SUSTAINABLE BIOFUEL PRODUCTION FROM AGRICULTURAL AND FOOD WASTE: A COMPREHENSIVE REVIEW

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Abstract

Agricultural and food wastes are highly potential sources of renewable biomass feedstock for the production of sustainable biofuels, while at the same time helping solve problems associated with waste management and environmental pollution. This paper reviews the main types and properties of agricultural and food waste and analyzes biochemical, thermochemical, physicochemical, and integrated processes of conversion of these wastes into biogas, bioethanol, biodiesel, bio-oil, and syngas. The attention is paid to the anaerobic digestion, fermentation, pyrolysis, gasification, and transesterification methods and the significance of the pretreatment and characterization of biomass. The environmental, economic, and sustainability factors of waste-based biofuels are discussed, including greenhouse gases emissions reduction, resource recovery, circular economy principles, costs of production, and life-cycle assessment. However, despite the significant potential of such biofuels, there are many challenges connected with biomass collection and heterogeneous composition, its transportation, pretreatment, conversion yield, scaling, and commercialization. Integrated biorefinery and smart technologies are perspectives in this context. The sustainable conversion of agricultural and food waste to biofuels can be an important solution for renewable energy production, decrease in fossil fuel consumption, improvement in waste management, and circular bioeconomy.

Keywords: *Agricultural waste; Food waste; Biofuels; Biomass conversion; Anaerobic digestion; Bioethanol; Biodiesel; Pyrolysis; Gasification; Circular bioeconomy; Sustainability*

1. INTRODUCTION

The growing demand for energy and the negative consequences caused by the consumption of fossil fuels are reasons why there is an ever-growing need to find renewable energy sources which would not harm our planet. Biofuels based on renewable biological resources seem to be good alternatives for fossil fuels and especially when talking about electricity is not a convenient option. Meanwhile, agriculture and food industry are generating huge amounts of organic waste that can be transformed into energy resources.

Residues left after cultivation of agricultural crops, like straw, husk, stalk, shell, bagasse and even animal manure, as well as various food wastes including fruits and vegetables, food-processing residues, used cooking oils, and many other organic materials can be converted through biochemical, thermochemical, and integrated methods into renewable energy [1]. Utilization of such biomass as feedstock will also decrease the amount of waste and dependence on fossil fuel [2].

The advantage of using waste materials as the source of energy, compared to energy crops, is that it can help to avoid the competition of agricultural land and its products (food) [3]. Furthermore, it will provide opportunities to develop the idea of resource recovery and to develop a circular economy. For instance, through anaerobic digestion process it is possible to obtain biogas and nutrient-rich residue, and thus recover energy and material resources from waste [4].

However, the conversion of agricultural and food waste into biofuels poses many problems including the variability of feedstock, its high moisture content, seasonality, requirement of transportation, pretreatment of raw materials, and conversion rate of biomass into fuel. Moreover, some processes require much energy to dry the material [5]. Therefore, the sustainability of waste-derived biofuels must be assessed at all stages of the process.

The present review was undertaken with the following objectives:

- To examine the major types and characteristics of agricultural and food waste that can be utilized as feedstocks for biofuel production.
- To review the major biochemical, thermochemical, and physicochemical technologies used to convert agricultural and food waste into biofuels.
- To evaluate the environmental, economic, and sustainability implications of waste-derived biofuel production.

- To identify the major technological challenges and future opportunities for large-scale and sustainable utilization of agricultural and food waste for biofuel production.

2. AGRICULTURAL AND FOOD WASTE AS FEEDSTOCKS FOR BIOFUEL PRODUCTION

Feedstocks for biofuel generation from agricultural and food wastes vary in their characteristics and hence suitability for use as biofuels due to their physical and chemical nature. Agricultural wastes might arise from crops themselves, as well as from further agricultural processing of such crops [6]. The most common examples include rice husks, wheat straw, corn stalks, sugarcane bagasse, cotton residues, fruit peels, nut shells, and manure. Food waste is a product of households, restaurants, markets, food-processing facilities, and other links in the food supply chain. According to recent literature review, the classification of agricultural wastes might include crop residues, animal wastes, processing waste, and others [7].

The chemical composition is one of the key factors in selection of an appropriate technology of feedstock conversion [8]. The main constituents of lignocellulosic agricultural residues are cellulose, hemicellulose, and lignin. Carbohydrate fractions obtained through hydrolysis and fermentation can be converted to bioethanol and other substances. At the same time, lignin can be a part of thermochemical conversion [9]. Food waste contains higher percentage of easily biodegradable carbohydrates, proteins, and lipids and thus is very suitable for anaerobic digestion and fermentation. Waste oil and fat are ideal for biodiesel production.

Moisture content is yet another factor to consider. Food waste usually has a high content of water, which is favorable for biological conversion, but not for thermochemical technology because it requires much energy for drying. The heterogeneity of food waste creates certain difficulties in process control because variations in carbohydrate, protein, lipid, mineral, and moisture contents can influence microbial activity and gas generation.

Pretreatment becomes necessary when lignocellulosic residues are used as a source of biomass because of structural association between cellulose, hemicellulose, and lignin that limits their enzymatic or biological conversion. Pretreatment includes mechanical, chemical, physicochemical, and biological approaches to increase accessibility and improve conversion rate. Nevertheless, it increases energy, chemical, capital, and environmental demands and should be adjusted according to the feedstock and desired fuel.

Table 1. Major Agricultural and Food-Waste Feedstocks and Their Potential Conversion Routes

Waste/feedstock	Major useful components	Suitable conversion route	Potential biofuel
Rice husk and straw	Cellulose, hemicellulose, lignin	Pretreatment + fermentation; pyrolysis; gasification	Bioethanol, bio-oil, syngas
Wheat straw	Cellulose, hemicellulose, lignin	Pretreatment + fermentation; thermochemical conversion	Bioethanol, bio-oil, syngas
Sugarcane bagasse	Cellulose, hemicellulose, lignin	Fermentation; pyrolysis; gasification	Bioethanol, bio-oil, syngas
Corn residues	Cellulose, hemicellulose, lignin	Pretreatment + fermentation; gasification	Bioethanol, syngas
Fruit and vegetable waste	Easily degradable carbohydrates, moisture	Anaerobic digestion; fermentation	Biogas, biomethane, bioethanol
Food-processing residues	Carbohydrates, proteins, organic matter	Anaerobic digestion; fermentation	Biogas, bioethanol
Used cooking oil	Lipids/triglycerides	Transesterification	Biodiesel
Animal manure	Organic matter, biodegradable nutrients	Anaerobic digestion	Biogas/biomethane
Agricultural processing residues	Variable carbohydrates and lignocellulosic fractions	Biochemical or thermochemical conversion	Bioethanol, biogas, bio-oil, syngas

Feedstock suitability should thus be judged on the basis of its composition, availability, moisture level, geographic location, collection needs, and distance to processing facilities. An evaluation of agricultural waste biofuels has found that the same four criteria influence future development.

3. TECHNOLOGIES FOR BIOFUEL PRODUCTION FROM AGRICULTURAL AND FOOD WASTE

There are several routes through which waste from agriculture and food processing industries can be converted into fuel [10]. Some of the methods that can be used include biochemical, thermochemical, and physicochemical methods. The choice of technology is determined by factors such as the nature of the waste, intended fuel, and prevailing conditions [11].

3.1 Biochemical Conversion

The biochemical method employs microorganisms for converting the biodegradable constituents of agricultural/food waste into valuable biofuels [12]. Of the different methods employed, anaerobic digestion is widely practiced for generating biogas, whereas fermentation is mostly adopted for carbohydrate-containing organic waste materials to produce bioethanol [13]. The two processes provide a comparatively sustainable way of using organic waste; however, the effectiveness of these technologies relies on feedstock properties [14].

- **Anaerobic Digestion:** Anaerobic digestion is a process which involves breaking down of degradable agricultural waste and food waste using microorganisms to produce biogas that consists of methane and carbon dioxide [15]. The process entails several steps including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The waste products include agricultural waste, animal dung, and food processing waste. Co-digestion may improve process efficiency and balance of nutrients. Methane production is affected by several factors including pH, temperature, feedstock composition, retention time, organic loading rate, and carbon to nitrogen ratio [16].
- **Fermentation and Bioethanol Production:** Bio-fermentation is an appropriate process in terms of carbohydrate abundance, which would yield bioethanol once the fermentable sugars have been released from carbohydrates [17]. Lignocellulosic material needs some pretreatment to enable the sugars in cellulose and hemicellulose to become available to the microorganism. Microbes like Saccharomyces cerevisiae would ferment the released sugars into ethanol. However, there is an obstacle associated with the lignocellulosic material itself, while more effective enzymes would boost ethanol formation.

3.2 Thermochemical Conversion

Thermochemical conversion refers to the use of heat to convert agricultural and food wastes into energy products [18]. This is especially applicable for dry and lignocellulosic wastes and includes processes like pyrolysis and gasification. These processes are capable of producing energy products like bio-oil, bio-char, syngas, among others but whose effectiveness will depend on operating parameters and properties of the feedstocks [19].

- **Pyrolysis:** In pyrolysis, decomposition of biomass occurs in the absence or limited presence of oxygen to obtain bio-oil, bio-char, and gases that do not condense. Agricultural wastes such as straw, husk, shells, and bagasse can be used by this method. Bio-oil obtained can be upgraded for usage in fuels while bio-char and gases can offer extra value. High levels of oxygen content, acidity, and instability in bio-oil may restrict its usage.
- **Gasification:** In gasification, biomass is converted into syngas containing hydrogen, carbon monoxide, methane, and carbon dioxide, with use of controlled amounts of oxygen, air, or steam. Agricultural waste is appropriate for gasification due to its lignocellulosic nature. Ash generation, formation of tar, moisture, reactors' needs, and gas purification continue to pose challenges for this process.

3.3 Physicochemical Conversion

- **Biodiesel Production:** The production of biodiesel is possible using waste cooking oil and fats through transesterification process, where the triglycerides are transformed to biodiesel. The use of this process offers a practical way of making use of the waste oil without competing for edible oil. But too many free fatty acids and water in the oil may necessitate pretreatment process.

3.4 Integrated Conversion Technologies

An integrated approach of converting agricultural and food waste involves the use of more than one technology to enhance the efficiency of using such waste. This can be achieved through a technology known as anaerobic digestion that is used to extract energy from biodegradable wastes, followed by pyrolysis of the remaining lignocellulosic components.

Table 1. Summary of Selected Literature on Biofuel Production from Agricultural and Food Waste

Author(s) & Year	Title of Study	Topic Covered
Dahiya et al. (2018) [20]	Food Waste Biorefinery: Sustainable Strategy for Circular Bioeconomy	Food waste conversion into biofuels and value-added products, with emphasis on resource recovery and the circular bioeconomy.
Awogbemi & Von Kallon (2022) [21]	Valorization of Agricultural Wastes for Biofuel Applications	Utilization and valorization of agricultural wastes as feedstocks for sustainable biofuel production.
Mekunye (2024) [22]	Production of Biofuels from Agricultural Waste	Biofuel production from agricultural waste and the potential of agricultural residues as renewable energy feedstocks.
Karmee (2016) [23]	Liquid Biofuels from Food Waste: Current Trends, Prospect and Limitation	Liquid biofuel production from food waste, including current technologies, prospects, and limitations.
Pattanaik et al. (2019) [24]	Biofuels from Agricultural Wastes	Biofuel production from agricultural wastes with emphasis on second- and third-generation feedstocks and renewable fuel production.

4. SUSTAINABILITY, ENVIRONMENTAL AND ECONOMIC PERSPECTIVES

Biofuel produced from waste materials can be sustainable depending on the entire process from feedstock gathering up to its usage as fuel. Life-cycle assessment is one of the most useful ways to evaluate the effectiveness of various biofuels [25,26].

- **Environmental Benefits:** Agricultural and food-waste-derived biofuels can minimize the amount of waste accumulation, open burning, and dependency on fossil fuels. Furthermore, they may minimize the pressure on land resources and the conflict between food and feed production that exists for some conventional biofuels. Nevertheless, emissions related to transportation, drying, and intensive processing operations make localized biofuel production more advantageous.
- **Circular Economy and Resource Recovery:** Waste-based biofuel systems can help to implement a circular economy concept due to energy, carbon and nutrients recovery from waste resources. Anaerobic digestion provides biogas and digestate, while pyrolysis provides bio-oil, biochar and gases [27,28]. This multiple product output increases the efficiency of resource recovery and value of agriculture and food waste.
- **Economic Considerations:** Economic sustainability of waste-to-biofuel conversion processes depends on the availability of feedstock, cost of its collection and transportation, pre-treatment, investments in production facility, energy needs and value of produced fuel. Decentralized plants, co-digestion, energy integration and biorefinery concepts can enhance economic performance by producing fuels alongside other value-added products.
- **Life-Cycle Assessment:** Life-cycle assessment assesses the sustainability of biofuels through estimation of greenhouse gas emissions, energy needs, water use, land use, acidification, eutrophication and resource depletion. Thus, waste-derived biofuels should be assessed throughout the entire production chain and not be considered as sustainable only based on their waste feedstock classification.

5. CHALLENGES, RECENT ADVANCES AND FUTURE PERSPECTIVES

Although there is a lot of potential that agricultural and food waste can offer in terms of making biofuels, there are some hurdles that make it difficult to implement on a larger scale [29,30].

- **Food waste logistics and feedstock availability:** Agricultural waste is usually dispersed in large regions and might be available only seasonally. Therefore, collection, storage, transportation, and preprocessing can increase the cost of production. The development of regional collection networks and decentralised processing plants can help minimize transportation needs.
- **Food waste heterogeneity:** There is significant variability in the moisture, carbohydrate, lipid, ash, contamination, and biodegradable content of food and agricultural waste. This variability can impact both process performance and fuel quality. The better feedstock characterization, sorting, and blending procedures should be developed for consistent biofuels production.

- **Pretreatment and conversion efficiency:** The pretreatment of lignocellulosic feedstocks is essential to increase the accessibility of cellulose and hemicellulose. But the use of traditional pretreatment techniques can result in higher energy consumption or undesirable substances formation. It is necessary to develop efficient low-energy and environment-friendly pretreatment.
- **Scale-up and commercialisation:** While there are a lot of promising technologies of waste to biofuels production developed on laboratory and pilot scales, there are still some challenges in their implementation at an industrial scale. Large-scale production needs the reliable feedstock delivery, optimisation of processes, adequate infrastructure, and techno-economic evaluation. The long-term pilot and demonstration projects can ensure their successful commercialisation.
- **Emerging technologies:** Recent developments in this field become more focused on the use of integrated conversion approaches combining biochemical and thermochemical conversion. Also, artificial intelligence, machine learning, and IoT technologies can play an important role in the development of such systems. Future technologies should pay attention to integrated biorefinery systems allowing for biofuels and additional product production such as chemicals, biochar, and fertilisers.
- **Policies and institutions:** The technological development is not enough for the large-scale commercialisation of the technology. The supportive policy, incentives, waste collection infrastructure, sustainable criteria, and proper regulatory framework are needed. The effective policies should encourage the use of agricultural and food waste in an environmentally responsible manner.

5. CONCLUSION

Agricultural and food waste are considered very good renewable sources for the sustainable production of biofuels and may provide a viable solution to the dual problems of energy as well as waste management. It can be seen from the review that different kinds of wastes may be efficiently converted using biochemical, thermochemical, physicochemical, and integrated techniques of conversion into biogas, bioethanol, biodiesel, bio-oil, and syngas. This can help reduce fossil fuel dependency, decrease waste accumulation, allow for resource recovery, and contribute to the emergence of a circular bioeconomy. However, problems associated with the availability and heterogeneity of feedstocks, transportation, pretreatment, low efficiency of the conversion process, economic viability, and commercialization on a larger scale remain a limiting factor. The future advancement is expected to be driven by more efficient pretreatment techniques, biorefinery systems, better process optimization, smart technologies, policy, and overall lifecycle and economic assessment. In conclusion, the sustainable use of agricultural and food waste can contribute significantly to the development of renewable energy if used correctly throughout the entire chain.

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