Review Article
A Review on Conversion of Agricultural Waste to Bioenergy: Processes and Environmental Impacts

ABSTRACT

Agricultural waste is a substantial and underutilized resource with the potential to contribute enormously to sustainable bioenergy production. The conversion technologies for these wastes is a significant step in the bioenergy process, therefore analyzing their impacts on the environment is considered valuable. A review of current literature, with an emphasis on studies that examines the relationship between agricultural wastes, different conversion technologies of wastes to bioenergy, and their environmental impacts was carried out. Databases like PubMed, Google scholar and Web of Science were searched using keywords like "Lignocellulosic biomass hydrolysis", "bioenergy", "Agricultural food wastes", and "environmental impacts". This review demonstrates how different conversion methods may alleviate climate change, enhance energy security while fostering sustainable development. We examined biochemical conversion methods such as anaerobic digestion and fermentation to show their advantages over the thermochemical approaches. It was found that these conversion processes are not only circular but also environmentally friendly with respect to biofuel production. Anaerobic digestion was identified as one of the most promising options because of its high energy yields and decentralized character. However, there are still issues in optimizing bioenergy conversion processes and conducting a comprehensive life cycle assessment that explains some of these challenges is required. This review highlights the current and emerging technologies for transformation of agricultural wastes into bioenergy and its environmental impacts, as it is necessary to transition into a bioenergy-driven economy to foster a healthy and robust future.

Keywords: Bioenergy, Bioethanol, Agricultural wastes, Environmental impacts, Biomass hydrolysis

1. INTRODUCTION

The global energy landscape is transforming due to urbanization which has led to increasing energy demands and environmental concerns [1,2]. Traditional energy sources, predominantly fossil fuels such as natural gas, coal and oil, have a limited nature and are contributing to the continuous emission of greenhouse gases into the atmosphere, which results in climate change and other environmental damages [2,3,4]. The urgency to mitigate these impacts has pushed global focus toward renewable energy sources which provide a cleaner and environmentally friendly option. Renewable energy sources including solar power, wind power, hydro-energy, and bioenergy, present opportunities to reduce carbon emissions and improve energy security [1,4,5].

Bioenergy produced from agricultural waste, is a prospective option among the various renewable energy sources available [6,7]. Agricultural wastes including residues from crop production, processing by-products, and other organic materials form a vast and often underutilized resource [7,8]. Transforming these wastes into bioenergy offers several advantages, such as decreasing the volume of waste released into landfills, curbing methane release from decomposition, and creating an energy source that supports sustainability in the agricultural sector [9,10,11]. By tackling waste management issues, this method of converting agricultural wastes to bioenergy promotes energy variety and boosts rural economies.

Although agricultural waste holds promise as a bioenergy source, additional research is necessary to determine the best conversion methods for agricultural waste-to-energy and understand the environmental consequences of these processes. This review seeks to present a comprehensive summary of the processes involved in converting agricultural waste to bioenergy and to evaluate their associated environmental impacts.

2. OVERVIEW OF AGRICULTURAL WASTE, ITS GENERATION AND DISPOSAL

Approximately 1300 million tonnes of waste with agricultural characteristics are produced annually in the agricultural sector. China, India, Nigeria, and the United States are the top four countries in the world in terms of yearly food waste production, with corresponding amounts of 91,646,213 tonnes, 68,760,163 tonnes, 37,900,000 tonnes, and 19,359,951 tonnes [5,9]. Various farming and processing activities generate agricultural wastes, which can be divided into organic and inorganic types [12]. Organic wastes originate from biological sources and are biodegradable [13]. Key types of organic agricultural wastes include residues from harvested crops, livestock wastes, and agro-industrial secondary products [14]. After harvesting, plants leave behind materials like wheat straw, barley straw, rice husks, and corn husks, which often amount to a considerable volume, constituting what is known as crop residues [15,16]. Livestock wastes include manure from cattle, pigs, and poultry, and bedding materials [17]. These are rich in organic matter and nutrients, making them a valuable resource if managed properly. The by-products of agro-industries, such as sugarcane bagasse (the fibrous material remaining after juice extraction), rice husks, and olive pomace (the residue from olive oil extraction), are generated during the processing of agricultural products and are accumulated in large quantities [18].

Traditionally, agricultural waste has been managed through techniques such as burning, landfilling, anaerobic digestion, composting or utilized in the feed of animals [13,14,19,20]. Burning which releases pollutants into the atmosphere and contributes to air pollution is still prevalent in many regions [21,22]. While landfilling reduces waste accumulation, it often leads to methane emissions, a potent greenhouse gas, and land degradation [23]. An environmentally friendly alternative is composting which involves the aerobic decomposition of organic waste to produce nutrient-filled compost which enhances the richness of the soil [13,24,25]. Anaerobic digestion involves decomposition of organic waste without the presence of oxygen, resulting in the production of biogas, which consists of a combination of methane and carbon dioxide, along with digestate, a by-product that is rich in nutrients [26,27]. Anaerobic digestion is mostly used for managing livestock manure and organic residues [28]. Certain agricultural by-products, like rice husks and some agro-industrial residues, are also repurposed as animal feed or feed supplements [29,30]. These conventional methods have several limitations, including environmental pollution, loss of valuable soil nutrients, and inefficient resource utilization [31]. Organic agricultural wastes are thus majorly used for bioenergy conversion, offering an eco-friendly and renewable energy source while addressing waste disposal challenges [7].

3. OVERVIEW OF BIOENERGY

Bioenergy is a form of renewable energy that is obtained from organic substances known as biomass, which includes plant and animal matter, agricultural by-products, forestry residues [32]. The World Economic Forum states that bioenergy serves as a sustainable energy alternative, reducing dependence on fossil fuels and alleviating the negative impacts of climate change [2,33,34]. Production-related manufacturing methods for bioenergy can be roughly divided into two groups. Biological and thermochemical technologies. Biomass is converted into energy via thermochemical procedures, which include liquefaction, combustion, gasification, and pyrolysis.

Bioenergy can be produced through the oxidation of biomass substrates, which can be divided into four categories: first-generation (edible food sources), second-generation (non-edible sources), third generation (biomass derived from algae), and fourth generation which uses genetic engineering to enhance organism for better biofuel production. This contains traits including enhanced photosynthesis, elevated lipid synthesis and improved utilization of sugar [32]. Algal substrates have advantages over other materials due to their quick growth, abundance, capacity to be grown in arable terrain, and low energy consumption. However, further research and development is still needed for their large-scale conversion procedures. Many different mechanisms, including biological, chemical, and thermal, can convert biomass into bioenergy. The International Energy Agency (IEA) reported that approximately 55% of the world's largest renewable energy comes from bioenergy. It also contributes significantly to the overall energy supply, representing over 6% of the global energy consumption [35].

3.1. Types of Biofuels

3.1.1. Bioethanol

Bioethanol, a widely utilized biofuel, is a type of alcohol produced by fermenting plant-based sugars. While traditionally made from food crops like corn or sugar cane (first-generation bioethanol), technological advancements have enabled the use of woody plants and grasses (second-generation bioethanol). Algae are being used as a potential source to produce bioethanol (third-generation bioethanol) [36,37]. Bioethanol has around 34% less energy per unit volume than gasoline.

3.1.2. Biogas

Biogas is a renewable gas produced from organic wastes like agricultural byproducts, manure, food scraps, and sewage [11]. It is created through anaerobic digestion, where methanogens or anaerobic microorganisms degrade organic matter in the absence of oxygen in a bioreactor, biodigester, or anaerobic digester [26,38,39]. The resulting gas from this procedure is primarily a mixture of carbon dioxide and methane, with other gases like moisture, siloxanes, and hydrogen sulfide (H2S) in trace amount [40,41]. Biogas can be incinerated directly for heat or used in engines to generate electricity. Its production efficiency and the composition are affected by various factors, including the type of waste utilized and the prevailing conditions (temperature, pH, and substrate concentration) within the digestion process [11,42,43].

3.1.3. Biodiesel

Biodiesel, also known as Fatty Acid Methyl Ester (FAME), is a renewable diesel fuel from biological materials such as vegetable oils, animal fats, or recycled greases. It is a clear to dark brown liquid with a high flash point compared to regular diesel. Compared to traditional diesel, biodiesel is slightly denser and has a lower energy content [44]. Despite these differences, biodiesel provides numerous environmental advantages such as a decrease in greenhouse gas emissions and enhanced air quality when compared to conventional diesel fuel. It is biodegradable and can be mixed with petroleum diesel to produce a less polluting fuel [45,46].

3.1.4 Biobutanol

The acetone-biobutanol-ethanol (ABE) fermentation process yields biobutanol, which has been reexamined in view of its potential application as a “drop in” liquid biofuel that may be mixed with gasoline. Gasoline and biobutanol can be combined up to 85% and utilized in cars without any changes. The synthesis of biobutanol can be achieved using acetone-butanol-ethanol (ABE) fermentation or petrochemical methods utilizing anaerobic bacteria, primarily belonging to the Clostridia genera [26,40].

Finding bacterial strains that can tolerate higher butanol concentrations is crucial because butanol is poisonous to bacteria. One way to do this is by using a “enrichment culture”, where the medium contains the molecule of interest. Bioethanol is produced from the same raw material as bioethanol, and offers significant advantages over ethanol when used as a fuel additive or as a biofuel [37].

3.1.5 Biomethane

A renewable energy source, biomethane is produced from the organic portion of municipal solid waste and biomass from agriculture and agro-industry[37]. It is produced in two primary steps: first, raw biogas is produced, primarily by anaerobic digestion of biomass; second, components that are incompatible with the entrance of CO2 into the network are removed.

Biomethane provides a more reliable energy source than other renewable energy sources like solar and wind energy, which are sporadic and weather-dependent. Furthermore, the synthesis of biomethane is not restricted by geographic elements like wind patterns, allowing its application in a greater number of locales. Additionally, because biomethane may be created from a variety of organic waste sources, it has a larger supply of feedstock[3], unlike bioethanol and biodiesel, which frequently rely on specialized energy crops that might compete with food production [26, 44].

In the transportation industry, biomethane can be utilized as a biofuel in the form of bio-LNG (liquefied natural gas) or bio-CNG (compressed natural gas). In industries like heavy-duty and maritime transportation that require decarbonization but are challenging to electrify, liquefied biomethane is highly helpful [35].

3.1.6 Biohydrogen

An easily biodegradable agricultural resource can be converted into biohydrogen. It is a renewable energy source that, upon combustion, releases fluid (water) since each hydrogen molecule has a high enough energy to be used as a fuel. Organic biodegradable compounds are needed for the processes involved in producing biohydrogen [33, 46]. These compounds are either employed as substrate during the autotrophic circumstance, the usage of certain organisms (algae, protists, and other single-celled microorganisms) that can facilitate the conversion of the sun’s energy to hydrogen directly is necessary.

3.2 Advantages of Bioenergy

Bioenergy's renewable nature makes it a valuable resource. It is made from organic components that may be renewed in a short amount of time, such as plant and animal waste. Sustainable forestry and agriculture methods provide bioenergy supplies, which are easily accessible in contrast to fossil fuels that require millions of years to develop. Bioenergy can be used as a long-term, renewable energy source because of its constant availability, strengthening the foundation of an increasingly resilient and sustainable energy system [47].

The possibility for bioenergy to be carbon neutral is another significant benefit. When biomass is burned to produce energy, the carbon dioxide (CO_2) emitted during combustion is offset by the CO_2 taken up by the plants as they grow, thereby establishing a closed carbon cycle. This lessens the effect of climate change by preventing input of new CO_2 to the atmosphere [48]. Bioenergy is an environmentally benign energy source since it may drastically reduce greenhouse gas emissions when utilized as a substitute for fossil fuels within well-managed systems.

By diversifying energy sources and lowering dependency on fossil fuels, bioenergy also improves energy security. Its local production can be achieved, thereby decreasing the reliance on energy imports and protecting economies from changes in the price of energy globally. Furthermore, the production of bioenergy boosts regional economies by generating employment in the forestry, agriculture, and bioenergy sectors [49]. This promotes stability and economic progress in the neighborhood while also bolstering energy security [50].

4. PROCESSES FOR CONVERSION OF AGRICULTURAL WASTE TO BIOENERGY

4.1. Biochemical Processes

4.1.1. Anaerobic Digestion

The series of procedures known as anaerobic digestion is how microbes decompose biodegradable materials when there is no oxygen present. There are four main phases of anaerobic digestion which include acidogenesis, acetogenesis, methanogenesis, and hydrolysis [51,52]. The overall procedure can be explained by the chemical reaction in figure 1, wherein anaerobic microorganisms biochemically decompose organic material such as glucose resulting in the production of carbon dioxide (CO_2) and methane (CH_4).

Figure 1: The anaerobic digestion process simplified

Biodegradable waste products including crop residues, grass clippings, food wastes, wastewater, and animal waste can all be used as feedstocks [53]. Woody wastes are an exception, as they are mostly untouched by digestion since most anaerobic microorganisms are unable to break down lignin [54,55]. Lignin can be decomposed by xylophagous anaerobes, or through high-temperature pretreatments such as pyrolysis. [54,55] For the purpose of producing biogas, anaerobic digesters can be supplied with energy crops that are grown specifically for them, such as silage.

Anaerobic digesters (methanogen species) are identified by their two standard operating temperature levels [56]. The optimal temperature range for mesophilic digestion lies between 30 and 38°C, with ambient temperatures ranging from 20 to 45 °C, where mesophilic bacteria are the dominant microorganisms. In contrast, thermophilic digestion involving thermophiles as the key microorganisms occur best at temperatures between 49 and 57°C or higher, up to 70°C [56,57]. The temperature at which a digester operates influences the types of bacteria present and how quickly waste breaks down. Higher temperatures can speed up the process but may need extra energy to maintain [57].

The retention time, which is the amount of time feedstock remains in the digester, is a crucial factor in digestion efficiency [58]. It depends on factors such as feedstock composition, digester design, and operating conditions [58,59]. Retention times for two-stage mesophilic digestions typically range from 15 to 40 days [60], whereas retention lengths for single-stage thermophilic digestions are often faster, taking about 14 days [61]. Because some of these systems are plug-flow, it is possible that the material has not fully degraded in this amount of time, leading to incomplete digestion. In this case, the digestate that leaves the system will smell stronger and have a darker color [62].

4.1.2. Fermentation

Microbial fermentation of sugar yields bioethanol [63]. Starch and cellulose, two major components of plant matter, are both composed of sugars. While theoretically both can be fermented into sugars, currently only those containing significant amounts of sugar (like sugarcane) or starch (like corn) are economically feasible for biofuel production [63].

Figure 2 shows an overview of the fermentation process in which ethanol and carbon dioxide are produced during the fermentation of glucose and other sugars found in agricultural wastes [64]. The fermentation process for ethanol is anaerobic when it involves yeast, but it can also be aerobic when it involves certain other microbes and enzymes [63,64,65]. Ethanol is a fuel that burns efficiently and produces fewer pollutants compared to other types of fuels [66]. It is a renewable energy source as it is derived from plant materials.

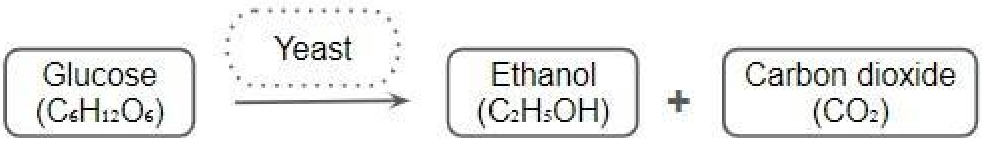

Figure 2: Overview of the fermentation process

While starch-based feedstocks are more common, ethanol can also be produced from cellulosic materials like wood, grasses, and agricultural residues [67]. However, cellulose must first be pretreated to break down its complex structure and release the sugars it contains [68,69]. This pretreatment step often involves the use of enzymes or chemicals [69,70]. A combination of shredding, enzyme hydrolysis and fermentation can also be employed. This involves enzymatic hydrolysis of shreds of agricultural waste to liberate simple sugars from complex polysaccharides like cellulose, which are subsequently fermented to yield bioethanol or biogas [63]. This optimizes the breakdown of lignocellulosic biomass in order to produce biofuel.

4.2. Thermochemical Processes

4.2.1. Combustion

Biomass is converted into heat via biomass heating systems [71]. The systems can generate heat through gasification, anaerobic digestion, combined heat and power (CHP), direct combustion, or aerobic digestion [72,73]. Biomass heating systems can be either fully or partially automated, or they may function as combined heat and power systems [73].

As biomass uses waste from urban, rural, and industrial areas as well as agricultural wastes to create heat with less of an effect on the environment compared to fossil fuels, it is advantageous to use biomass in heating systems [8,74,75]. In the past, biomass utilized as wood fuel supplied most of the human warmth until fossil fuels were used in large numbers [8,76]. Also, the carbon contained in biomass is an integrated natural carbon cycle, in contrast to the carbon found in fossil fuels which is not part of this cycle [76,77]. The combustion of fossil fuels results in a permanent release of carbon into the atmosphere, thereby indicating that this method of energy production has a restricted long-term environmental impact or carbon footprint [77].

4.2.2. Pyrolysis

The process of thermally breaking down substances at high temperatures, frequently in an inert environment without oxygen availability is known as pyrolysis [78]. In most cases, pyrolysis involves heating the material above the point at which it breaks down chemically to release the bonds between its components [79,80]. Usually, the pieces unite to form residues with a greater molecular mass, even amorphous covalent solids, but they can also become smaller molecules [78]. In many circumstances, there may be some oxygen, water, or other substances present, allowing for the possibility of hydrolysis, combustion, or other chemical processes in addition to the actual pyrolysis. In other cases, such as when burning firewood, making charcoal the old-fashioned way, or steam cracking crude oil, those chemicals are introduced on purpose.

Many common organic compounds decompose between 100 and 500 °C [81]. Sugars degrade at temperatures between 160 and 180°C, while cellulose, found in wood, paper, and cotton, breaks down at approximately 350°C [82,83]. Another important component of wood, lignin, begins to decompose at 350 °C and can continue to release volatile compounds until 500 °C [84,85]. Water, carbon monoxide (CO), carbon dioxide (CO_2) and a variety of organic compounds are typically among the breakdown products [85]. Combination of pyrolysis and algae biomass cultivation is feasible, where the CO2 produced during pyrolysis can be captured and used to cultivate algae, which in turn can be processed into biofuels or used for biogas production through anaerobic digestion. This reduces greenhouse gas emissions while providing an additional source of biomass [81].

4.2.3. Gasification

The process of gasification involves the transformation of carbon-rich materials sourced from biomass or fossil fuels into gaseous products, consisting of nitrogen (N2), carbon monoxide (CO), hydrogen (H2), and carbon dioxide (CO_2) [86,87]. To accomplish this, the feedstock material undergoes a reaction at high temperatures typically exceeding 700 °C without burning, by regulating the level of oxygen and/or steam present in the reaction [88,89,90]. As the gas is mostly made of hydrogen (H2) and carbon monoxide (CO) which are flammable, the resulting gas mixture is known as syngas or producer gas, and it can be used as fuel on its own [91]. The process of gasification, which produces power when the resulting gas is burned, is referred to as a renewable energy source provided that the feedstock utilized to create the gasified compounds was biomass [86,87,90]. Gasification has been applied in combination with fermentation. Syngas, a mixture of hydrogen, carbon monoxide, and methane produced by gasifying agricultural waste, can be fed into a fermentation process that uses particular microbes to turn the syngas into ethanol or other liquid biofuels. This process makes it possible to turn a variety of biological waste materials into liquid fuels [86,90].

4.3. Emerging and Innovative Technologies

4.3.1. Hydrothermal Liquefaction

A possible technique for turning wet biomass into bio-crude that resembles the natural production of fossil fuels but happens considerably more quickly is hydrothermal liquefaction (HTL). HTL operates under subcritical or supercritical conditions in a water-rich environment, in contrast to traditional thermal processes like pyrolysis. The procedure usually entails heating wet biomass at pressures between 4 and 22 MPa and temperatures between 250 and 374 degrees Celsius while it is wet. These circumstances make it easier for the biomass's complex organic molecules to break down into smaller, more energy-dense compounds, which is how bio-crude is formed [92].

The capacity of HTL to process high-moisture feedstocks without the need for previous drying, which is energy-expensive, is one of its main advantages. Because of this, a variety of wet biomasses, including algae, sewage sludge, and agricultural leftovers, are especially well-suited for conversion via HTL [93]. High-pressure water serves as a medium for several reactions, including hydrolysis and depolymerization, which generate bio-crude, gases, solid and aqueous byproducts. With typical refining procedures, the bio-crude produced through hydrothermal liquefaction can be enhanced to yield transportation fuels including gasoline, diesel, and jet fuel. It has a similar composition to that of petroleum crude oil [94]. In addition, the gaseous phase—which is predominantly made up of carbon dioxide, methane, and hydrogen—may be used for energy recovery, while the aqueous phase contains important nutrients that can be recycled [92,93].

For biomass valorization, HTL provides a sustainable path with a negligible environmental impact. Its ability to convert a variety of wet biomass feedstocks into high-energy-density bio-crude makes this technology desirable for the production of sustainable energy, contributing to a decrease in dependence on fossil fuels and the emission of greenhouse gases [94].

4.3.2. Algal Bioenergy Production

Using agricultural wastewater to grow algae offers a sustainable way to produce biofuel while resolving environmental issues related to wastewater treatment. Nutrients like phosphorus and nitrogen, which are necessary for algae growth, are abundant in agricultural effluent. By using this wastewater, extra nutrients that would otherwise contribute to eutrophication and water pollution in natural water bodies are lessened for the environment, while also offering a cost-effective supply of nutrients [95].

Through photosynthesis, algae can effectively absorb these nutrients from the wastewater and transform them into biomass. Following processing, this biomass has the potential to be transformed into various types of biofuels, such as biodiesel, bioethanol, and biogas [96]. Algal farming combined with agricultural wastewater treatment can improve water quality before release or irrigation by means of bioremediation.

This technique still needs to be optimized for large-scale production. Important research topics include the algal strains selection with high fatty content, the variety in wastewater composition, and economical algal biomass collection and processing [97]. However, the combined advantages of producing renewable energy and treating wastewater make this a desirable path for the development of sustainable biofuels [96].

5. ENVIRONMENTAL IMPACTS OF AGRICULTURAL WASTE-TO-BIOENERGY CONVERSION

5.1 Positive Environmental Impacts

5.1.1 Reduction of Greenhouse Gas Emissions

One of the most significant advantages of converting agricultural waste into bioenergy is the reduction of greenhouse gas emissions. When these wastes are burned outdoors or allowed to break down naturally, they can emit gases into the environment, including methane (CH_4) and carbon dioxide (CO_2) [98,99]. Both are strong greenhouse gases and have a major role in climate change and global warming.

Technologies like anaerobic digestion, gasification, or combustion, which provide a controlled environment to harness energy while limiting harmful emissions, are frequently used in the production of bioenergy, notably biofuels generated from agricultural waste. For example, methane emissions are captured during anaerobic digestion, and this degrades organic waste in the absence of oxygen and generates biogas that can be used for heating, electricity or transportation fuel [100].

By using this procedure, [101,102] reported that methane which would have otherwise leaked into the atmosphere via landfills or open burning of garbage is prevented. Moreover, because bioenergy is regarded as carbon-neutral, a closed carbon cycle is established when the CO_2 emissions from burning it are offset by the CO_2 that plants absorb through their growth. Additionally, the use of bioenergy lessens reliance on fossil fuels, which account for around 75% of greenhouse gas emissions worldwide [99,101,102]. In comparison to traditional fossil fuels, bioenergy can cut greenhouse gas emissions by up to 90%. Thus, turning agricultural waste into bioenergy is essential to reducing global warming and helping nations fulfill their obligations to cut their carbon emissions under frameworks like the Paris Agreement [98].

5.1.2 Mitigation of Agricultural Waste Disposal Problems

Agricultural activities produce vast amounts of waste, including crop residues (e.g., straw, husks) and animal manure, estimated globally at 5 billion tons annually [103]. If not managed properly, these wastes can lead to significant environmental problems, such as contamination of air and water resources. Open burning of residues releases harmful pollutants such as particulate matter, carbon monoxide, and volatile organic compounds, which exacerbate air pollution and can lead to respiratory issues. Additionally, landfilling organic waste leads to the formation of leachate, which contaminates groundwater[104].

Converting agricultural waste into bioenergy addresses these challenges by using waste as feedstock for energy production, thereby reducing pollution. [105] reported that bioenergy reduces waste volume by up to 90%, minimizing its environmental footprint. Decentralized bioenergy systems, especially in rural areas, provide a sustainable alternative to traditional waste disposal methods. By setting up local facilities, agricultural residues can be continuously recycled into energy, reducing the need for harmful disposal practices and creating a circular, sustainable waste management system [103,104].

5.1.3 Improvement of Soil Health Through Biochar Application

Biochar is a byproduct of pyrolysis used to produce bioenergy and has several advantages for the sustainability of the environment and soil health. It is created by thermal decomposition of organic material in an oxygen-free environment, improving the composition of soil structure, increasing its ability to retain nutrients, and water-holding capacity. In the presence of degraded soils, biochar has been reported to increase crop yields by up to 30% [106], facilitating plant development by its porous nature, which traps moisture and nutrients.

Additionally, biochar raises soil organic carbon, bringing fertility back to areas that have lost nutrients and been degraded. According to [107], biochar may trap carbon for hundreds to thousands of years, capturing 1-3 gigatons of CO_2 yearly and assisting in the mitigation of climate change. Furthermore, biochar limits pollution from agricultural runoff and promotes sustainable farming methods by lowering nutrient leaching into groundwater.

5.2 Adverse Environmental Impacts

5.2.1 Air pollution from combustion processes.

Air pollution from the combustion of biomass is one of the major environmental concerns connected to the conversion of agricultural waste into bioenergy. In long-term carbon cycles, bioenergy is thought to be carbon-neutral; nevertheless, burning biomass can emit a considerable quantities of air pollutants, including sulfur dioxide (SO□), particulate matter (PM), nitrogen oxides (NO_x), and volatile organic compounds (VOCs) [108,109]. The neighboring populations' respiratory health problems, acid rain, and poor air quality are all caused by these pollutants.

[110] reported that depending on the feedstock and combustion method employed, burning biomass can release particulate matter up to amounts that are on par with or even greater than those from burning conventional fossil fuels. Specifically, it is recognized that agricultural waste products like straw and husks can generate significant levels of fine particulate matter (PM2.5) when burned inefficiently, posing considerable dangers to both human health and the environment. These emissions have the potential to worsen the regional air quality in rural areas, as bioenergy plants are frequently situated close to agricultural sources. Moreover, inefficient combustion of agricultural waste can result in the potent greenhouse gasses carbon monoxide (CO) and methane (CH3) being released. Even with the development of more effective combustion systems and emissions control mechanisms, biomass energy plants continue to be a source of air pollution despite technological breakthroughs [109,111]. As an illustration of the continued difficulties with air quality, a 2022 assessment found that even the most advanced biomass power facilities in Europe released 10–20% more PM2.5 than natural gas power plants[109,110].

5.2.2 Potential water contamination from leachate and runoff

Leachate, a liquid byproduct of organic waste breakdown during anaerobic digestion or storage, can be produced during the production of bioenergy. When leachate is not controlled, it can seep into the soil and contaminate both surface and groundwater [112]. It can also carry organic contaminants, heavy metals, and minerals like phosphorus and nitrogen. When agricultural waste is converted to bioenergy, one major environmental risk is water contamination. Aquatic habitats may be harmed by eutrophication, which is caused by algae blooms that reduce oxygen levels. [113] reported that nutrient-rich leachate from bioenergy plants is a major cause of North American algal blooms.

Furthermore, the growth of bioenergy feedstocks, mainly switch grass and maize, can produce runoff that contaminates surrounding waterways with fertilizers and pesticides. Water contamination from bioenergy is still a serious problem despite regulatory measures, particularly in locations where the sector is expanding rapidly [104],[114].

5.2.3 Land use and biodiversity considerations

The growth in the generation of bioenergy from agricultural waste has significant implications on biodiversity and land use. While using agricultural wastes reduces the strain on resources, increased demand for bioenergy feedstocks, such as energy crops, frequently results in habitat degradation and land change [115]. Large-scale bioenergy projects need specialized land, which means they must replace natural ecosystems and agricultural areas that are often utilized to produce food. The International Union for Conservation of Nature (IUCN) reported in 2022 that the biodiversity in Europe is declining as a result of wetlands and grasslands being converted into monoculture energy crop plantations, which only marginally support wildlife [116].

Additionally, there is growing rivalry for land between the production of food and bioenergy. Growing concerns regarding the loss of arable land for food arise as the demand for bioenergy rises, especially in areas where there is food insecurity. According to [117], the World Resources Institute revealed that 12% of global arable land could be diverted for bioenergy feedstocks by 2030, exacerbating food shortages and raising food prices.

Greenhouse gas emissions can also be attributed to land-use changes related to bioenergy. The benefits of bioenergy for the environment are offset by deforestation and the deterioration of ecosystems rich in carbon, which releases stored carbon. While crop rotation and agroforestry can lessen some negative effects, continuous bioenergy expansion runs the danger of causing more environmental degradation if not accompanied by effective, sustainable land-use planning and initiatives for biodiversity protection [115,118].

5.3 Impacts Comparison of Conversion Processes for Bioenergy Production

Thermochemical and biochemical approaches for turning agricultural waste into bioenergy influence the environment that is different from the other. Biochemical conversion methods, such as fermentation and anaerobic digestion, strongly rely on microbial action to degrade organic material. For instance, agricultural wastes are converted into bioenergy in Germany, one of the leading countries in the generation of biogas with over 9,000 plants. This biochemical method lowers emissions of nitrogen oxides (NOx) and particulate matter (PM) in comparison to fossil fuels [119]. However, methane leakage remains a critical concern. According to a study by [120], biogas facilities may lose 3-5% of their methane, negating the climatic advantages they might otherwise provide. Additionally, anaerobic digestion generates nutrient-rich effluents that need a lot of water, which might pollute water in places like rural China where small-scale biogas facilities don't have access to adequate wastewater treatment [119,120].

Conversely, thermochemical processes use high temperatures to decompose biomass through chemical reactions. For example, in the United States, gasification is frequently used to turn agricultural residues like corn stover into syngas for electricity; a 2022 Midwest case study found that while gasification emits fewer greenhouse gases (GHGs) than coal, it produces more sulfur dioxide (SO□) and particulate matter (PM2.5). In Brazil, large-scale combustion of sugarcane bagasse for energy is efficient, but it produces high emissions of PM and NOx, which adversely affect air quality [121,122].

In Kenya, agricultural waste is converted by pyrolysis into biochar and bio-oil. The carbon sequestered by the biochar improves soil fertility [123]. However, pyrolysis has faced criticism for potentially harming the environment due to emission of carbon monoxide (CO) and volatile organic compounds (VOCs). Thermochemical processes are more effective and adaptable than biological ones, although producing greater pollutants. Though they produce beneficial byproducts like organic fertilizers and emit less emissions, biochemical processes like anaerobic digestion are ultimately environmentally favorable [124]. Strict water management regulations and enhanced methane capture technology are needed to propel anaerobic digestion approach forward. Scaling up such innovations, particularly in regions focused on air quality and sustainability, can help expand the adoption of anaerobic digestion as a cleaner energy solution worldwide [124,125].

6. CONCLUSION

The transformation of agricultural waste into bioenergy presents a promising solution to address critical global challenges, including climate change, waste management, and energy security. This review has examined the sources of agricultural waste, the diverse technologies available for converting waste into energy, and their associated environmental impacts. Importantly, the choice of bioprocess methods for hydrolysis depends on several factors, including the substrate being processed, environmental conditions, and the desired end product. Biological approaches for saccharification, such as enzymatic hydrolysis and microbial fermentation, represent the eco-friendliest methods for this conversion and should be promoted for their environmental benefits. These biological methods, by reducing the need for harsh chemicals and extreme temperatures, contribute to a more sustainable approach to bioenergy production. Promoting these techniques can play a crucial role in developing greener energy solutions for a sustainable future. Although substantial progress has been made in this field, there remains considerable potential to further optimize bioenergy production processes, improve economic viability, and reduce negative externalities.

CONSENT

Not applicable

ETHICAL APPROVAL

Not applicable

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Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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ABBREVIATIONS

HTL - Hydrothermal Liquefaction
CHP - Combined Heat and Power