Waste Agricultural Biomass as a Renewable and Sustainable Source of Energy

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Abstract

Growing concern about the feasibility of generating carbon dioxide (CO_2) emissions from burning fossil fuels has had a significant impact on climate change worldwide, which has raised interest in renewable energy sources and alternative energy-producing technologies. The increasing energy demand and environmental concerns have driven the search for sustainable and renewable source of energy to reduce the dependency on fossil fuel. Agricultural waste, a major by-product of farming activities are simply burnt in some region of India, presents a promising alternative as a bioenergy source. This review paper provides a comprehensive overview of the processes involved in converting agricultural residues into biomass fuels, their physicochemical characteristics, and their potential utilization in compression ignition (CI) engines. The paper discusses the technological, environmental, and economic perspectives of agricultural waste-to-energy pathways and reviews recent studies on the performance, emission characteristics, and challenges of using bio-oil, biodiesel, and biogas in diesel engines.

Keywords: Agricultural Waste; Alternative Fuel; Biomass Energy; Diesel Engine; Sustainable Fuel

1. Introduction

As coal and oil continue to be the world's top primary energy sources, biomass appears to be one of the most important renewable energy sources for the foreseeable future, ranking third [1]. However, there do not appear to be any new technologies that could jeopardize the ability to generate energy from biomass waste given the characteristics and amounts of the world's energy needs. Because biomass contains no sulfur, it contributes very little to acid rain and absorbs the same amount of carbon dioxide (CO_2) when burned as fuel, which has a minor influence on global warming. Due to biomass's widespread availability, renewable energy sources, and potential to mitigate global warming [2]. The installed capacity of renewable energy in India is shown in figure 1.

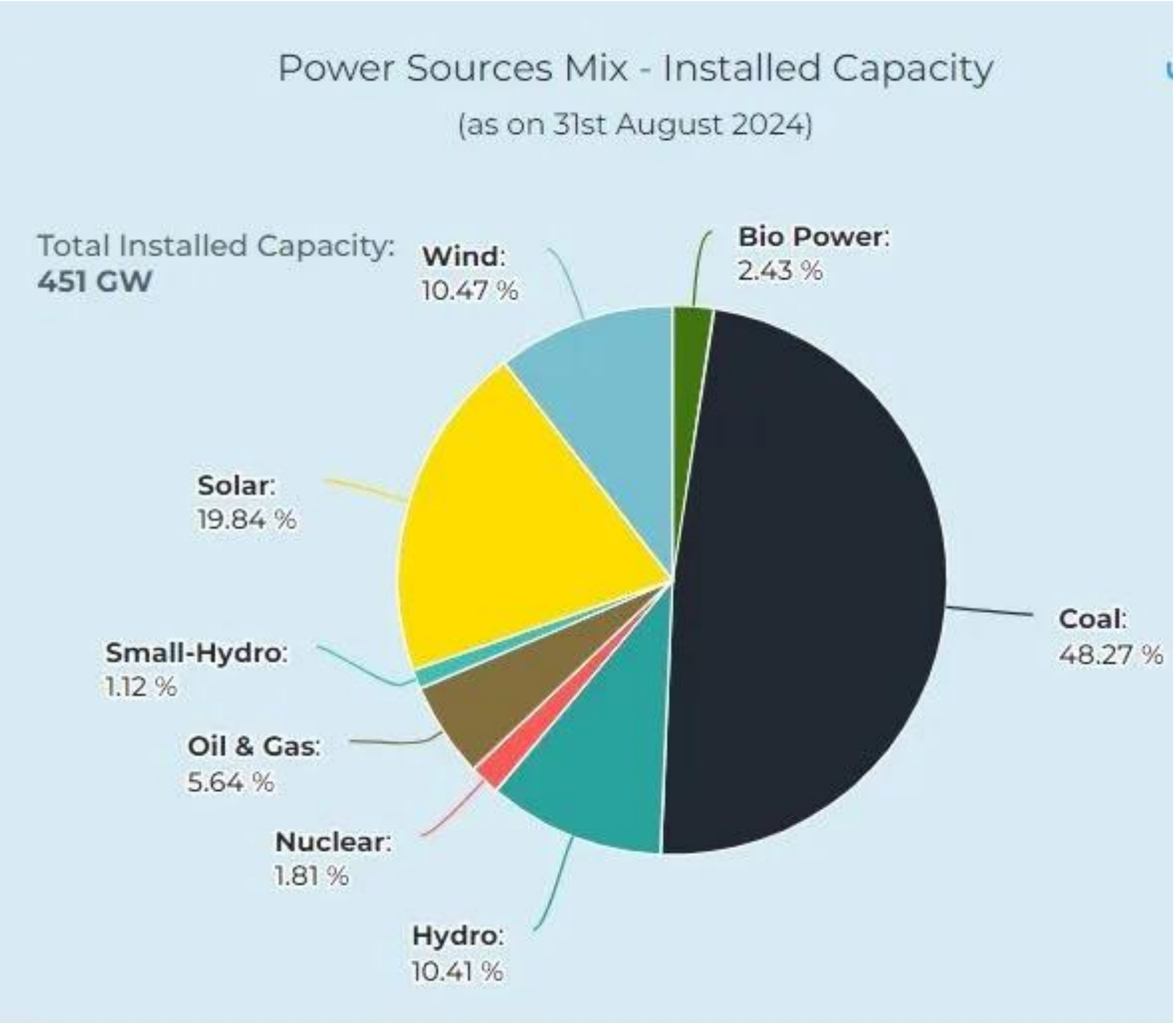

Fig.1. Installed capacity of renewable energy source

In India, there are currently 288 projects with a combined capacity of 2,665 MW that are devoted to producing and co-producing biomass power. On the other hand, independent biomass power plants provide 999 MW of capacity in 130 projects, while 158 bagasse co-generation projects provide 1,666 MW to the total capacity [3]. A group of 30 biomass power projects with a combined capacity of 350 MW has been built as part of the country's development efforts. Seventy surplus-capacity cogeneration projects supplement this, increasing the total capacity to 800 MW. States like Andhra Pradesh, Tamil Nadu, Maharashtra, Karnataka, and Uttar Pradesh have a notably high concentration of bagasse cogeneration projects. On the other hand, states like Andhra Pradesh, Gujarat, Maharashtra, Chhattisgarh, Madhya Pradesh, and Tamil Nadu are at the forefront of biomass power projects[4].

The global dependency on fossil fuels has led to significant environmental issues, including greenhouse gas emissions and resource depletion[5]. In this context, renewable energy, particularly bioenergy from agricultural waste, offers a viable solution. Agricultural residues like rice husk, wheat straw, corn stover, and sugarcane bagasse are abundantly available and underutilized. Converting this waste into useful energy forms can help manage waste sustainably and reduce reliance on fossil fuels. This paper reviews current methods for converting agricultural waste into biofuels suitable for diesel engines and evaluates their potential applications.

2. Types and Availability of Agricultural Waste

Agricultural waste refers to the residues and by-products generated during various agricultural operations, including harvesting, threshing, processing, and storage[6]. These wastes are generally considered underutilized resources with considerable potential for conversion into bioenergy [7]. Based on their origin and characteristics, agricultural wastes can be broadly classified into two categories: Agricultural waste is classified into two categories as shown in figure 2:

- Primary residues: Generated during harvesting (e.g., straw, husks).
- Secondary residues: Produced during processing (e.g., bagasse, bran, shells).

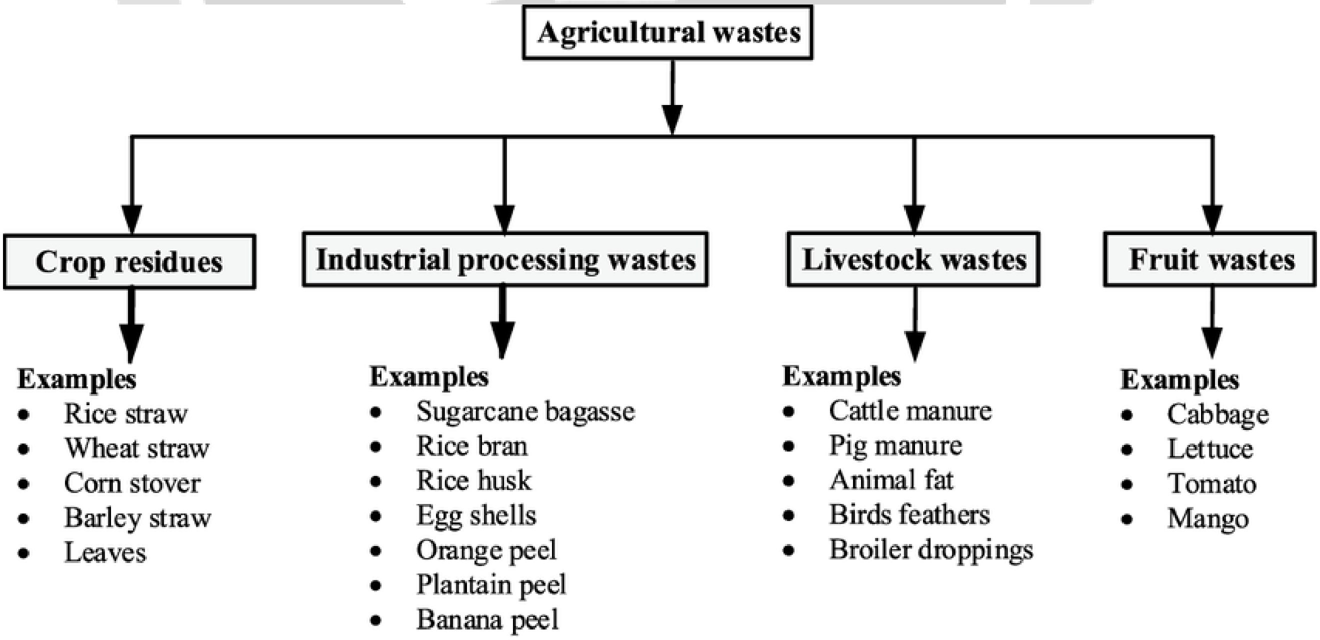

Fig.2. Classification of agricultural waste

These are wastes generated directly from field operations such as harvesting and post-harvest handling[8]. They are typically left in the field or disposed of by open burning, which contributes to environmental pollution. Examples include: Straw (e.g., wheat, rice, and barley straw), Stalks (e.g., maize and sorghum stalks), Husks and Shells (e.g., rice husk, groundnut shells), Corn cobs and stover. The approximately available major agricultural residues are shown in figure 3.

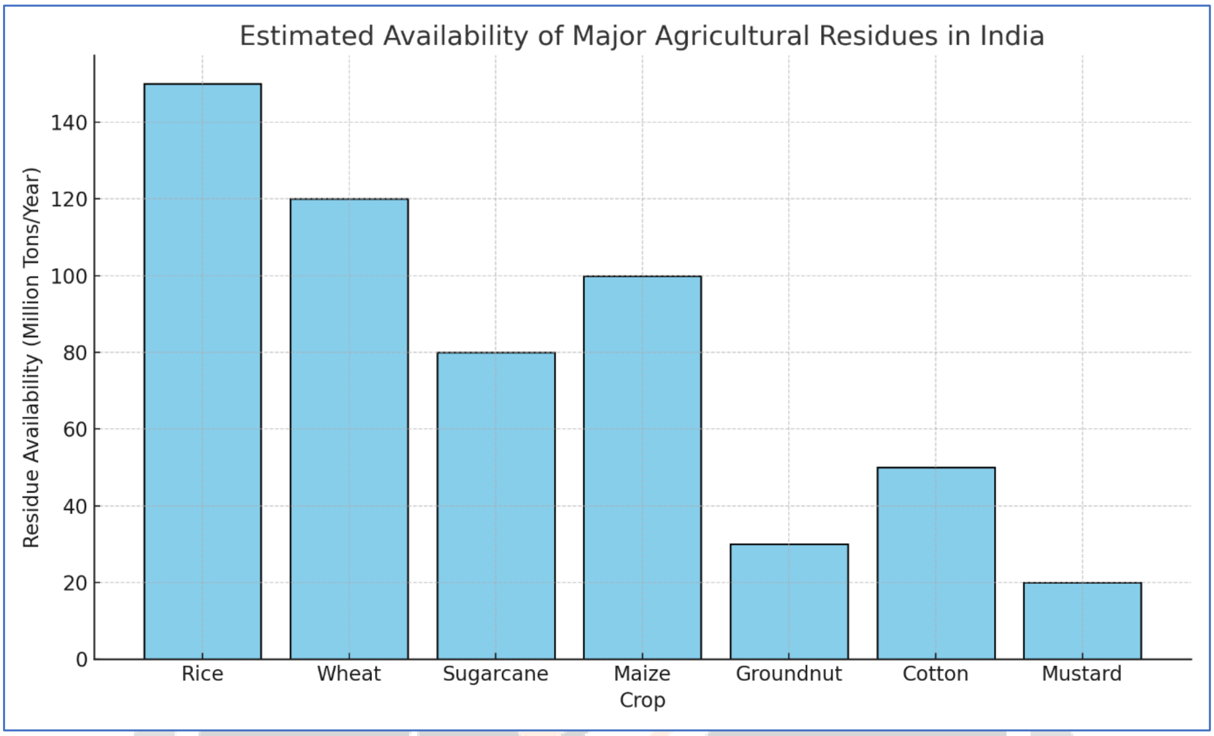

Fig.3. Approximately available major agricultural residues

3. Agricultural Waste to Energy

Several technologies are used to convert agricultural waste into usable energy forms:

a. Anaerobic Digestion

Organic agricultural waste is decomposed by anaerobic bacteria to produce methane-rich biogas, which can be used for cooking, electricity, or vehicle fuel[9]. Biogas production via anaerobic digestion (AD) is a sustainable and efficient method of converting organic waste into a clean, renewable energy source. Anaerobic digestion involves the microbial breakdown of biodegradable materials in the absence of oxygen, resulting in the generation of biogas—a mixture primarily composed of methane (CH_4) and carbon dioxide (CO_2)—and a nutrient-rich slurry known as digestate. This technology is increasingly recognized for its role in waste management, renewable energy generation, and climate change mitigation. The anaerobic digestion process occurs in four key stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis [10]. During hydrolysis, complex organic matter like carbohydrates, proteins, and fats are broken down into simpler compounds. Acidogenesis and acetogenesis further convert these compounds into volatile fatty acids, hydrogen, and carbon dioxide. Finally, methanogenic bacteria convert these intermediates into methane and carbon dioxide, forming biogas. A wide range of feedstocks can be used for biogas production, including [11]:

- Animal manure (e.g., cattle, pig, and poultry waste)
- Agricultural residues (e.g., crop stubble, spoiled silage)
- Food waste and kitchen scraps
- Sewage sludge and industrial organic waste

Biogas systems range from small household digesters used in rural areas to large-scale industrial plants integrated with municipal or agricultural operations. Countries like Germany, India, and China have established national programs to promote biogas technology for both rural development and energy diversification.

b. Biomass Combustion

Dry agricultural residues are burned to generate heat and electricity. This is one of the most direct methods but requires careful emission control. Biomass combustion is one of the oldest and most widely used methods for producing energy from organic materials [12]. It involves the direct burning of biomass—such as wood, crop residues, and other plant-based materials—to produce heat, which can be used directly or converted into electricity through steam turbines. As a renewable energy source, biomass combustion plays a crucial role in reducing dependence on fossil fuels and lowering greenhouse gas emissions, especially in rural and off-grid communities.

The combustion process oxidizes the carbon-rich biomass in the presence of oxygen, releasing energy in the form of heat. This thermal energy is then used to heat water and generate steam, which can drive turbines for electricity generation or provide heat for residential, industrial, and agricultural applications [13]. Modern biomass combustion systems are designed to operate at high efficiency with controlled emissions. Biomass combustion can utilize a wide range of solid biomass materials, including:

- Firewood and wood chips
- Agricultural residues such as straw, husks, and bagasse
- Energy crops like switchgrass and miscanthus
- Organic municipal solid waste (in certain cases)

Several combustion technologies exist, ranging from simple open fires and traditional stoves to advanced systems such as fixed-bed combustion (grate firing) common in small to mediumscale applications, Fluidized bed combustion offers high efficiency and low emissions for large-scale power generation, Pellet burners and boilers used for residential and commercial heating, offering consistent fuel and clean combustion. The advantages of biomass combustion include:

- The CO_2 released during combustion is offset by the CO_2 absorbed during plant growth.
- Biomass is locally available and reduces reliance on imported fuels.
- Provides heat, electricity, or combined heat and power (CHP).
- Utilizes agricultural and forestry residues that would otherwise go unused or be burned in the open.

Biomass combustion remains a viable and accessible energy solution, especially in developing regions and for decentralized power needs. With modern technologies and proper emission controls, it can contribute significantly to renewable energy portfolios, rural development, and sustainable waste management. Continued innovation and policy support are essential for enhancing its efficiency and environmental performance.

c. Gasification

Solid biomass is converted into syngas (a mixture of CO, H_2, and CH_4) at high temperatures in a low-oxygen environment. Syngas can be used in internal combustion engines or for producing biofuels. Biomass gasification is a thermo-chemical process that converts organic materials such as agricultural residues, wood chips, and animal waste—into a combustible gas mixture called syngas (synthetic gas)[14]. This process occurs in a gasifier, typically at high temperatures (700–1000 °C), with limited oxygen or air, ensuring partial combustion. The resulting syngas primarily consists of carbon monoxide (CO), hydrogen (H_2), methane (CH_4), and traces of carbon dioxide (CO_2) and nitrogen (N_2). Syngas can be used as a clean fuel for internal combustion engines, gas turbines, or for electricity and heat generation in combined heat and power (CHP) systems. It also serves as a feedstock for producing chemicals and synthetic fuels.

Gasification provides an efficient and environmentally friendly route for biomass utilization [15]. Unlike direct combustion, gasification yields higher energy conversion efficiency and produces lower emissions of particulates, sulfur oxides (SO_x), and nitrogen oxides (NO_x). The process can handle a wide variety of biomass types, including low-moisture and high-ash materials, which are often unsuitable for other thermal conversion methods. Moreover, gasification supports decentralized power generation, making it highly suitable for rural and remote areas.

Modern advancements in gasifier designs—such as fixed-bed, fluidized-bed, and downdraft gasifiers—have enhanced reliability, scalability, and fuel flexibility. However, challenges remain in the form of tar formation, ash-related issues, and feedstock variability, which require further research and optimization. Despite these hurdles, biomass gasification is gaining prominence as a promising renewable energy technology contributing to energy security, waste reduction, and carbon-neutral development. Potential technologies for conversion of agricultural waste into energy are shown in figure 4.

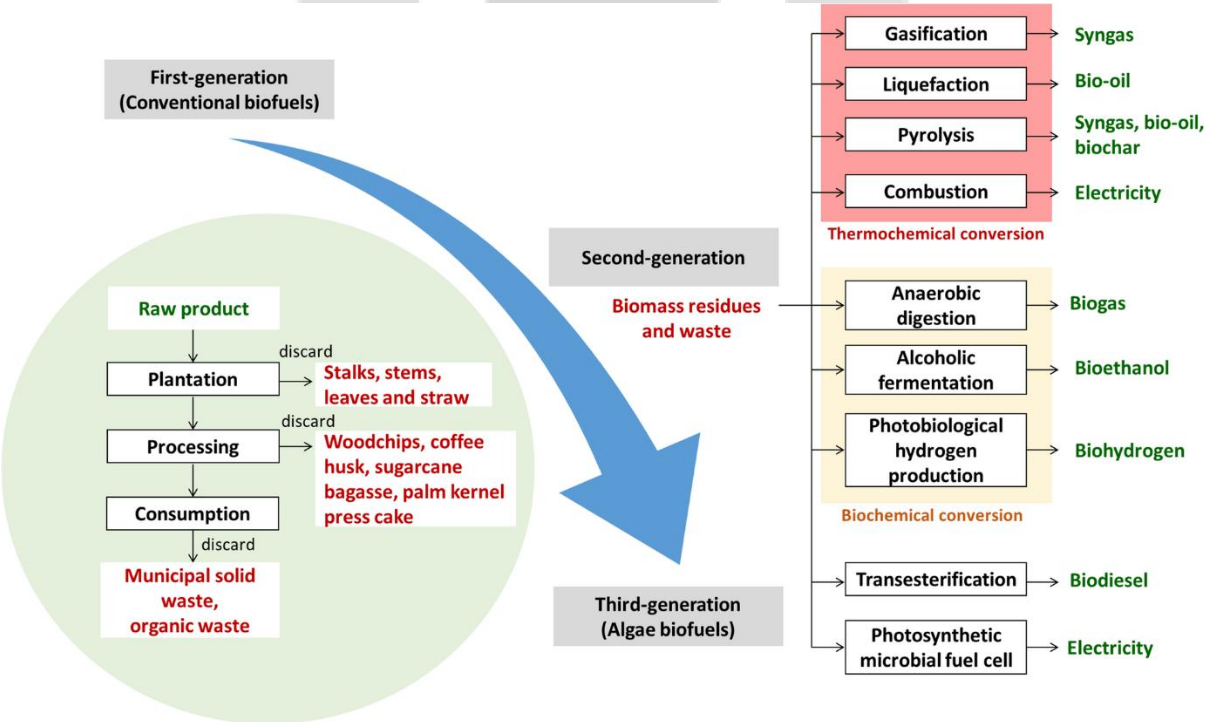

Fig.4. Potential technologies for conversion of agricultural waste into energy [16]

d. Pyrolysis

Biomass is thermally decomposed in the absence of oxygen to produce bio-oil, biochar, and syngas. These products can be used as fuel or soil amendments. Biomass pyrolysis is a thermal decomposition process that converts organic materials—such as agricultural residues, wood, and manure—into valuable bio-products in the absence of oxygen[17]. Typically occurring at temperatures between 300°C and 600°C, pyrolysis breaks down the complex organic molecules in biomass into three main products: biochar (solid), bio-oil (liquid), and syngas (gas) [18]. The proportions of these products depend on the operating conditions and the type of biomass used.

Fast pyrolysis, which involves rapid heating and short residence times, is particularly effective for maximizing bio-oil production, while slow pyrolysis favors biochar yield. One of the major advantages of biomass pyrolysis is its ability to convert low-value or waste biomass into high-value renewable fuels and materials. Bio-oil can be used as a substitute for fossil fuels in boilers, turbines, or further refined into transportation fuels. Biochar is a stable carbon-rich solid with significant potential for soil amendment, carbon sequestration, and water filtration. Syngas, though produced in smaller quantities in pyrolysis compared to gasification, can be used for heat or electricity generation.

Pyrolysis offers several environmental and economic benefits. It reduces greenhouse gas emissions by diverting biomass waste from open burning or decomposition and capturing carbon in biochar. It also provides an opportunity for rural development and decentralized energy production. However, challenges such as the instability and corrosiveness of raw bio-oil, tar management, and process optimization need further research and technological development. Biomass pyrolysis is a versatile and scalable technology that contributes significantly to sustainable energy systems, circular economy models, and climate change mitigation efforts.

e. Bioethanol and Biodiesel Production

Lignocellulosic agricultural residues can be fermented to produce bioethanol, while oil-rich seeds (like jatropha or soybean) can be processed into biodiesel. The production of bioethanol and biodiesel from agricultural waste presents a promising pathway for sustainable biofuel generation while addressing waste management and environmental concerns. Agricultural residues such as rice husk, wheat straw, corn stover, sugarcane bagasse, and non-edible oilseeds offer abundant, low-cost, and renewable feedstock for second-generation biofuels, reducing reliance on food-based resources and fossil fuels.

Bioethanol is primarily produced through the fermentation of sugars derived from lignocellulosic biomass [19]. The process involves several steps: pretreatment (to break down complex lignocellulose structure), enzymatic hydrolysis (to convert cellulose and hemicellulose into fermentable sugars), and microbial fermentation (usually by yeast or bacteria) to produce ethanol. This lignocellulosic bioethanol is a clean-burning fuel that can be blended with gasoline to reduce greenhouse gas emissions and improve energy security.

Biodiesel, on the other hand, is typically produced through the transesterification of oils or fats using an alcohol (usually methanol) in the presence of a catalyst [20]. Agricultural waste such as used cooking oil, non-edible oilseeds (like Jatropha or neem), and animal fats can serve as cost-effective raw materials. Biodiesel is biodegradable, non-toxic, and exhibits lower emissions of particulates, CO, and hydrocarbons compared to petroleum diesel.

Using agricultural waste for biofuel production not only enhances energy sustainability but also mitigates environmental pollution from open burning or landfilling of residues. Moreover, it provides additional income opportunities for farmers and supports rural economies. However, challenges such as high processing costs, feedstock variability, and technological limitations in large-scale implementation need to be addressed through continued research and policy support. It can be suggested that converting agricultural waste into bioethanol and biodiesel represents a vital step toward cleaner, renewable energy and a circular bioeconomy.

The potential benefits of converting agricultural waste into useful form of energy are:

- Reduces open burning and landfill waste, thus lowering air and soil pollution.
- Promotes decentralized and renewable energy generation, especially in rural areas.
- Provides farmers with additional income sources and job creation in biomass supply chains.
- By-products like biochar can enhance soil fertility and carbon sequestration.

4. Conclusion

Agricultural waste holds significant promise as a renewable energy source. Harnessing its potential through appropriate technologies and supportive policies can contribute to energy security, rural development, and climate change mitigation. Future efforts must focus on integrating waste-to-energy systems within existing agricultural practices, improving technology accessibility, and encouraging public-private partnerships. The major challenges and limitations are as follows:

- Gathering dispersed agricultural residues is logistically challenging and costly.
- Many advanced technologies are still expensive or require technical expertise.
- Inadequate government support or policy frameworks in many regions hinder large-scale adoption.
- Agricultural waste availability is seasonal, affecting continuous plant operations.

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