a dry, energy-dense material that is easier to store and transport. This technique is increasingly applied to agricultural residues and wood waste, creating a uniform feedstock suitable for co-firing in coal power plants. Similarly, palletization compresses biomass into dense, uniform pellets, which are less susceptible to moisture uptake and microbial degradation. In the United States, large-scale pellet production facilities, particularly in the Southeastern states, supply domestic and international markets, illustrating the global trade potential of biomass pellets. Bulk storage solutions, such as silos and bunkers, are also essential for maintaining the quality of biomass feedstocks. For example, in Canada, the bioenergy industry employs large silos for wood pellets and agricultural residues, ensuring they remain dry and uncontaminated. These storage facilities are often equipped with automated handling systems to streamline the delivery of biomass to conversion plants. Effective biomass storage not only ensures a consistent supply of high-quality feedstock but also supports the scalability of bioenergy projects. By implementing advanced storage solutions, biomass can be utilized more efficiently and sustainably, contributing to the broader goal of transitioning to renewable energy sources.

3.4. Environmental functions of bioenergy production

Much attention is presently placed on the negative repercussions of land use change, such as biodiversity loss, greenhouse gas emissions, and soil and water body degradation, notably as a result of forest conversion and farmland development. However, biomass generation for energy can provide major benefits. For example, harvesting forest waste can improve replanting conditions while also lowering the risk of root rot and wildfires. In agriculture, biomass can be grown in multifunctional plantations that offer extra environmental benefits. These plantations can treat nutrient-rich water, restrict erosion, trap nutrients, and reduce the amount of silt and contaminants that reach streams. Perennial crops, such as those utilized in the USDA Conservation Reserve Program, help to reduce soil erosion, improve nutrient retention, and provide organic matter to the soil, ensuring long-term productivity (Soares et al. 2018). Using sewage sludge as fertilizer in vegetation filters can increase these benefits even more. By integrating well-chosen locations, designs, and management practices, biomass production can offer environmental advantages that complement its role in sustainable energy production.

3.5. Climate change impact

Climate change is expected to alter rainfall patterns and increase water transpiration and evaporation as temperatures rise. Predicting the net effect is difficult, with significant variation expected across worldwide regions. Semi-arid and dry regions are especially vulnerable, with lower water supply and increased problems in river basins (Perea-Moreno, García-Cruz, et al. 2017). Overall, climate change's negative effects are expected to outweigh the advantages of freshwater systems, reducing water supply and irrigation potential in many areas. Biomass poses both environmental dangers and advantages, depending on appropriate management. Maximizing biomass's potential for reducing greenhouse gas emissions necessitates understanding and avoiding related risks, as well as accepting trade-offs for long-term benefits.

4. Biomass Applications

Biomass has diverse applications, ranging from energy production to environmental benefits. Below are some key applications of biomass.

4.1. Biomass for heat applications

Producing heat from biomass is the traditional way to utilize this energy source, and biomass-to-heat systems are commercially viable and often economically competitive. The cost-effectiveness of these systems depends on specific context and the price of fossil fuel alternatives. Combustion, the oldest and most common method for converting solid biomass to energy, remains a straightforward and well-understood process. It supports a wide range of commercial technologies suited to various biomass types and application scales. These technologies include domestic heating systems, district heating and cooling networks, industrial systems, and gasification systems (García et al. 2015). Biomass combustion systems have proven adaptable and scalable, making them a viable option for both small-scale residential use and large-scale industrial applications. As technology evolves, further improvements in efficiency and emissions control are anticipated, enhancing the viability of biomass as a sustainable energy source for heat production across diverse settings.

4.2. Biomass for power and CHP applications

There are numerous combinations of feedstock and conversion technologies for producing power and combined heat and power (CHP), each at various stages of development and deployment. The economic viability of a bioenergy option for power and CHP depends not only on the specific technology (including capital and operating costs, conversion efficiency, process reliability, and economies of scale) but also on local conditions for biomass supply (quality, type, availability, and cost) and final energy demand (cost of alternative energy production, heat demand and value, grid accessibility, support policies, etc.) (Bagherian et al. 2021). The broad range of costs for most technologies indicates the significance of economies of scale (e.g., for steam turbines) and that many technologies are still in the demonstration stage. Several conversion power technologies include biomass-based power plants (steam turbine cycles), municipal solid waste-to-energy plants, biomass-based cogeneration (CHP) plants, distributed cogeneration units (Stirling engine and Organic Rankine Cycle), co-firing, gasification, and anaerobic digestion (Coady and Duquette 2021).

4.3. Biomass for transport applications

Biofuels for transport applications are typically categorized into different 'generations' based on their developmental stage and the feedstocks utilized, though these classifications are not universally standardized. First-generation biofuels include established technologies for producing bioethanol from sugar and starch crops, biodiesel and renewable diesel from oil crops and animal fats, and biomethane from the anaerobic digestion of wet biomass. Second-generation biofuels cover a range of innovative biofuels derived from new feedstocks, such as bioethanol and biodiesel produced from novel starch, oil, and sugar crops like Jatropha, cassava, or Miscanthus, as well as various conventional and novel biofuels (e.g., ethanol, butanol, syndiesel) made from lignocellulosic materials (fibrous biomass like straw, wood, and grass) using biochemical and thermochemical technologies still in the demonstration phase. Third-generation biofuels, or advanced biofuels, involve production methods in the early stages of research and development or far from commercialization, such as biofuels from algae and hydrogen from biomass (Gracia, Velázquez-Martí, and Estornell 2014). There are several pathways to produce diesel-type fuels from biomass, with transesterification and hydrogenation being mature and commercially available first-generation technologies that create biodiesel from vegetable oil and animal fats. Transesterification is a straightforward catalytic process and is the dominant technology in this category. Alternatively, biogas can be upgraded to biomethane and injected into the natural gas network for use in gas-powered vehicles. Biomass-to-Liquids (BTL) processes convert a wide variety of biomass feedstocks into liquid and gaseous transport fuels like synthetic diesel and gasoline, methanol, ethanol, dimethyl ether (DME), methane, and hydrogen through thermochemical conversion. Gasification-based methods combine gasification with the catalytic upgrading of syngas to liquid fuels, such as through the Fischer Tropsch process, to produce synthetic biofuels (synfuels) with low greenhouse gas intensity. These methods are particularly attractive and have received significant attention in Europe and North America. Additionally, liquid-phase catalytic processing of biomass-derived compounds and hydrogen production from biomass are emerging areas in the biofuel sector (Wang, Shuai, and Chen 2007).

4.4. Biomass for industrial applications

Biomass is increasingly used in industrial applications due to its versatility and renewable nature. One of the key uses is in the production of bio-based chemicals and materials. Biomass can be processed into a variety of bioproducts such as bioplastics, solvents, adhesives, and pharmaceuticals. These bioproducts are derived from biomass through processes like fermentation, enzymatic conversion, and thermochemical methods. For example, lignocellulosic biomass can be converted into biochemicals that serve as building blocks for bioplastics, offering a sustainable alternative to petrochemical-derived plastics (Kalak 2023). Furthermore, biomass can be used in industrial boilers to generate process heat and steam, which are essential for various manufacturing processes (Proskurina et al. 2017). This not only reduces the reliance on fossil fuels but also lowers greenhouse gas emissions, contributing to a more sustainable industrial sector. The integration of biomass into industrial processes is supported by advancements in biorefinery technologies, which enable the efficient conversion of biomass into a spectrum of high-value products, thus enhancing the economic viability of biomass utilization in industries.

4.5. Biomass for construction

Biomass as material, extracted from plant and animal products, is known to be renewable (Al-Hamamre et al. 2017) and has many uses in construction (Ryłko-Polak, Komala, and Białowiec 2022). Biomass is common in the formation of bio-concrete; this is concrete that has been strengthened by organic fibers, the use of which decreases the emissions of carbon dioxide. Smitha et al. (Smitha et al. 2022) studied the microbiological induction of bacterial biomass in concrete mixtures to enhance the mechanical and durability properties. He concluded that the induction of bacillus megaterium into concrete mixtures can be used to improve the mechanical and durability properties of concrete. Concrete made with **c**ells/ml bacillus megaterium exhibited compressive strength, split tensile strength, and flexural strength 11.3%, 97.5%, and 8.6%, respectively higher than the control at 28 days (Smitha et al. 2022). A large application is in bio composites for which materials such as hemp are made to form panels, insulation, and other structures in construction. Muhit et al. (Muhit, Omairey, and Pashakolaie 2024) study presents a comprehensive examination of the characteristics of hemp fibre and hempcrete as construction materials, delving into their suitability for building and highway applications. His study concludes hempcrete's significant application as a building insulation material due to its exceptional hygrothermal properties. The material also shows promise in enhancing the asphalt mix for pavement construction. Evidence from life cycle analysis supports the claim that hempcrete can be considered a carbon-negative material (Muhit et al. 2024). Wood, a typical biomass material, continues to be widely used because of the prospects of low-carbon construction when sourced from renewable sources.(Švajlenka, Kozlovská, and Spišáková 2017) concluded that the modern method of construction based on wood contributes to sustainability by several of its properties and parameters. Bamboo, a plant that has the fastest growth rate and is lightweight while strong, is used for construction purposes such as beams, and flooring, among others (Fahim et al. 2022). (Manandhar, Kim, and Kim 2019) study suggests bamboo can be used for the speedy construction of houses, either permanent or temporary, in disaster-stricken areas like post-earthquake areas. Rice husks and coconut coir from agricultural operations can be used to make boards and bricks as well as insulation material for housing. (Pode 2016) concludes rice husk ash (RHA) is an economical and sustainable construction material. In Cambodia, its high silica content makes RHA-concrete a viable low-cost option. In Bangladesh, RHA has been effectively used to develop building bricks, thermal insulating bricks, and pozzolanic cement, demonstrating enhanced strength and durability properties (Pode 2016). Thus, the incorporation of these biomass materials into construction processes enables meeting the goals of Sustainability while also improving energy consumption and waste management in the construction industry.

4.6. Biomass for residential and commercial applications

Biomass has significant potential in residential and commercial settings, primarily for heating and cooking purposes. In many rural and developing regions, biomass remains a primary source of energy for household cooking and heating. Traditional biomass stoves are being replaced by improved cookstoves that are more efficient and emit fewer pollutants, thereby improving indoor air quality and reducing health risks. In urban and suburban areas, biomass pellet stoves and boilers are gaining popularity for residential heating. These systems use compressed biomass pellets made from wood waste, agricultural residues, or energy crops, providing a clean and efficient heating solution (Stephen et al. 2016). Additionally, commercial buildings and institutions such as schools and hospitals are adopting biomass heating systems to reduce energy costs and environmental impact. These systems can be integrated with existing heating infrastructure, making the transition to biomass relatively straightforward (Toka et al. 2014). The use of biomass in residential and commercial applications is further supported by government incentives and policies aimed at promoting renewable energy sources and reducing carbon footprints.

4.7. Biomass for agricultural applications

Biomass plays a crucial role in sustainable agriculture by providing renewable energy and enhancing soil health. Agricultural residues, such as straw, husks, and manure, can be utilized to produce bioenergy through processes like anaerobic digestion and direct combustion. Anaerobic digestion of agricultural waste produces biogas, which can be used for heating, electricity generation, or as a vehicle fuel, while the digestate can be used as a nutrient-rich fertilizer. This creates a closed-loop system that maximizes resource efficiency and minimizes waste (Nguyen and Toan 2024). Additionally, the incorporation of biochar, a stable form of carbon produced from biomass through pyrolysis, into agricultural soils can improve soil fertility, water retention, and crop yields. Biochar also sequesters carbon, helping to mitigate climate change. Farmers can also grow dedicated energy crops, such as switchgrass and miscanthus, which can be harvested for bioenergy production without competing with food crops. These energy crops can be integrated into crop rotation systems, providing additional income streams and enhancing farm sustainability (Hamidzadeh et al. 2023). The use of biomass in agriculture not only supports energy self-sufficiency but also contributes to more resilient and sustainable farming practices.

5. Global implementation of bioenergy

Bioenergy is under gradual implementation in many countries, and this has led to the use of various technologies and methods Figure 1, illustrate the use of biomass technologies in different parts of the world. In Brazil and Poland particularly, bioethanol which is produced from sugarcane is blended with gasoline and widely used in the transport sector (Mączyńska et al. 2019). Brazil has always been the pioneer in the application of bioethanol as a main fuel for automobiles (Luo, van der Voet, and Huppes 2009) . The United States is the global leader in biomass power with the ability to convert agricultural and forestry residuals into electricity. Agricultural and forestry residues, animal manure and municipal solid waste are replenishable and widely available in the United States. The utilization of all available wastes and residues in the contiguous United States can generate 3.1–3.8 exajoules (EJ) of renewable energy (Liu and Rajagopal 2019) .Sweden is among the leaders in district heating systems with wood pellets and other types of biomasses as the source of heat for homes and commercial buildings (Werner 2017). India pays significance to biogas from agricultural residuals, especially in rural regions where cow dung and crop residues are used for power production. In rural regions of India, biomass has been used as a fundamental source of domestic energy for cooking and lighting. Animal dung, agricultural leftovers including bagasse and rice husk, and wood fuels including waste wood and charcoal are examples of biomass energy (Duarah et al. 2022). Germany uses biomass in the generation of electricity through co-combustion with coal (Hartmann and Kaltschmitt 1999). On the other hand, China funds biomass-electricity projects to convert agricultural and forestry residue into electricity to cater to its increasing power demand. An example that can be made to understand how a much more extended biogas application has been managed in China is the "Hebei Rural Renewable Energy Development Project" launched in 2015 and operational until 2021 for the sustainable use and production of biogas. It embraces broad biogas facilities management with six plants in Hebei region for recycling agricultural wastes to stable clean energy for the villagers (Tagne et al. 2021).

6. Social impact and community engagement

Bioenergy projects offer significant social benefits, particularly in terms of community development, job creation, and rural livelihoods (Rogers et al. 2012). By utilizing local biomass resources, these projects can stimulate economic activity in rural areas where traditional industries may be declining or absent. They create employment opportunities not only in the construction and operation of bioenergy facilities but also in ancillary sectors such as biomass collection and processing. This can lead to improved income levels and enhanced quality of life for rural populations. Moreover, bioenergy initiatives can contribute to community development by funding local infrastructure projects, supporting educational programs, and fostering community engagement (Eswarlal et al. 2014). However, to maximize these benefits, it is crucial to ensure active involvement of local communities and stakeholders throughout the project lifecycle. Engaging with local populations early in the planning process helps to address concerns, gather valuable input, and build trust. This collaborative approach can prevent conflicts, enhance social acceptance, and ensure that the benefits of bioenergy projects are equitably distributed. By prioritizing stakeholder engagement and incorporating local perspectives, bioenergy projects can achieve greater sustainability and contribute positively to the social fabric of the communities they serve.

Figure 1. Biomass implementation in different countries

7. Discussions

The role of biomass in the future energy landscape is multifaceted, and its impact on sustainable development extends beyond mere energy production. It is critical to evaluate biomass energy not only for its potential to reduce greenhouse gas emissions but also for its broader environmental, social, and economic implications. For instance, sustainable biomass production can support rural development by creating jobs and generating income in agricultural communities. This socio-economic benefit is particularly significant in developing countries, where rural poverty is prevalent. However, ensuring that these benefits are equitably distributed requires careful planning and governance. Policies must be designed to protect smallholders and local communities, preventing land grabs and ensuring that biomass production does not lead to the displacement of vulnerable populations. Moreover, the integration of biomass into the energy mix must be balanced with the need to preserve biodiversity and maintain ecosystem services. The cultivation of energy crops should avoid monoculture practices that can lead to soil degradation, water scarcity, and loss of habitat. Instead, adopting agroforestry systems and intercropping can enhance biodiversity, improve soil health, and provide additional ecosystem services. These practices also contribute to carbon sequestration, further amplifying the climate benefits of biomass energy. To achieve these outcomes, a holistic approach to land-use planning is essential, one that considers the ecological, economic, and social dimensions of sustainability.

As biomass energy scales up, the challenge of maintaining sustainability becomes more pronounced. Large-scale bioenergy projects must incorporate robust environmental and social safeguards to prevent adverse impacts. For instance, lifecycle assessments can help identify potential hotspots of greenhouse gas emissions and resource use, enabling the design of more efficient and sustainable supply chains. Advances in technology, such as precision agriculture and biotechnological improvements, can enhance the efficiency of biomass production and conversion processes, reducing environmental footprints. However, the deployment of these technologies must be coupled with strong regulatory frameworks to ensure that they are used responsibly and equitably. The interplay between bioenergy and food security remains a critical issue. The competition for land between food and fuel crops can exacerbate food insecurity, particularly in regions where land and water resources are already scarce. To mitigate these risks, it is vital to promote the use of marginal lands for energy crops and to develop second and third-generation biofuels that do not compete directly with food production. Additionally, enhancing agricultural productivity and reducing food waste can alleviate some of the pressures on food systems, enabling a more harmonious coexistence of food and biofuel production.

Furthermore, the global bioenergy market is influenced by a complex web of economic, political, and environmental factors. International trade policies, subsidies, and carbon pricing mechanisms all play crucial roles in shaping the viability and sustainability of bioenergy projects. Transparent and consistent policy frameworks are needed to provide stability and encourage long-term investments in sustainable bioenergy. International cooperation and knowledge-sharing can also accelerate the development and deployment of best practices, ensuring that bioenergy contribute positively to global energy security and climate goals. Finally, it is essential to recognize that bioenergy is not a silver bullet solution. It should be part of a diversified energy strategy that includes a mix of renewable energy sources, energy efficiency measures, and demand-side management. By integrating biomass with other renewable technologies, such as solar and wind, we can create more resilient and sustainable energy systems. This integrated approach will help us transition to a low-carbon economy while addressing the multifaceted challenges of sustainable development.

8. Conclusion

Bioenergy holds a significant promise as a sustainable energy source capable of reducing greenhouse gas emissions, enhancing energy security, and providing economic and social benefits, particularly in rural areas. However, the sustainability of bioenergy production and use is complex and multifaceted, encompassing environmental, economic, and social dimensions.

Key Points:

1. Advancements in Technology: Innovations in biomass conversion technologies and the utilization of diverse biomass resources are making bioenergy more efficient and viable.
2. Environmental and Economic Benefits: Bioenergy can significantly reduce greenhouse gas emissions and provide economic opportunities, particularly in rural and agricultural communities.
3. Challenges: Despite its potential, bioenergy faces challenges such as environmental impacts, competition with food production, and the need for robust regulatory frameworks.
4. Holistic Approach: Sustainable bioenergy development requires integrating sustainable land-use practices, technological innovations, and comprehensive policy support.

Future research should focus on addressing these challenges to maximize the potential of bioenergy in contributing to a sustainable energy future. By doing so, bioenergy can play a crucial role in the global transition to renewable energy, supporting sustainable development goals and helping to mitigate climate change.

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