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Exploring Food Waste Potential for Bioethanol Production in Sustainable Energy and Emission Reduction

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Abstract

The increasing global reliance on fossil fuels, coupled with the rapid growth of the global population, has exacerbated climate change, energy insecurity, and socio-economic instability. Fossil fuels dominate the current global energy mix, significantly contributing to greenhouse gas emissions, particularly CO_2, which accelerates global warming. Additionally, the mismanagement of municipal solid waste, especially food waste, is a major environmental issue, contributing nearly 10% of global greenhouse gas emissions. Innovative solutions to mitigate waste and improve resource efficiency are urgently required. Biofuels, particularly bioethanol, produced from food waste, offer a promising alternative to fossil fuels. Bioethanol production from agricultural by-products and food waste, such as pineapple peel, apple pomace, and food waste, can reduce greenhouse gas emissions and promote sustainable energy. Anaerobic digestion and fermentation technologies convert organic waste into biogas and bioethanol, thus addressing both energy production and waste management challenges. Moreover, bioethanol blends, particularly E10 and E85, demonstrate significant reductions in harmful emissions, including nitrogen oxides (NO_x), particulate matter, and hydrocarbons. However, challenges remain, including the efficient use of feedstocks, pre-treatment processes, and the environmental impact of by-products like vinasse. The development of infrastructure to support higher ethanol blends, especially in regions where flexible-fuel vehicles (FFVs) are not widely available, is another barrier to widespread adoption. Despite these challenges, bioethanol and biodiesel produced from waste materials offer a promising path toward sustainable energy, requiring continued research and development to overcome existing barriers and enhance production efficiency.

Keywords

Bioethanol, Food Waste, Sustainable Energy, Emissions Reduction, Biofuel Production

1. Introduction

Dependence on fossil fuels like coal and petroleum contributes to global climate change and increases costs and risks related to energy security, impacting socio-economic and political stability. Additionally, rising global population is driving higher energy demand. The global energy matrix is currently dominated by crude oil (31.6%), coal (26.7%), natural gas (23.5%), hydropower (6.7%), nuclear energy (4%), wind energy (3.3%), solar energy (2.1%), biofuels (0.7%), and other renewables (1.4%) [1]. The combustion of fossil fuels releases CO_2 and other greenhouse gases, contributing to the buildup of heat-trapping gases and global warming. Worldwide greenhouse gas emissions are composed of CO_2 (76%), CH_4 (16%), N_2O (6%), and fluorinated gases (2%) [2]. Exposure to common hazardous air pollutants, including NO_x, SO_x, CO, H_2S, NH_3, and volatile organic compounds (VOCs), is linked to chronic respiratory conditions and cancer. Photocatalysis, a key technology in these materials, can effectively decompose harmful pollutants like VOCs into harmless CO_2 and H_2O, making it ideal for removing low-concentration pollutants in indoor environments [3].

Bratovcic and Tomasic (2023) present key findings in photocatalytic CO_2 reduction, highlighting the importance of optimizing reaction parameters, including CO_2 adsorption and photocatalyst composition, to enhance product selectivity and reaction efficiency. The development of highly active and selective photocatalysts, along with optimized photoreactors, remains one of the central challenges in the photocatalytic reduction of CO_2 to valuable products such as methane and methanol. They explore various advanced photocatalytic materials, including metal oxides, Z-scheme composites, and carbon nitrides, while also discussing strategies for improving photocatalytic performance and the design of integrated systems for efficient solar-driven CO_2 reduction [4].

The UN Environment Programme (UNEP) report highlights that humanity produces between 2.1 billion and 2.3 billion tonnes of municipal solid waste annually [5]. This waste pollution poses a substantial risk to human health, economic stability, and exacerbates the triple planetary crisis, which includes climate change, biodiversity loss, and pollution. If immediate measures are not taken, the annual generation of municipal solid waste is projected to reach 3.8 billion tonnes by 2050. According to the UNEP report, households are responsible for the majority of global food waste, accounting for 631 million tonnes, or approximately 60 percent, of the total food discarded. The food service and retail sectors contribute 290 million tonnes and 131 million tonnes, respectively. On average, each individual wastes 79 kilograms of food per year, which the report authors emphasize is equivalent to 1.3 meals per day for every person affected by hunger worldwide. One fifth of food is thrown away [6]. Improper management of food waste, caused by insufficient treatment methods, negatively affects the environment. Food waste also has a significant environmental impact, serving as a major source of potent greenhouse gas (GHG) emissions and the depletion of natural resources. Consequently, minimizing food waste and promoting proper food storage can play a crucial role in lowering global GHG emissions, enhancing food security, and fostering healthier food systems.

The term "wasted food", as used by the US EPA, emphasizes the potential value that can be recovered through alternative uses, in contrast to the more commonly used term "food waste". "Food loss" refers to agricultural, forestry, and fishery products that are uneaten, typically occurring during the production and distribution stages. It results from either a decrease in the quantity or quality of food. In contrast, "food waste" pertains to edible food intended for human consumption that is discarded or expires, often during preparation, sales, or food service. This includes plate waste, spoiled food, and discarded peels and rinds. The term "food loss and waste" encompasses both types of inefficiencies involving unused food within the food system.

Food loss and waste occur at every stage of the global food value chain, including production, postharvest handling, storage, processing, distribution, and consumption. In many developing countries, early harvesting practices contribute to higher food waste. According to the FAO (2011) [7], 42% of fruits and vegetables and up to 30% of grains produced in Asia and the Pacific are wasted or lost before reaching consumers. Food loss and waste (FLW) is a growing environmental and societal issue, but also presents opportunities for conversion into energy, chemicals, and bio-based materials. Food loss occurs in primary and industrial sectors (e.g., farms, fish farms, factories), while food waste arises from retailers and consumers. This not only results in FLW but also wastes the energy and resources used in food production. Despite increased awareness and efforts to improve supply chain efficiency, over 1000 million tons of FLW are still generated annually due to preferences, safety concerns, and inefficiencies. Additionally, over 5000 million tons of plant biomass by-products (e.g., pomace, straw, peels) are produced yearly. First, second, and third-generation biorefineries can utilize such biomass, along with materials from forests, cattle, fish, and algae. These biorefineries use various treatments to produce a range of energy sources, chemicals, materials, and even food and feed products [8]. According to the FAO 2011, the term "food waste" refers to the loss of food at the final stages of the supply chain, along with the waste of resources such as labor, water, energy, and land, affecting both suppliers and consumers. Household food waste includes uncooked vegetables and other ingredients that are discarded. It can also stem from leftovers in commercial settings, such as restaurants and canteens. Food waste affects health, generates unpleasant odors, and attracts pests [9]. The continuous generation of waste and the migration of people from rural to urban areas have long-term impacts.

Experts predict that by 2050, 68% of the global population will live in cities, leaving only 30% of the population responsible for producing the large amounts of fruits, vegetables, animal products, and other essentials needed for both rural and urban communities [10]. In 2022, 1.05 billion tons of food were wasted, while 783 million people went hungry, and a third of the global population faced food insecurity. Food loss and waste contribute 8% - 10% of global greenhouse gas emissions—nearly five times the aviation sector's total emissions—and lead to significant biodiversity loss, using up nearly a third of agricultural land. Reducing food waste can lower emissions, improve resource efficiency, and increase food availability for those in need, thus enhancing food security. Incorporating food waste reduction into climate strategies will benefit both people and the planet in the long term [11].

2. Methods of Conversion of Food Waste

Biomass can be converted into biofuels through mechanical, thermochemical, and biological processes (**Figure 1**).

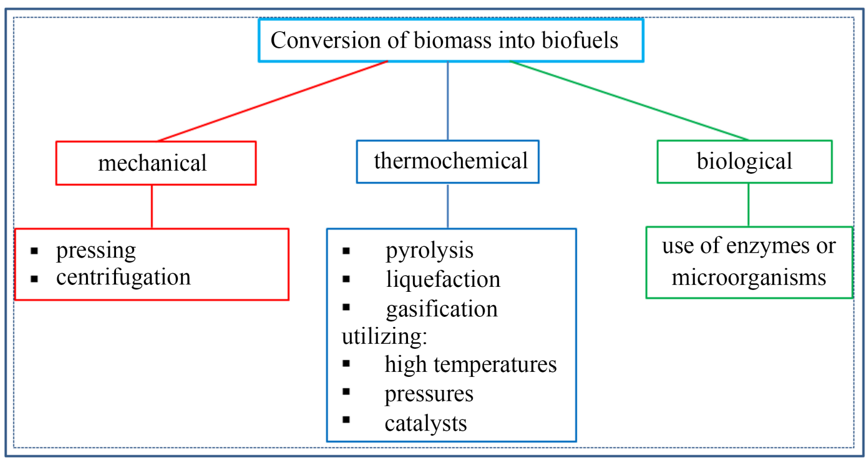

Figure 1. Schematic representation of various methods for converting biomass into biofuels.

Mechanical methods primarily involve techniques like pressing and centrifugation to extract bioactive compounds, including biofuels, from materials such as oilseed crops and algae. Thermochemical conversion includes processes like pyrolysis, liquefaction, and gasification, which use high temperatures, pressures, and catalysts to transform biomass into various forms of solid, liquid, and gaseous biofuels. Pyrolysis heats biomass in an oxygen-free environment to produce bio-oil and biochar, which can be further refined into transportation fuels. Gasification turns biomass into synthesis gas, which can be used to produce fuels such as hydrogen and synthetic liquids. Liquefaction involves the use of catalysts and solvents to break down organic compounds in biomass, yielding bio-crude oil with fuel properties similar to those of liquid transportation fuels. Biological conversion employs enzymes or microorganisms to decompose biomass components like cellulose and hemicellulose into simple sugars (pentoses and hexoses), which can be fermented to produce biofuels and other biochemical products, such as bioethanol, biobutanol, biohydrogen, biomethane, and organic acids like acetic, butyric, and lactic acids, through fermentation and anaerobic digestion [12].

2.1. Difference between Fermentation and Anaerobic Respiration

The primary difference between fermentation and anaerobic respiration lies in the cellular respiration mechanisms involved. Both processes occur in the absence of oxygen and utilize hexose sugars as the substrate, which is first broken down through glycolysis to generate ATP necessary for cell functions. The key distinction is that fermentation bypasses the citric acid cycle (Krebs cycle) and the electron transport chain, while anaerobic respiration proceeds through these pathways. Despite this difference, in practical terms, especially within the context of anaerobic digestion and the biogas industry, the distinction between the two is often not significant. Fermentation is a chemical process that anaerobically breaks down molecules such as glucose. Lactic acid fermentation, for example, is a form of fermentation that is commonly associated with processes like wine and beer production, which have been practiced for over 10,000 years.

Methane fermentation and anaerobic digestion are both processes used to produce biogas from organic waste under anaerobic conditions, but they differ in their chemical pathways and specific processes.

2.2. Methane Fermentation

Methane Fermentation is a specific type of anaerobic digestion that focuses primarily on the production of methane gas (CH_4) through the microbial breakdown of organic materials. The process involves various stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis. In methane fermentation, specialized microorganisms (methanogens) play a key role in converting intermediate products (such as acetic acid and hydrogen) into methane. This system is typically optimized for methane production and is used in applications like biogas plants.

Anaerobic digestion refers to the broader process by which organic materials are decomposed by microorganisms in the absence of oxygen, resulting in the production of biogas (a mixture of methane, carbon dioxide, and trace gases). Anaerobic digestion encompasses several steps, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, but it is not always solely focused on methane production. The primary goal of anaerobic digestion can be the stabilization of organic waste, reduction of pathogens, or nutrient recovery, alongside biogas production.

In summary, while both processes occur under anaerobic conditions and involve microbial breakdown of organic waste, methane fermentation specifically emphasizes the production of methane as the end product, whereas anaerobic digestion may have broader goals, including the stabilization and reduction of organic waste [13]. Fermentation and anaerobic respiration are both mechanisms of cellular respiration used to generate ATP for cellular activities, occurring in environments lacking oxygen (**Figure 2**). Both processes utilize hexose sugars as their substrate, which is initially broken down through glycolysis. The key distinction between fermentation and anaerobic respiration is that fermentation does not proceed through the citric acid cycle (Krebs cycle) or the electron transport chain, whereas anaerobic respiration includes both of these pathways.

Fermentation	**Anaerobic respiration**
Fermentation refers to any group of chemical reactions induced by microorganisms to convert sugars into carbon dioide and ethanol	Anaerobic respiration refers to a type of cellular respiration that occurs in the absence of oxygen
An extracellular proces	An intracellular process
Induced by low oxygen concentrations	Occurs in the absence of oxygen
Glycolysis does not follow citric acid and electron transport chain	Glycolysis follows citric acid and electron transport chain
Total ATP production is four	Total ATP production is thirty eight
Enzymes extracted from the fermenting cells can process the reaction in an extracellular medium	Enzymes extracted from the cells cannot process the anaerobic respiration in an extracellular medium

Figure 2. Comparison of the main differences between fermentation and anaerobic respiration.

Fermentation processes can be categorized into aerobic and anaerobic types. Aerobic fermentations typically proceed faster but demand higher energy for aeration, agitation, and cooling, which can complicate scaling up in bioreactors. Oxygen limitation is a significant issue in aerobic fermentations due to the low solubility of oxygen in water. In contrast, anaerobic fermentations generally require less energy but are much slower in comparison [14]. In this paper, the processes of conversion of fruit/vegetable to ethanol and conversion of waste oils to biodiesel as biofuel by chemical processes were studied (**Figure 3**).

Fleshy fruits are categorized into berries (e.g., tomatoes, bananas), pomes (e.g., apples, pears), drupes (e.g., peaches, plums), and hesperidia (e.g., oranges, lemons). When not discarded, their waste can be used as animal feed or compost for fertilizers. However, untreated fruit waste can lead to microbial contamination, pest growth, and greenhouse gas emissions (mainly CH_4 and CO_2). This waste is high in moisture and contains valuable nutrients, including carbohydrates, proteins, lipids, minerals, and bioactive compounds like polyphenols and flavonoids, which are useful for developing beneficial bioproducts [15]. Yet, much of this potential is underutilized, with waste often left to rot [16].

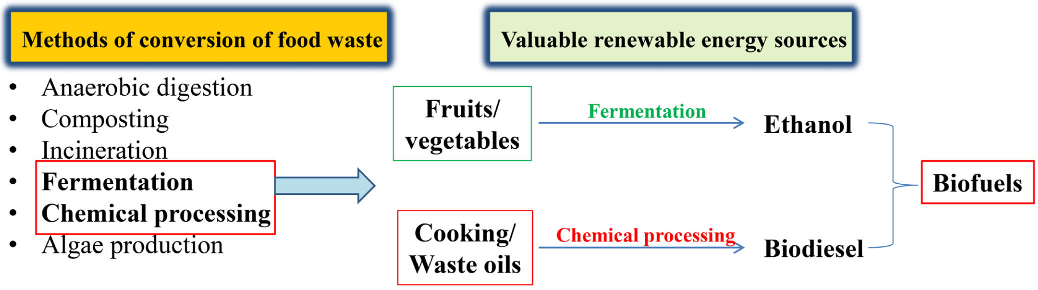

Figure 3. Methods of conversion of food waste into valuable renewable energy sources.

2.3. Anaerobic Digestion/Fermentation

Anaerobic digestion/fermentation is a process where microorganisms break down organic materials, like plant and animal products, in the absence of oxygen, producing biogas. This process recycles organic waste, generating biogas for energy and useful soil by-products (liquids and solids). Anaerobic digestion generates biogas, mainly composed of methane (CH_4) and carbon dioxide (CO_2), which can be used for cooking, heating, or electricity generation. Biogas is considered carbon neutral because its carbon was recently absorbed by plants through photosynthesis, unlike fossil fuels. Therefore, biogas offers a sustainable alternative to natural gas. Additionally, the remaining nutrients, such as nitrogen, phosphorus, and micronutrients, stay in the effluent, making it a valuable organic fertilizer and soil amendment [17]. Biogas production from organic waste through anaerobic digestion is a proven bioenergy technology. Efficient electron transfer between syntrophic bacteria and methanogens is essential for balancing acidogenesis and methanogenesis, ensuring stable operation of the digester [18].

Anaerobic fermentation occurs when oxygen is replaced with nitrogen, carbon dioxide, or other by-products, leading to slower processes. Louis Pasteur first demonstrated anaerobiosis in the 1850s by boiling the medium to expel oxygen and introducing inert gases, revealing that Clostridium butyricum was responsible for butyric acid fermentation. By the 1960s and 1970s, anaerobic chambers enabled the cultivation of strict anaerobes, including *C. botulinum*. During World War I, Perkins and Weizmann advanced industrial anaerobic fermentation, focusing on acetone-butanol-ethanol (ABE) with *C. acetobutylicum*. Anaerobes thrive under low-oxygen conditions due to unique enzymes, requiring minimal energy for cell suspension. This process is cost-effective, as agricultural waste can be used as substrates. Anaerobic fermentation is crucial for industrial applications such as ethanol production, food preservation, and waste treatment. However, studying mixed-culture processes is challenging due to instability, and obligate anaerobes require specialized conditions, making their genetic manipulation more complex than aerobic organisms [14].

Anaerobic fermentation is a complex metabolic process that converts food waste into biogas. It occurs in three stages: first, bacteria break down fats, proteins, and carbohydrates into simpler organic compounds like fatty acids, amino acids, and sugars; second, acidogenic bacteria convert these into shorter fatty acids, such as propionic and butyric acids; and third, hydrogen gas and acetic acid are produced. Finally, methane is formed from acetic acid and hydrogen with the help of methanogenic bacteria. Food waste, as an organic material, is well-suited for anaerobic fermentation [19].

2.4. Chemical Processing/Transesterification Reaction

The esterification reaction transforms triglycerides from oil into fatty acids, which are then reacted with methanol to produce methyl ester, a biodiesel product, through the esterification process [20]. **Figure 4** shows the environmental and economic benefits of food waste conversion.

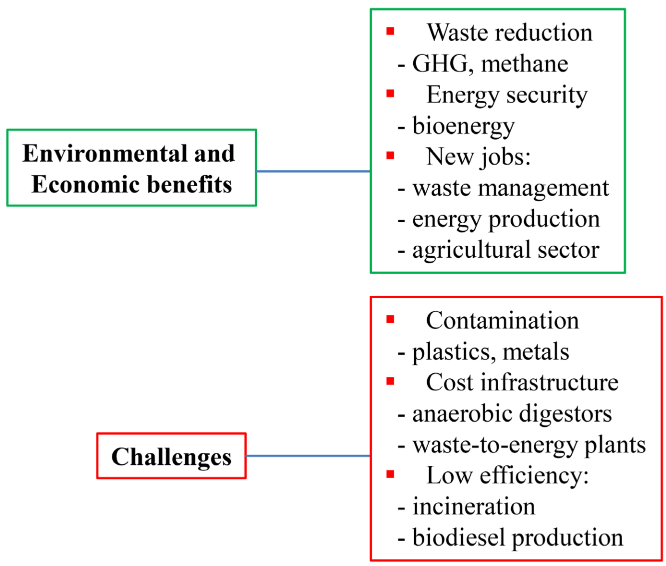

Figure 4. Environmental and economic benefits of food waste conversion.

The chemical industry is a major consumer of fossil fuels and emitter of greenhouse gases, highlighting the urgent need to transition to sustainable production through electrification and the use of renewable energy. This paper explores innovative methods such as recycling metal-rich waste and agricultural biomass for use in green catalytic processes aligned with circular economy principles. These recycled materials support a range of applications including hydrogen and biofuel production, pollution control, and the development of bio-based chemicals and polymers [21].

3. Biofuel Production from Food Wastes

Food wastes (FWs) offer several advantages for bioethanol production, including their abundance, low cost, and high sugar content. Utilizing FWs not only supports waste reduction and promotes sustainable practices but also provides a cost-effective and eco-friendly alternative to non-renewable fuel sources. FWs represent a promising, renewable resource for bioethanol production, contributing to both waste management and the renewable energy sector, despite challenges like seasonal availability and waste composition. Supplementing FWs with additional fermentable sugars, such as millet or sorghum flour, can enhance enzyme activity for sugar hydrolysis, boosting bioethanol yields. This process also reduces organic waste in landfills, mitigating environmental harm. As inexpensive byproducts of the food industry, FWs are a cost-effective raw material for bioethanol production, offering a reliable, sustainable supply for the agriculture and food processing sectors. The energy-efficient conversion of FWs, especially those with high fermentable sugar content, highlights their potential as a sustainable bioethanol source. Mgeni *et al.* (2024) [22] explores optimal FW-to-sugar ratios, evaluates various FWs, and examines the scalability of this process for commercial bioethanol production using natural enzymes.

3.1. Biofuels

Biofuels are categorized into first, second, third, and fourth generations based on the raw materials used. First-generation biofuels, produced from feedstocks like starch, sugar cane, animal fats, and vegetable oils, convert these materials into bioalcohol through FAME (Fatty Acid Methyl Esters) processes. However, there are concerns about the use of such food-based feedstocks. Second-generation biofuels, derived from lignocellulosic biomass, are gaining traction as they utilize nonfood feedstocks, although they face challenges such as high production and maintenance costs, as well as technical issues. In third and fourth generations, algae are utilized to convert lipids into biofuels. In the third generation, algae are directly used for biofuel production, while in the fourth generation, photosynthetic microorganisms are employed to generate carbon reservoirs. Biofuel production also relies on catalysts (chemical, magnetic, or enzymatic), with process parameters like pH, temperature, and pressure playing crucial roles in the conversion process [23]. Biofuels have increasingly come under scrutiny in recent years due to several concerns. For example, the energy output from certain biofuels, such as corn ethanol, is nearly equivalent to the energy input required for their production, and in some cases, there is a net energy deficit. Additionally, current biofuel production relies heavily on feedstocks that demand substantial resources, including land, water, and fertilizers. In some instances, biofuel cultivation has been linked to deforestation, particularly in rainforest regions. Furthermore, the "food versus fuel" debate has emerged, as the allocation of land for fuel production directly competes with food cultivation, leading to higher food prices and negatively impacting developing nations in a global economy. In contrast, biogas produced from waste materials does not present these challenges. Rather than utilizing land and crops for fuel production, biogas is derived from organic waste that would otherwise constitute a societal burden [24].

3.1.1. Bioethanol

Bioethanol is an alcohol produced through the fermentation of sugars and starches from crops like wheat, corn, and sugar beets. Bioethanol, known for its excellent chemical and physical properties, is extensively used as a fuel in the transportation and energy sectors. It is commonly blended with petrol as a fuel additive. Ethanol derived from biofuels is a renewable energy source that is sulfur-free and environmentally friendly [22]. The production of ethanol-based biofuels has grown significantly in the 21st century. Currently, the United States, Brazil, the European Union, China, and Canada are the leading countries and regions supporting the global use of bioethanol. Among these, the United States and Brazil have the largest biofuel ethanol industries [25]. A specific method for converting waste into energy is crucial for ethanol production from food waste. Various food wastes, such as banana peels, sugar beet pulp, pineapple waste, grape pomace, potato peels, citrus waste, and cafeteria and household food waste, can be used for bioethanol production [19]. Due to the complex lignocellulosic structure of food waste, several pretreatment methods, including alkali, acid, enzymatic, and thermal treatments, are applied to improve cellulose digestibility. Ethanol as a fuel has some challenges. Its low ignition temperature makes cold starting difficult, leading to incomplete combustion. Additionally, ethanol is corrosive to certain engine parts, requiring materials with adequate physical resistance. While engines could theoretically run on an 85:15 ethanol-to-gasoline blend, the practical limit without engine modifications is around 20% [26].

3.1.2. Biodiesel

Biodiesel, primarily composed of fatty acid methyl esters (FAMEs), is produced from various feedstocks, including oilseed rape, waste cooking oil, palm oil, vegetable oil, and animal fats. Biodiesel is a renewable fuel with many similarities to diesel, but it offers several advantages. Environmentally, biodiesel is much cleaner, emitting minimal sulfur compared to petrochemical diesel, which contains virtually no sulfur. Biodiesel is regarded as an environmentally friendly fuel due to its minimal emissions of pollutants such as sulfur oxides (SO_x), carbon oxides (CO_x), nitrogen oxides (NO_x), and particulate matter during combustion. Diesel emissions consist of about 20% particulate matter and 10% carbon monoxide, making biodiesel a better alternative in terms of emissions. Biodiesel also has good lubricity and a higher viscosity than petrochemical diesel, which helps reduce wear on engine components like the fuel injection pump, engine block, and connecting rods, extending their lifespan. Additionally, biodiesel is versatile and can be used in diesel engines without the need for modifications. It is also highly adaptable to different climates and has superior ignition performance compared to regular diesel [27].

3.2. Bioethanol Production from Fruit/Vegetable Waste

As shown in **Table 1**, a comprehensive review of bioethanol production from fruit and food waste is provided, highlighting key processes, sources, and findings related to this method of biofuel production.

Table 1. Bioethanol production from fruit and food waste.

Waste	Specific condition	Bioethanol, %	Ref.
Pineapple with bakery yeast (*Saccharomyces cerevisiae*)		45	[29]
Pinapple juice alone		36	
	With further distillation	85	
Food hydrolysate using immobilized *Saccharomyces cerevisiae* 74D694	pretreated with dilute sulfuric acid, increasing the reducing sugar content from 46% to 62%; 40 hours of fermentation	47 mg/g	[32]
Apple pomace	pre-treatment stage, the pomace is milled, pressed and fermented (at 30˚C for 144 hours)	99.5%.	[33]
Pineapple peel	Hydrolyzing the pineapple peel with *Trichoderma harzianum* following a 30-minute sonication time enhanced the saccharification process; 48 hours of fermentation	197.6 ± 9.9 g/L or 25.0% v/v	[35]

In 2019, corn accounted for 50% of ethanol production, followed by wheat at 25% and sugar at 14%. Notably, 99% of bioethanol produced in Europe is derived from locally sourced raw materials [28]. Bioethanol is recognized not only as a renewable fuel but also for its high efficiency in combustion engines. This enhanced efficiency leads to lower fuel consumption and a reduction in harmful emissions. For instance, transitioning from E5 to E10 results in a 34% decrease in nitrogen oxides (NO_x), over a 90% reduction in particulate matter, and a 60% decrease in hydrocarbons, with even greater improvements expected when using E85. Gasoline vehicles manufactured after 2000 can typically operate on gasoline-bioethanol blends up to 10% (E10), which is compatible with approximately 90% of the vehicles in the current fleet. Bioethanol can also be used in higher concentrations. A blend of 85% ethanol and the rest gasoline, called E85, is widely available in Sweden, France, Germany, and more sporadically in Hungary, Austria, the E85 reduces emissions of CO_2, CO, particulate matter, and harmful toxicants like benzene, a known human carcinogen. It requires "flex-fuel vehicles" (FFVs) that can run on E85, gasoline, or any combination of both, without the need for separate fuel tanks. More explanation about FFV will be in the discussion section. In 2003, Brazil was the first to introduce FFVs, and they now represent over 90% of new car sales in the country. Converting a gasoline-powered car to an FFV is simple and cost-effective. However, Europe lags behind and needs to improve its infrastructure to support wider E85 deployment [28].

In another study from Mgeni *et al.* (2024) [29] examined bioethanol production from pineapple waste juice using two methods: one with bakery yeast (*Saccharomyces cerevisiae*) and the other without. The yeast-amended mixture produced bioethanol with an alcohol content of 45%, compared to 36% from pineapple juice alone. Re-distillation further increased the bioethanol content from 25% to 45% and then to 85%, aligning with E85 fuel specifications, thus demonstrating the potential of bioethanol as a fuel source. This suggests that bioethanol derived from pineapple fruit waste is a promising renewable energy option. Both methods were tested at room temperature to assess their efficiency in converting pineapple waste juice into bioethanol. The production of bioethanol from pineapple waste involves several stages, with pre-treatment being a critical first step. Pre-treatment breaks down the complex lignocellulosic biomass—comprising cellulose, hemicellulose, and lignin—releasing fermentable sugars essential for efficient bioethanol production. This process increases yield by maximizing sugar availability and reducing the formation of inhibitory compounds that could hinder fermentation. Various pre-treatment methods are employed, including physical approaches (e.g., microwaves and water treatment), chemical methods (e.g., acid, alkaline, organosolv, and oxidative treatments) [30], and biological techniques. Biological pretreatment utilizes fungi, bacteria, or enzymes to selectively degrade lignin and hemicellulose, offering an environmentally friendly option, though it is slower. Hydrolysis plays a crucial role in bioethanol production by converting polysaccharides in biomass into simple sugars such as glucose and xylose. This process can be carried out through enzymatic hydrolysis, where specific enzymes break down cellulose and hemicellulose, or through acid hydrolysis, which uses strong acids but may result in the formation of undesirable by-products [31].

Gundupalli and Bhattacharyya (2019) studied ethanol production from acid-pretreated food waste hydrolysate using immobilized *Saccharomyces cerevisiae* 74D694 under various conditions in a batch process. Food waste was pretreated with dilute sulfuric acid, increasing the reducing sugar content from 46% to 62%. The optimization of ethanol production was conducted using central composite design as part of response surface methodology, predicting a maximum ethanol yield of 0.044 g/g at 40 hours of fermentation and a bead ratio of 54:100. Under optimal conditions, an actual yield of 47 mg/g was achieved [32]. Rebolledo-Leiva *et al.* (2024) [33] developed a design and process model for a platform intended to produce bioethanol and extract total phenolic compounds (TPC) from apple pomace, aiming for the efficient utilization of by-products from the apple juice production industry. The bioethanol production process involves key stages such as pressing, fermentation, and distillation, among others. The findings reveal that the bioethanol production process has a global warming (GW) profile of 3.17 kg of CO_2 equivalent per kilogram of product, with vinasse treatment (the by-product generated after distillation) being the most significant contributor to environmental impact. The apple juice manufacturing process is an example of the high waste generation that occurs during the industrial production of apple-based products. The primary by-product, apple pomace, consists of a heterogeneous mixture including peel, core, seed, calyx, stem, and soft tissue, with an estimated annual production of approximately four million tonnes. Historically, apple pomace has been primarily sold for animal feed or disposed of in landfills and incinerators.

The latter disposal methods incur significant economic costs and have adverse environmental impacts, including greenhouse gas emissions and groundwater contamination. Additionally, such practices lead to the loss of valuable nutrients, vitamins, dietary fiber, and phenolic compounds. Despite its high moisture content (70% - 85%), apple pomace is rich in lignocellulosic components, comprising 7% - 44% cellulose, 4% - 24% hemicellulose, and 15% - 23% lignin [34], which makes it suitable for the production of valuable products in various downstream processes of the bio-based value chain. Current studies on apple pomace-based biorefineries focus on the production of products such as acrylic acid, n-butanol, electricity, and ethanol. In the pre-treatment stage, the pomace is milled to create a homogenized flow and then pressed to extract the free liquid phase, which is subsequently directed to the fermentation section. The solid phase is processed further in a facility dedicated to the extraction of phenolic compounds. During fermentation, it is assumed that 5% of the fermentable sugars are used for inoculum preparation (*i.e.*, yeast production). Nutrients are added at a concentration of 0.4 g/L, and the fermentation reaction is carried out at 30˚C for 144 hours. In the purification stage, distillation columns are employed to recover and purify ethanol, with the distillate serving as the upgraded ethanol product and the raffinate remaining as vinasse, a subproduct requiring additional processing. After distillation, ethanol dehydration is performed to produce fuel-grade ethanol with a purity of 99.5%. The proposed biorefinery design plays a pivotal role in facilitating the transition toward a more sustainable production model, in alignment with Sustainable Development Goal 12. This approach is driven by the objective of valorizing a by-product from the food industry, thereby optimizing the utilization of residual biomass. The primary findings indicate that the composting treatment of vinasse is the key factor influencing the environmental profile of bioethanol production [33].

Casabar *et al.* (2020) demonstrated that pineapple peel can serve as a viable feedstock for bioethanol production, achieving a bioethanol concentration of 25.0% v/v under optimal conditions. The study identified that hydrolyzing the pineapple peel with *Trichoderma harzianum* following a 30-minute sonication time enhanced the saccharification process. This microbial hydrolysis significantly increased the extraction of fermentable sugars from the polysaccharide-rich cellulose present in the peel. The optimal conditions resulted in a fermentable sugar yield of 567.6 ± 58.4 g/L of reducing sugars. Following 48 hours of fermentation, the final bioethanol yield was 197.6 ± 9.9 g/L (25.0% v/v), accompanied by an energy productivity of 126.9 MJ/hr [35]. Dhande *et al.* (2021) [36] evaluated the use of waste pomegranate fruits as a feedstock for second-generation ethanol production and investigated the performance of ethanol-gasoline blends in a spark-ignited engine. Ethanol was extracted through fermentation and steam distillation, and four ethanol blends (10%, 15%, 20%, and 25% ethanol) were tested at a constant compression ratio of 10:1 and wide-open throttle across various engine speeds. The results showed that ethanol enrichment improved engine performance. Indicated power increased with higher ethanol concentrations, with the

WPFE15 blend demonstrating the highest indicated power. Thermal efficiency also improved, with WPFE15 achieving 28.33%, outperforming pure gasoline and WPFE25 (26.41%). The mechanical efficiency of the engine increased with ethanol blending, with WPFE10 and WPFE15 blends showing the most significant improvements, especially at lower engine speeds. Volumetric efficiency slightly decreased with increasing engine speed, but ethanol blends with 15% and 25% ethanol showed some improvement due to ethanol's higher oxygen content. In terms of emissions, HC, CO, and CO_2 emissions decreased with ethanol blends. The WPFE20 blend produced the largest reduction in HC, while WPFE10 showed the most significant reduction in CO_2 emissions. CO emissions were reduced most effectively with WPFE25. However, NO_x emissions increased with ethanol blending, likely due to higher flame temperatures and increased oxygen content. Regarding combustion characteristics, ethanol blending resulted in higher in-cylinder pressure and a broader heat release profile, indicating more stable combustion. Combustion stability was confirmed with coefficient of variation (COV) values below 3.5 for all blends. Overall, waste pomegranate fruits are a promising feedstock for ethanol production. While ethanol blending improves engine performance and reduces some emissions, NO_x emissions increased, necessitating further research into emission reduction methods.

3.3. Biodiesel Production from Waste Oil

Producing biodiesel from edible oils is economically unviable, as raw materials, which account for 60% - 80% of the total production cost, create a competition between biodiesel production and the use of these oils for human consumption. Waste edible oil (WEO), generated in large quantities globally and unsuitable for human consumption, has been identified as an alternative, renewable feedstock for biodiesel production. In Europe alone, it is estimated that between 100,000 and 700,000 tons of WEO are produced annually [37]. Utilizing WEO for biodiesel synthesis could potentially lower production costs by 60% - 90%. The process of biodiesel production generally involves transesterification, where oils (such as WEO) react with alcohols (such as methanol, ethanol, or other alcohols) in the presence of a suitable catalyst. Both homogeneous and heterogeneous catalysts, whether alkaline or acidic, can be employed to optimize the reaction and increase biodiesel yields. In this study [38], the transesterification of WEO with methanol using a CaO@MgO nanocatalyst was investigated for biodiesel production. The findings revealed that the highest biodiesel conversion yield (98.37%) was achieved under the following optimal conditions: a reaction time of 7.08 hours, a temperature of 69.37˚C, a methanol-to-oil ratio of 16.7:1, and a catalyst concentration of 4.571 wt%. These parameters resulted in the highest biodiesel yield ever recorded from waste edible oil. Borges *et al.* (2011) [39], used a natural porous silica, pumice, as a heterogeneous catalyst for the transesterification of sunflower and frying oils with methanol to produce biodiesel. To enhance its catalytic activity, pumice was subjected to ion exchange with an aqueous KOH solution. Pumice granules (1.40 - 3.0 mm) were dried at 120˚C for 2 hours to remove surface water before undergoing ionic exchange at varying KOH concentrations (0.5 - 4 M) for 24 hours. Following this, the pumice granules were re-dried at 120˚C for 3 hours to produce the potassium-loaded catalyst. The transesterification reaction was carried out at temperatures between 50˚C - 60˚C with 100 g of oil, and methanol-to-oil molar ratios ranging from 6:1 to 24:1. The catalyst amount varied between 4 and 20 wt% of oil weight, and the reaction time was between 1 and 4 hours. After the reaction, the solid catalyst was separated by filtration, and the liquid phase was subjected to rotary evaporation to remove excess methanol. The upper phase contained the biodiesel (FAME), while the lower phase consisted of glycerol. The KOH-exchanged pumice was an efficient catalyst for transesterification at low temperatures (55˚C), yielding high FAME from both sunflower and waste frying oils. The catalyst demonstrated bifunctional behavior, with good reusability and simple, cost-effective preparation. The reaction at 55˚C yielded biodiesel with viscosity and methyl ester content that met UNE-EN 14,124 standards. However, reactions at 50˚C led to higher viscosity and lower FAME yield, falling outside commercial biodiesel regulations. Increasing the methanol-to-oil ratio from 6:1 to 24:1 improved FAME yield and decreased viscosity, with optimal conversion at a 24:1 ratio. Additionally, increasing the catalyst amount from 4 to 20 wt% boosted FAME yield from 62% to 93.2%. This catalyst could be a promising option for industrial biodiesel production, enabling the use of waste oils while meeting commercial standards.

4. Discussion

The development and utilization of bioethanol as a renewable energy source have garnered significant attention due to its potential to reduce reliance on fossil fuels, mitigate environmental impacts, and promote sustainability. The discussion of bioethanol production from different feedstocks such as corn, wheat, sugar, pineapple waste, apple pomace, food waste, pineapple peel, and pomegranate waste highlights the diverse potential for bioethanol production across various sectors. This critical analysis evaluates the key findings presented in the studies and their implications for both bioethanol production and its use in automotive applications. In 2019, corn accounted for 50% of global bioethanol production, while wheat and sugar accounted for 25% and 14%, respectively. The data on ethanol production demonstrates the significant role of agriculture in bioethanol production, particularly in regions such as the United States and Brazil. Europe's commitment to sourcing 99% of its bioethanol from local raw materials aligns with regional sustainability goals, supporting the development of a circular economy where renewable energy is derived from local agricultural waste and biomass. However, challenges remain in scaling up production and diversifying feedstocks to reduce dependency on staple crops like corn, which are often, associated with land use and food security concerns. From an environmental perspective, bioethanol is seen as an effective means of reducing greenhouse gas emissions and improving air quality. The transition from E5 to E10 blends, as highlighted, can reduce harmful emissions such as nitrogen oxides (NO_x), particulate matter, and hydrocarbons. The use of higher ethanol blends like E85 further enhances these environmental benefits, demonstrating the potential for significant reductions in CO_2 emissions and other toxicants, including carcinogenic compounds like benzene. However, these benefits are largely contingent on the widespread adoption of flexible-fuel vehicles (FFVs) and the development of infrastructure to support the use of such fuel blends. FFVs are designed to operate on multiple fuel types, typically a combination of gasoline and ethanol, or on pure ethanol alone. A widely used fuel blend for these vehicles is E85, which consists of 85% ethanol and 15% gasoline. In the United States, FFVs are commonly referred to as "E85 vehicles". In Brazil, they are popularly known as "total flex" or simply "flex" cars, while in Europe, they are often called "flexifuel vehicles" [40].

A significant challenge in bioethanol production is the efficient use of feedstocks. As demonstrated by the study by Mgeni *et al.* (2024) [29], bioethanol production from pineapple waste juice can be optimized using yeast, achieving an alcohol content of up to 45%, in line with E85 specifications. This shows promise for utilizing agricultural by-products that might otherwise go to waste, contributing to a more sustainable bioethanol industry. However, the need for effective pre-treatment of biomass, particularly lignocellulosic materials, remains a key challenge. Pre-treatment methods like microwave treatment, acid hydrolysis, or biological processes, as seen in studies on pineapple peel and apple pomace, are crucial to breaking down the complex biomass structure and releasing fermentable sugars. These technologies have the potential to lower production costs and increase yield, but they also pose challenges related to cost-effectiveness, scalability, and environmental impact, particularly concerning the disposal of by-products like vinasse. Vinasse is a residual liquid produced during ethanol manufacturing, particularly from the fermentation of sugarcane or sugar beet. It is high in organic content and nutrients, and is commonly repurposed as a fertilizer or used in biogas generation [41]. Moreover, the studies reviewed highlight that second-generation bioethanol derived from food waste or fruit by-products, such as the work on food waste hydrolysate by Gundupalli and Bhattacharyya (2019) [32], and pineapple peel by Casabar *et al.* (2020) [35], offers a promising avenue for reducing the environmental footprint of bioethanol production. These approaches utilize waste materials that would otherwise contribute to landfill overflow and greenhouse gas emissions, thus addressing both waste management and energy generation. However, these processes still face challenges related to efficiency, fermentation rates, and the need for specialized enzymes or microorganisms to optimize sugar conversion. One of the critical issues identified in the studies is the environmental impact of bioethanol production, particularly in the treatment of by-products such as vinasse. As shown in the research by Rebolledo-Leiva *et al.* (2024) [33], the treatment of vinasse is a key factor influencing the overall global warming potential of bioethanol production. Developing sustainable and cost-effective methods to manage by-products like vinasse is critical to improving the life-cycle sustainability of bioethanol. Finally, while bioethanol blends such as E10, E15, and E20 have demonstrated improvements in engine performance and emissions reduction, as seen in Dhande *et al.* (2021) [36], concerns over increased NO_x emissions due to higher ethanol concentrations must be addressed. While ethanol blends can enhance engine efficiency and lower CO_2 emissions, the increase in NO_x emissions may require further technological advancements in engine design, combustion optimization, or the development of emission-reducing additives to fully realize the environmental potential of bioethanol.

The growing use of bioethanol as a renewable fuel offers significant environmental benefits, particularly in reducing harmful emissions and improving fuel efficiency. Transitioning from E5 to E10 bioethanol blends leads to notable reductions in nitrogen oxides (NO_x), particulate matter, and hydrocarbons, while higher ethanol blends like E85 reduce carbon dioxide (CO_2), carbon monoxide (CO), and other pollutants, with E85 showing the most promising emissions reductions. This highlights bioethanol's potential to improve air quality. Bioethanol also offers the advantage of being compatible with existing gasoline engines, as most vehicles built after 2000 are compatible with E10. The flexibility of bioethanol blends, especially E85, allows for higher ethanol content without the need for new vehicle infrastructure, provided vehicles are flex-fuel enabled. Brazil's success with flex-fuel vehicles (FFVs), which make up over 90% of new car sales, demonstrates the viability of bioethanol when the proper infrastructure is in place. Additionally, using waste materials such as pineapple juice, apple pomace, and food waste as feedstocks further contributes to bioethanol's sustainability. However, the environmental impact of bioethanol production is a concern, as growing feedstocks like corn and wheat can lead to soil degradation, water pollution, and greenhouse gas emissions. The use of food crops for fuel also raises ethical concerns, particularly in regions where food security is a priority. Furthermore, there is limited infrastructure for higher ethanol blends in many regions, especially Europe, where refueling stations and vehicle compatibility for E85 are lacking. Converting gasoline cars into flex-fuel vehicles is inexpensive but may be hindered by upfront costs and a lack of consumer awareness. The scalability and cost-effectiveness of bioethanol production from waste feedstocks like pineapple peel remain challenging, as the processes involved can be resource-intensive. By-products from the distillation process, such as vinasse, also contribute to the environmental impact and require proper treatment. Although bioethanol blends generally reduce emissions, higher ethanol blends may increase NO_x emissions due to higher combustion temperatures, requiring technological advancements to address this issue. Despite these challenges, bioethanol offers clear environmental benefits, and ongoing research in feedstock sustainability, infrastructure development, and production efficiency is essential for its broader adoption. Regarding biodiesel production, using edible oils as feedstocks faces significant economic challenges due to the high cost of raw materials, which can account for 60% - 80% of total production costs. Waste edible oil (WEO) has emerged as a promising alternative, offering cost savings of 60% - 90%. The process of converting WEO into biodiesel involves transesterification with methanol or ethanol, using catalysts to optimize the reaction. Research by Foroutan (2020) demonstrated that the use of a CaO@MgO nanocatalyst achieved a high biodiesel conversion yield of 98.37% [38]. Additionally, Borges *et al.* (2011) [39] showed that pumice, a natural porous silica, could be used as a cost-effective catalyst for biodiesel production, yielding high FAME at relatively low temperatures. However, the variability of WEO, including contaminants, can complicate the process and reduce catalyst efficiency. Pre-treatment of WEO adds extra steps, which may offset some of the cost savings. The recycling of heterogeneous catalysts is also challenging, as degradation over time can reduce their effectiveness. The environmental impact of biodiesel production is another concern, as the use of methanol or ethanol, typically derived from fossil fuels, may reduce the net environmental benefit. Furthermore, the disposal of by-products such as glycerol and spent catalysts requires proper management to avoid environmental contamination. Despite these challenges, WEO-based biodiesel production offers a promising solution to reduce production costs, reliance on edible oils, and waste disposal issues. Continued research in catalyst development and process optimization could make WEO-based biodiesel a more viable and sustainable option in the renewable energy sector.

Comparative Environmental Analysis of Bioethanol Feedstocks

Bioethanol can be produced from various feedstocks (**Table 2**) categorized into three main types:

Table 2. Bioethanol feedstocks.

Feedstock	Conversion method	Advantages	Disadvantages	Maximum ethanol (EtOH) yield	Ref.
Sugarcane	Fermentation of sugars Pretreatment and saccharification	High yield, low GHGs, by-product reused	Water use, land use impact	High-yielding feedstock, especially in tropical climates. The yield varies depending on soil quality, climate, and management practices 7.57 v/v%	[43]
Corn	Starch hydrolysis + fermentation	Mature tech, high output	Food vs. fuel, GHGs, inputs	The highest for first-generation feedstocks, it is less sustainable due to land and water use. 0.50 g EtOH/g total sugar	[44]
Cellulosic biomass	Pretreatment + hydrolysis + fermentation	Non-food, low GHGs, uses waste	Expensive, tech limits	Yields vary widely based on feedstock (e.g., switchgrass, wheat straw, etc.) and conversion efficiency. It is promising but more expensive due to complex processing. 182 g EtOH	[45]
Algae	Fermentation or termochemical	High yield, CO_2 absorption, no land competition	Expensive, early stage, high inputs	Has the potential for very high yields compared to terrestrial crops, but current commercial production is still limited. The actual yield depends on algae species and cultivation methods. EtOH 40 g/L	[46] [47]

1) Food crops like corn, sugarcane, cassava, sweet potato, sugar beet (the first-generation bioethanol).

2) Lignocellulosic biomass like agricultural residues or wood, (the second-generation bioethanol).

3) Algae and other advanced bio-resources (the third-generation bioethanol) [42].

Studies by Konti *et al.* [48] highlight significant variation in life-cycle assessment (LCA) approaches to bioethanol production from food waste, including differences in feedstock types, system boundaries, and functional units. This heterogeneity makes direct comparisons between studies challenging. Despite these differences, most research emphasizes greenhouse gas (GHG) emissions, aligning with climate policy priorities. Overall, bioethanol from food waste shows strong potential for reducing environmental impacts, particularly GHG emissions.

Yin *et al.* [49] conducted a comprehensive LCA of bioethanol production from corn cobs, corn straw, and wheat straw, evaluating energy output, emissions, and co-product utilization (xylose, lignin, and steam). Among the three, corn cobs showed the most favorable performance, with a net energy balance (NEB) of up to 13,213 MJ/Mg and net energy ratio (NER) of 1.80, as well as the lowest environmental impacts across multiple categories like GWP and acidification. The study used GREETR2022 software to assess emissions throughout the entire life cycle from cultivation and transport to production based on a functional unit of 1 Mg of bioethanol. Though corn cobs perform best environmentally, their availability is lower than that of straw, suggesting that a mixed feedstock strategy could optimize both sustainability and resource use.

To enhance the feasibility and scalability of biofuel production from food waste, it is important to consider several economic and policy factors. Carbon pricing mechanisms, including carbon taxes and cap-and-trade systems, are effective policy tools that place a financial cost on greenhouse gas emissions, encouraging the shift from fossil fuels to low-carbon alternatives like bioethanol [50]. By internalizing the environmental cost of emissions, these mechanisms make bioethanol from food waste more economically competitive, especially given its lower lifecycle emissions. They also promote investment and innovation in cleaner energy technologies by creating economic incentives for emissions reductions. In the context of bioethanol production, integrating carbon pricing can enhance its viability and scalability, particularly if producers can benefit from carbon credits or subsidies for reducing emissions through waste valorization. Future research should explore how different carbon pricing scenarios impact the feasibility of food waste-based bioethanol and its role in broader climate and energy strategies. Addressing these factors is key to making bioethanol production from food waste more feasible and scalable, alongside its environmental benefits.

5. Conclusion

Future research on bioethanol production from food waste should focus on several key areas to enhance sustainability and scalability. First, exploring a wider range of underutilized feedstocks, such as urban food waste, could increase resource availability and improve the environmental impact. Process optimization, particularly integrating pretreatment, fermentation, and distillation methods, is crucial for improving yields and reducing energy consumption. Additionally, comprehensive, region-specific life-cycle assessments (LCAs) should be conducted to better understand the economic and environmental implications, including local feedstock availability, transportation costs, and market dynamics. There is also significant potential in utilizing co-products like lignin and xylose, which could contribute to a circular economy model and improve profitability. Policy frameworks, government incentives, and carbon pricing mechanisms should be examined to better understand how they influence the widespread adoption of biofuels. Scaling up bioethanol production to an industrial level requires research on energy and water efficiency, as well as integration with existing biofuel infrastructure. By addressing these research gaps, bioethanol from food waste can become a more viable, sustainable, and economically competitive renewable energy source.

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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