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SUSTAINABLE BIOENERGY FROM PLANT-BASED FEEDSTOCKS

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Abstract

The urgent need to mitigate climate change and reduce dependence on fossil fuels has positioned biofuels as a key component of renewable energy strategies. However, despite their apparent environmental benefits, biofuels remain controversial due to concerns over land use, food security, and lifecycle emissions. This review critically evaluates biofuel feedstocks and conversion technologies, emphasizing sustainability trade-offs and technological limitations. First-generation biofuels, primarily derived from food crops, dominate current production but raise significant ethical and environmental concerns. Second- and third-generation biofuels offer promising alternatives, yet their large-scale implementation is constrained by technological and economic barriers. This study synthesizes current knowledge and highlights research gaps, advocating for integrated approaches that balance energy production with ecological and socio-economic sustainability.

Key words: Biodiesel, Bioethanol, Biofuels, Life cycle assessment, Lignocellulosic biomass, Sustainability

1.Introduction

The increasing global demand for energy, coupled with concerns regarding climate change, environmental degradation, and fossil fuel depletion, has accelerated the search for renewable and sustainable energy alternatives. Fossil fuels currently account for a substantial proportion of global primary energy consumption; however, their continued use contributes significantly to greenhouse gas (GHG) emissions and global warming (International Energy Agency [IEA], 2024). Consequently, international agreements such as the Paris Agreement have emphasized the necessity of transitioning toward low-carbon energy systems that can simultaneously support economic development and environmental sustainability (United Nations Framework Convention on Climate Change [UNFCCC], 2023).

Among various renewable energy options, bioenergy occupies a unique position because it can provide solid, liquid, and gaseous fuels compatible with existing energy infrastructures. Unlike intermittent renewable resources such as solar and wind energy, bioenergy offers storage flexibility and dispatchable energy production, making it an important component of future energy portfolios (World Bioenergy Association, 2024).

Plant-based bioenergy systems are particularly attractive because plants convert solar energy into chemical energy through photosynthesis, producing biomass that can subsequently be transformed into various biofuels. These include bioethanol, biodiesel, biogas, biohydrogen, renewable diesel, bio-oil, and sustainable aviation fuels (Cherubini & Strømman, 2011).

Despite these advantages, the sustainability of bioenergy remains controversial. Early enthusiasm surrounding first-generation biofuels was challenged by concerns regarding indirect land-use change, food-versus-fuel competition, biodiversity loss, water consumption, and uncertain greenhouse gas mitigation benefits (Searchinger et al., 2008; Fargione et al., 2008). These concerns stimulated intensive research into advanced biofuel systems based on lignocellulosic biomass, agricultural residues, dedicated energy crops, and algal feedstocks.

Recent developments in biotechnology, metabolic engineering, biorefinery design, and circular bioeconomy concepts have further expanded opportunities for sustainable bioenergy production. Modern bioenergy systems increasingly aim to maximize resource efficiency while minimizing environmental impacts through integrated utilization of biomass resources and waste streams (Bhatia et al., 2022).

This review critically examines plant-based feedstocks used for bioenergy production, evaluates their sustainability characteristics, and discusses emerging technological innovations that may support the transition toward environmentally and economically sustainable bioenergy systems.

2. Plant-Based Feedstocks for Bioenergy Production

The sustainability of bioenergy systems largely depends on the characteristics of the feedstocks used. Feedstocks influence energy yields, conversion efficiencies, environmental impacts, land requirements, water consumption, and economic feasibility. Plant-based feedstocks can generally be classified into three major categories: first-generation feedstocks, second-generation lignocellulosic feedstocks, and third-generation algal biomass.

2.1. First-Generation Biofuel Feedstocks

First-generation biofuels are produced directly from food crops containing fermentable sugars, starches, or vegetable oils. These feedstocks include corn, sugarcane, wheat, sugar beet, soybean, rapeseed, sunflower, and palm oil.

Bioethanol production from sugarcane and corn remains the dominant liquid biofuel pathway worldwide. Brazil and the United States account for the majority of global bioethanol production, relying primarily on sugarcane and corn, respectively (IEA, 2024).

Sugarcane-derived ethanol is generally considered one of the most efficient first-generation biofuels because sugarcane exhibits high photosynthetic efficiency and favorable energy balances. Studies have reported substantial greenhouse gas emission reductions relative to gasoline when ethanol is produced under optimized agricultural and industrial conditions (Bhatia et al., 2022).

Similarly, vegetable oils obtained from soybean, rapeseed, sunflower, and palm oil are extensively utilized for biodiesel production. Biodiesel offers several advantages, including biodegradability, reduced sulfur emissions, and compatibility with conventional diesel engines (Atabani et al., 2019).

However, first-generation biofuels remain controversial because they directly compete with food production systems. Expansion of biofuel crops may increase pressure on agricultural land, potentially contributing to food price volatility and land-use change (Searchinger et al., 2008). Furthermore, intensive cultivation often requires substantial fertilizer, pesticide, and irrigation inputs, which may offset environmental benefits through increased emissions and ecosystem degradation (Soós & Makszim, 2024).

These limitations have led many researchers to conclude that first-generation biofuels alone cannot provide a sustainable long-term solution for global renewable fuel demand (Fargione et al., 2008).

2.2. Second-Generation Lignocellulosic Feedstocks

Second-generation biofuels utilize non-food biomass sources composed primarily of cellulose, hemicellulose, and lignin. These feedstocks include agricultural residues, forestry residues, perennial energy crops, and industrial biomass wastes (Makszim et al., 2025).

Lignocellulosic biomass has attracted considerable attention because of its abundance and reduced competition with food systems. Globally, billions of tons of agricultural residues such as wheat straw, rice straw, corn stover, sugarcane bagasse, and cotton stalks are generated annually (Lal, 2020).

The utilization of agricultural residues offers several sustainability advantages. First, residues represent an existing biomass resource that does not require additional land conversion. Second, their use can contribute to waste reduction and circular economy objectives. Third, residue-based biofuels generally exhibit lower life-cycle greenhouse gas emissions compared with first-generation alternatives (Cherubini & Strømman, 2011).

Dedicated energy crops represent another important category of second-generation feedstocks. These crops are specifically cultivated for biomass production and often include perennial species with high productivity and environmental resilience.

Miscanthus

Miscanthus × giganteus is widely regarded as one of the most promising energy crops due to its exceptional biomass productivity, efficient nutrient use, and extensive root systems. Long-term studies have demonstrated that Miscanthus plantations can accumulate substantial amounts of soil organic carbon while maintaining high biomass yields under diverse climatic conditions (McCalmont et al., 2017).

The deep rooting systems of Miscanthus improve soil structure, reduce erosion, and enhance carbon sequestration. Moreover, perennial growth habits reduce tillage requirements and associated greenhouse gas emissions.

Switchgrass

Switchgrass (*Panicum virgatum*) is another widely studied perennial bioenergy crop. Native to North America, switchgrass exhibits high adaptability to marginal lands and variable environmental conditions. Research has shown that switchgrass can provide favorable energy balances while simultaneously supporting biodiversity and soil conservation objectives (Werling et al., 2014).

Short-Rotation Woody Crops

Willow (*Salix* spp.) and poplar (*Populus* spp.) are commonly used short-rotation woody crops. These species are characterized by rapid growth rates, high biomass yields, and suitability for cultivation on degraded lands (Makszim et al., 2024).

Woody energy crops often provide additional ecosystem services, including habitat creation, nutrient retention, and carbon storage. Their extensive root systems contribute to long-term soil improvement and environmental restoration.

2.3. Third-Generation Feedstocks: Algal Biomass

Microalgae and macroalgae represent third-generation biofuel feedstocks and have gained increasing attention due to their exceptional productivity and reduced land requirements.

Unlike terrestrial crops, algae can be cultivated in saline water, wastewater, or non-arable environments. Consequently, algal cultivation minimizes competition with food production systems and agricultural land resources (Chisti, 2007).

Microalgae possess several characteristics that make them attractive biofuel feedstocks:

- Rapid growth rates
- High photosynthetic efficiency

- Elevated lipid accumulation
- Potential carbon dioxide capture
- Wastewater treatment capabilities

Certain microalgal species can accumulate lipid contents exceeding 50% of dry biomass under optimized conditions, making them suitable for biodiesel production (Chisti, 2007).

Despite these advantages, commercial-scale algal biofuel production remains economically challenging. High cultivation, harvesting, dewatering, and processing costs continue to limit large-scale deployment. Significant technological advances are required before algal biofuels become economically competitive with conventional fuels and advanced lignocellulosic alternatives.

2.4. Emerging Feedstock Sources

Recent bioenergy research increasingly emphasizes waste-based and integrated feedstock systems. Agricultural residues, food processing wastes, municipal organic wastes, and agro-industrial by-products are being explored as sustainable biomass resources within circular bioeconomy frameworks.

The valorization of biomass waste streams offers multiple environmental benefits. It reduces waste disposal requirements, decreases methane emissions from landfills, improves resource efficiency, and supports integrated biorefinery systems capable of producing fuels, chemicals, and biomaterials simultaneously (Bhatia et al., 2022).

Moreover, integrated feedstock approaches can improve the overall economic viability of bioenergy systems by diversifying revenue streams and reducing dependence on single biomass sources.

3. Comparative Sustainability of Plant-Based Feedstocks

No single feedstock can be universally considered the most sustainable option. Sustainability outcomes depend on regional climate, land availability, water resources, agricultural practices, technological infrastructure, and policy frameworks.

First-generation feedstocks currently dominate commercial production but face substantial sustainability concerns. Second-generation lignocellulosic feedstocks generally provide improved environmental performance and reduced food competition. Third-generation algal systems offer remarkable theoretical potential but remain technologically immature and economically expensive.

Consequently, future sustainable bioenergy systems will likely rely on diversified feedstock portfolios tailored to regional ecological and socioeconomic conditions rather than a single universal solution. Climate-resilient and drought-tolerant alternative crops may also contribute to more diversified and sustainable biomass production systems under changing environmental conditions (Csabai et al., 2022; 2023; 2025).

4. Conclusion

Plant-based bioenergy has considerable potential to contribute to sustainable energy production and greenhouse gas mitigation. However, its overall sustainability depends on feedstock selection, biomass conversion technologies, and responsible resource management. While first-generation biofuels remain important in current markets, second-generation lignocellulosic biomass offers greater environmental benefits by reducing competition with food production. Third-generation algal feedstocks present promising future opportunities but require further technological and economic development before large-scale commercialization.

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