

Review Article

Bioconversion of Agricultural Waste into Biofuels

ABSTRACT

Agricultural waste represents a largely untapped resource that could be utilized for the production of biofuels through various conversion pathways. As the global demand for renewable and sustainable energy grows, biofuels offer solutions to mitigate climate change impacts while improving waste management. This review analyzes the potential of using agricultural residues and by-products as feedstocks for biofuel production through biological, thermochemical and chemical conversion processes. The different types of lignocellulosic biomass available from agricultural activities are discussed, along with their compositions. While agricultural waste has advantages like wide availability and low cost, challenges relating to heterogeneous composition, pre-existing contamination and seasonal availability must be addressed. Fermentation, anaerobic digestion, pyrolysis and gasification are examined as established routes for converting agricultural waste into liquid biofuels and biogas. Pretreatment methods, enzyme production pathways and synthesis of fuels like ethanol, butanol and diesel substitutes are outlined. Environmental benefits of biofuels from waste, including greenhouse gas mitigation and recycling of soil nutrients, are evaluated against fossil fuel alternatives. Case studies on operational plants and feasibility studies provide insights into technical and economic viability at scale. Challenges regarding feedstock logistics, conversion efficiency, commercial scale-up and sustainability assessment are identified for future research focus. In conclusion, the review finds that agricultural waste is a promising renewable resource for biofuel production when integrated with appropriate thermochemical, biochemical or anaerobic digestion technologies. While the field is advancing, further improvements in areas such as feedstock supply, pretreatment technologies, and demonstration of sustainability will be critical to realize the full potential of this emerging bioeconomy sector. The review recommends steps to accelerate commercialization and policy frameworks to incentivize waste-to-energy solutions.

Keywords: Agricultural waste, Lignocellulosic biomass, Fermentation, Anaerobic digestion, Pyrolysis, Gasification, Sustainability, Biofuels.

1. INTRODUCTION

In the last few decades, biofuels have gotten a lot of attention as low-carbon, renewable options to fossil fuels like gasoline, diesel, and jet fuel. With more people owning cars and flying around the world, the demand for transportation energy is steadily rising [1]. Still, the transportation industry is very dependent on oil, which makes greenhouse gas emissions and the rise in global temperature worse. This has made people look for biofuels that are sustainable and have low emissions that can be used in cars instead of petroleum goods. When it comes to environment and energy security, biofuels are much better than fossil fuels in a number of important ways. Unlike oil supplies, which can only be used up, these fuels can be made over and over again from biomass feedstocks that can be grown and replaced. The closed carbon cycle is created when they are burned because the amount of carbon

dioxide released is the same as or less than the CO₂ taken in during plant growth [2,3]. Because of this, biofuels are better for the environment than fossil fuels, which release "new" carbon that was put away millions of years ago. Making biofuels also helps the country become less reliant on oil imports and improves energy security. By replacing oil with biofuels, harmful pollutants like particulate matter, carbon monoxide, unburned hydrocarbons, and sulfur dioxide are reduced, which is good for both the environment and general health [4]. Some studies show that biofuels could help cut down on up to 30% of greenhouse gas emissions from transportation by 2050, provided that technology gets better and more of them are used [5]. As part of the Paris Agreement's goals, this could make a big difference in the world's efforts to stop climate change.

First-generation biofuels made from food crops like corn, sugarcane, and vegetable oils got a lot of government support. But now it is clear that we need next-generation biofuels made from lignocellulosic feedstocks that aren't edible [6]. This is because using food and feed crops to make fuel causes problems with food prices, competition for farmland, and changes in land use that make it harder to save greenhouse gases [7]. Lignocellulosic feedstocks are good options because they don't threaten food security, can be grown on poor land, and lower greenhouse gas emissions more through cellulosic ethanol or other advanced biofuels. However, the marketing of advanced biofuels has been slow because of many technical and economic problems [8], even though research and development have made a lot of progress. One of these problems is that lignocellulosic material has a complicated and uneven structure that makes it harder and more expensive to break down than simple sugars, starches, and oils in food crops. The current methods for getting feedstock and changing biochemicals and thermochemical also need to be improved in order to reach economies of scale and lower the high costs of production compared to regular petroleum fuels. Corn, wheat, rice, sugarcane, oilseeds, and other crops generate over 1 billion tons of farm waste annually, according to [9]. About 30 to 50% of field wastes can be removed without harming soil or crop production. This depends on the crop and the area. Lifecycle assessments (LCAs) show that about 500 million tons of corn stover and 150 million tons of wheat straw could be found in a way that is good for the environment in the US and Europe, respectively.

In the same way, animal manure is a common waste product—every year, cattle produce over 64 billion tons [10]. Some things that hurt the environment when they are not handled properly are chicken litter, cow/pig manure slurry, and poultry litter [11]. Because it is high in carbohydrates, fats, and proteins, manure has a lot of energy. This means that it can be turned into biofuels through anaerobic processing or other methods. Along with residues and manure, wastes from processing fruits and vegetables, such as bagasse, rice husks, nutshells, city solid waste, and algal residues, are also great sources of feedstock [12]. Each year, these wastes add up to several hundred million tons around the world. This gives waste-based biorefineries a chance to make bioenergy and bioproducts with extra value [13]. Using agricultural waste to make biofuel has many benefits over growing crops specifically for energy. Residues are lignocellulosic materials that don't need farmland or other inputs to grow, so using them keeps food and fuel from competing with each other. As trash, they don't cost much or anything at all, which is good for the economy [14,15]. Because they are spread out and only happen during certain times of the year, they need

decentralized, small-scale technology uses that work well in rural areas and developing economies.

At the same time, planning how to gather, pre-treat, and convert waste effectively requires planning how to move things around. There are also limits to the steady supply of residues throughout the year because of changes in crop yield and weather effects [16]. However, using them for advanced biofuels could have big benefits, like increasing incomes in rural areas, lowering the cost of managing waste, lowering greenhouse gas emissions by diverting garbage from landfills, and making use of materials that aren't being used enough right now.

Agricultural waste is a huge, underused renewable resource that could help biofuel development in the long term if it is combined with the right tools for conversion. To reach this capacity, it is important to solve problems related to the supply of feedstock, logistics, the efficiency of conversion, and the ability to make money on a large scale. The parts that follow will talk about the biological and thermochemical ways that agricultural waste can be turned into biofuels. These will be followed by case studies, effects on the environment, and directions for future research.

1.1 Scope

This review addresses the merits and cons of using agricultural waste biomass to make biofuels sustainably. Globally produced agricultural waste will be included. Waste from cultivating cereals, sugarcane, oilseeds, and fibers is included. Agricultural waste and animal dung from large animal feed producers will also be examined. The literature will be examined to examine waste stream biomass, compositional variability, and predicted levels. It will examine thermochemical, biochemical, and chemical strategies to convert lignocellulosic crop waste into liquid biofuels and biogas. Biochemical processes like anaerobic digestion and fermentation will be emphasized. Thermal processes, including pyrolysis, gasification, and biomass synthesis gas fuels, will be discussed.

It will examine demonstration and commercial-scale biofuel facilities worldwide that use various agricultural wastes. Techno-economic factors will include feedstock handling and preprocessing, fuel conversion, energy balances, fuel costs, and earnings. It will also examine how residue removal influences soil carbon and nitrogen dynamics and how much greenhouse gas emissions are conserved compared to fossil fuels. The review aims to improve information on agricultural waste biomass qualities and conversion technology best practices. It will identify the key technological, economic, and environmental barriers to large-scale integrated biorefinery utilization. Biofuel growth policy assistance, sustainable feedstock production, and waste management will also be discussed. Finally, the study will identify the most significant research areas to maximize agricultural waste's potential for carbon-negative biofuels. These include overcoming feedstock shortages, improving energy efficiency, generating autonomous models, and demonstrating process longevity. This website is for bioenergy and farm waste-based bioeconomy enthusiasts.

1.2 Objectives

- [1.] Provide a thorough analysis of agricultural waste resources and bioconversion technologies for producing biofuels from these residues. This includes evaluation of waste types, quantities, characteristics, as well as thermochemical, biochemical and chemical conversion processes.
- [2.] Critically assess the technical, economic and environmental aspects of bioconversion pathways based on case studies and literature and identify key challenges for large-scale implementation.
- [3.] Synthesize knowledge on agricultural waste biofuels to outline critical research gaps and recommendations, with the aim of realizing their potential for sustainable bioenergy production.

2. LITERATURE REVIEW

2.1 Agricultural Waste as a Feedstock for Biofuel Production

A lot of different kinds of waste are made every year by agricultural operations. There are three main types of these wastes: lignocellulosic biomass, food residues, and animal manure [17,18]. Things like straw, wood, energy crops, and pulping waste are all examples of lignocellulosic biomass. [19] say that cereal straws from wheat, rice, and corn, bagasse from sugarcane, orchard pruning and nut shells, and corn cobs and stover are some of the most important crop leftovers. Over 300 million tons of sugarcane bagasse are made every year around the world [20], making it one of the most common waste materials.

There is also a lot of trash from animal farming. At concentrated animal feeding operations, a lot of garbage comes from the manure of cattle, chickens, and pigs [19]. Over 1 billion tons of manure are thought to be made every year in the US alone from raising animals [21]. A lot of agricultural garbage is made up of agro-industrial waste from making food and paper, like rice husk, corn fiber, fruit pomace, and sugarcane trash [22]. These residues are the leftovers from different conventional and organic processes used in the food and biomass processing businesses [23].

2.2 Composition and Characteristics of Agricultural Waste

Agricultural residues can have very different makes-ups based on the type of crop or animal source [24]. Lignocellulosic materials found in most leftovers are lignin, hemicellulose, and cellulose, along with different amounts of ash, proteins, and extractives (Ali et al., 2019). 30–50% of the dry matter in residues is cellulose, which makes rigid microfibrils that are linked to other polymers. There are no clear shapes in hemicellulose (20–30%), which connects cellulose to lignin (10–25%). Lignin is a complicated protein that makes plant cell walls stiff [5].

Table 1: Composition and characteristics of agricultural waste

Component	Percentage Range	Description
Cellulose	30-50%	Rigid microfibrils, linked to other polymers
Hemicellulose	20-30%	No clear shapes, connects cellulose to lignin

Lignin	10-25%	Complicated protein, makes plant cell walls stiff
Moisture Content	10-60%	Varies based on waste type and season, affects handling and energy density
Ash Content	2-20%	Inorganic residue remaining after combustion
Macro and Micronutrients	-	Varies in composition
Carbon and Oxygen	High	Suitable for processes like anaerobic digestion and thermal/chemical methods
Sulfur	Low	Suitable for processes like anaerobic digestion and thermal/chemical methods

The moisture content is a key property that can change. It can be anywhere from 10 to 60%, based on the type of waste and the time of year. It is harder to collect, move, and store things that are wet, and the energy density goes down [25]. Ash content (2–20%) and macro and micronutrients present are two other types of variety [26]. Lignocellulosics can be used as feedstocks for processes like anaerobic digestion and thermal/chemical methods to make fuels and value-added products because they have high carbon and oxygen content and low sulfur content [27]. However, different types of trash also cause problems.

2.3 Advantages and challenges of agricultural waste

Utilizing large amounts of agricultural waste has many advantages over growing straight food and energy crops. Remains are leftovers that have low or no production costs and don't cause problems with food versus fuel [28]. Additionally, their use helps with waste management objectives by avoiding problems with open burning or dumping [29]. Crop residues that are collected and removed help the soil's nutrient cycle and organic matter replenishment [28]. Waste materials can be turned into useful energy [30]. Hence can improve the economic viability of combined biomass supply and conversion systems.

Moreover, life cycle studies show that when handled in a way that doesn't harm the environment, waste biomass-based biofuels save more greenhouse gases than fossil fuels. Diverse composition, seasonal changes, decentralized generation, and the lack of standardized supply systems are still problems [31]. Distribution of small-scale garbage generators and changes in waste quality and quantity make collection and transport more difficult. Supplies are still very expensive because of this [32]. According to [26], the sustainable removal rates and soil fertility/carbon effects also need to be carefully studied and managed. Unfortunately, farm waste can be useful as long-lasting and inexpensive feedstock's if these problems can be fixed.

The biomass resources in agricultural waste are plentiful and not being used to their full potential. If they are grown sustainably as biofuel feedstocks, they could have technical and economic benefits. Composition varies but usually includes lignin, hemicellulose, and cellulose, which can be converted in different ways. To fully utilize this potential on a commercial level, it will be necessary to solve problems related to decentralized supply, seasonal changes, and unknown impacts.

2.4 Biological Pathways for Bioconversion of Agricultural Waste

2.4.1 Fermentation Processes

Pretreatment methods

Pretreatment is needed to break down tough material by changing its structure so that enzymes can break it down and ferment it better [33]. Some common pretreatments are chemical (alkalis, organic liquids), physicochemical (steam explosion, ammonia fiber expansion), biological (microbes and enzymes), and physical (milling and irradiation). Before the process, lignin-carbohydrate complexes and crystallinity are broken up, which makes more surface area and pores available [33]. Soaking in an alkaline solution helps get rid of lignin and hemicelluloses, and using high-pressure and high-temperature water in a steam explosion breaks up the structure of plant cell walls [34]. The choice relies on things like the type and makeup of the biomass, the end products that are wanted, and the available technologies [34].

Enzymatic hydrolysis

Pretreatment makes cellulose and hemicellulose more easily broken down by enzymes like cellulase and xylanase cocktails. These groups of enzymes work together to split glycosidic bonds in carbohydrate chains into single sugars [35]. Endoglucanases, exoglucanases, and β -glucosidases are enzymes that are often used to break down cellulose efficiently [36]. Variables like pH, temperature, substrate loading, and enzyme dosage can be used to improve the process and increase sugar outputs [30].

Fermentation of sugars to biofuels

Biomass hydrolysis produces monomeric sugars that are used as fermentation substrates by microbes to turn them into energy products that are wanted. Some methanogens, like *Saccharomyces cerevisiae*, use hexoses to make ethanol, while more advanced forms also use pentoses [37]. During prep, crops like sorghum naturally make extracts that can be fermented. Bacteria and fungi that have been genetically modified can turn mixed sugars into butanol, isopropanol, and other alcohols [38]. To get high product titers, yields, and productivities at a low cost, process factors like inoculum size, nutrient supplementation, and product inhibition controls are fine-tuned.

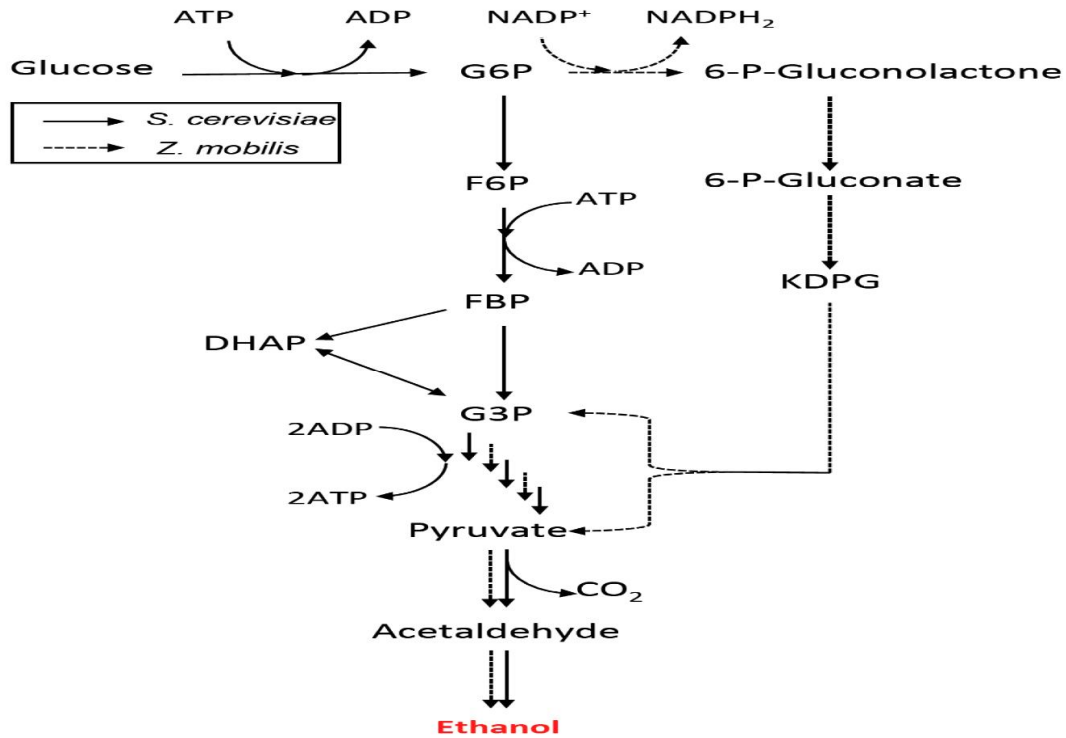


Figure 1: Ethanol fermentation pathways in *S. cerevisiae* (solid line, EMP glycolysis pathway) and *Z. mobilis* (dashed line, ED glycolysis pathway). While the EMP pathway produces two ATPs per glucose molecule, the ED pathway produces only one ATP molecule per glucose molecule. KDPG, 2-keto-3-deoxy-6-phosphogluconate; G6P, glucose 6-phosphate; F6P, fructose 6-phosphate; FBP, fructose 1,6-diphosphate; DHAP, dihydroxyacetone phosphate; G3P, glyceraldehyde 3-phosphate.

Source:[41].

2.4.2 Anaerobic digestion

Process overview

Anaerobic digestion (AD) is a biological process that uses bacteria and archaea when there is no oxygen present [39]. It can be found naturally in many places and is also used in industry to stabilize waste and make green energy [40]. The AD process has four main steps: exoenzymes break down complex organics, sugars and amino acids are acidogenesis, volatile fatty acids are acetogenesis, and CO₂ and H₂ are used to make methane [39]. For the best process stability, system design can be either wet or dry, depending on the type of trash [40].

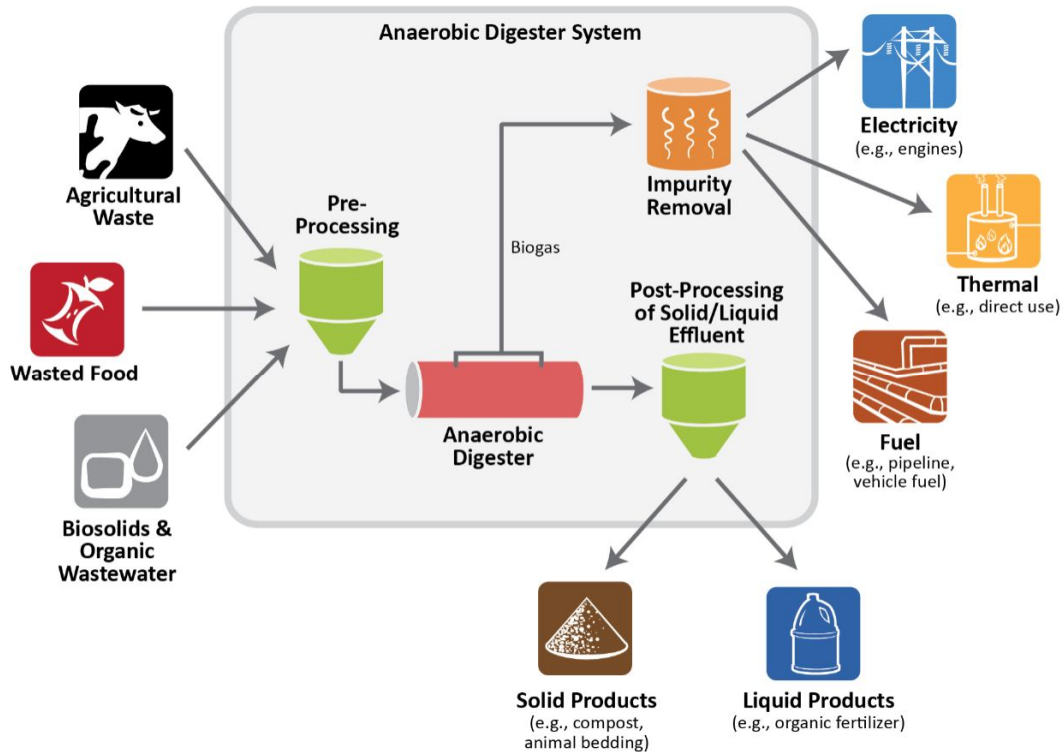


Figure 2: Anaerobic digestion
 Source: Anaerobic digestion. (n.d.).

Bioogas production

Biomass amounts are reduced by anaerobic digestion, which creates biogas that are high in methane (CH₄) and carbon dioxide (CO₂). It is possible to burn biogas to make heat and electricity directly (Chen et al., 2008). Newer types can also be used instead of natural gas in some situations (Ahring, 2003). In addition to the type of feed, temperature (mesophilic 35°C or thermophilic 55°C), holding time, the carbon to nitrogen ratio, pH, and nutrients all affect the activity of microbes and the amount of methane they produce [40]. Digesting farm waste along with animal waste increases biogas potential in a way that works well with each other.

Factors affecting biogas yield

The production of biogas relies on the properties of the biomass itself, such as its structure, the amount of carbon and nitrogen it contains, and how quickly it breaks down [39]. Temperature, mixing, loading rate, and solids content are some of the operational factors that affect microbial groups and conversion rates [40]). Pathogens, ammonia, heavy metals, sulfide, and organic acids are some of the toxic chemicals that come from industrial and farm trash that stop methane producers from working if they are not stopped [40]. To get the most biogas out of farm waste, it is important to do good pretreatment and process optimization. Fermentation and anaerobic digestion are both well-known biological ways to turn lignocellulosic waste biomass into biofuels, power, and products with extra value. For them to be used on a big scale, they need to be combined with the best pretreatment, hydrolysis, and fermentation methods.

2.5 Chemical and Thermochemical Conversion Pathways

Pyrolysis

Thermochemical conversion technology called pyrolysis breaks down biomass into solid, liquid, and gaseous parts without air [42]. Based on the time and temperature of stay, it is split into slow, fast, and flash pyrolysis [6]. Slow pyrolysis (400–550°C) makes more solids like ash, while fast pyrolysis (400–650°C) makes the most liquid bio-oil [42]. Fast pyrolysis is a good way to go because it makes bio-oil that can be used instead of chemicals and fossil fuels (75%). Oxygenated hydrocarbons, water, organic acids, aldehydes, ketones, phenolics, and biomass-derived sugars make bio-oil a thick, dark brown liquid [9]. Pyrolysis bio-oil's chemical and physical properties depend on feedstock and heating settings [6].

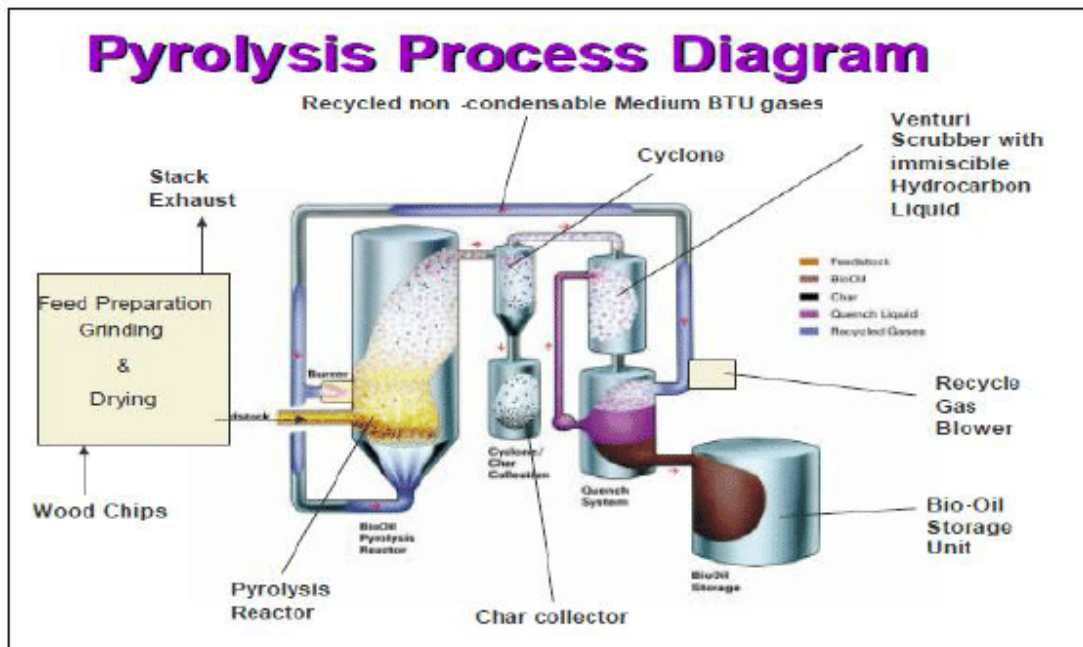


Figure 3: Pyrolysis Process
Source: Popoola, et al (2015)

Due to its high-water content (20–30%), corrosive components, low heating value, and thermal instability, bio-oil cannot immediately replace petroleum fuels [14]. So, numerous upgrading procedures are applied to make bio-oil better and more stable for end goods. Catalytic and thermal cracking are two ways to improve things by getting rid of oxygen, increasing energy density, and reforming parts [42]. Emulsification, catalytic reforming, hydrotreating, and liquid liquefaction are some other methods [6]. The bio-oils that have been upgraded and refined have qualities that make them a good replacement for regular fuel oils. Some improved pyrolysis oils can even be processed along with other oils in oil plants that are already in use, such as FCC units [14]. Overall, fast pyrolysis along with the right upgrading routes is a good way to turn farm waste into liquid fuels and bio-products with high value.

Gasification

A controlled amount of air, oxygen, and steam is used to partially oxidize or steam reform wood at high temperatures (800–1500°C) in gasification. This creates syngas, which is a

mixture of CO, H₂, CO₂, and CH₄ (Arregi et al., 2018). Gasification is better than burning because it gives you more fuel options and uses less energy because the product gas is cleaned up and used [33]. After pollutants are taken out, the syngas stream has a high heating value and can be burned directly for heat and power purposes [14]. Nevertheless, syngas is also a key step in the production of liquid fuels for vehicles through catalytic processes like Fischer-Tropsch synthesis.

Syngas from wood gasification goes through catalytic conversion reactions in the Fischer-Tropsch (FT) process to make different types of liquid hydrocarbons [37]. Chemicals that are based on iron or cobalt are used to turn gases into liquids that boil in the range of diesel to gasoline [10]. FT makes drop-in green liquid fuels that are better than bio-oils made through pyrolysis. To protect catalysts and get the most production out of syngas before FT, it needs to be cleaned of any impurities [13]. Gasification and FT synthesis can turn farm garbage into green liquid fuels thermochemically. Farm biomass may be converted into fuels and products via pyrolysis and gasification. Better improvements and multi-product biorefineries could make waste biomass more cost-effective, technologically feasible, and durable.

2.6 Biofuel Production from Agricultural Waste Is Good for The Environment

Greenhouse gas emission reduction

Research shows that agricultural waste-based transportation fuels emit less GHG than fossil fuels. Chandra et al., 2012) found that integrated biorefining of residual biomass reduces emissions by approximately 80%. Photosynthesis absorbs airborne carbon instead of fossil carbon that has been concealed for a long period (Pandey, 2011). Anaerobic digestion of garbage to make biogas also stops the release of methane, a greenhouse gas that is highly harmful to the environment. Together, waste-to-fuel routes and renewable energy can get very close to having no greenhouse gas emissions (Gillingham & Stock, 2018).

Waste management and resource recovery

Making biofuels from food waste helps cut down on the amount of farm waste and the pollution that comes from burning it, which is bad for the environment and people's health (Awogbemi & Von Kallon, 2022). It makes something useful out of cheap, easily accessible materials that would otherwise break down and release pollution (Panpatte & Jhala, 2019). This helps reach goals for sustainable waste management and offers green options to fossil fuels (Whalen et al., 2017). Biorefining also gets minerals that are stuck in waste and puts them back on farmland (Chandra et al., 2012).

Soil nutrient recycling

When lignocellulosic leftovers are harvested strategically, the nutrients are left in the ash and the extra carbon is taken away for biofuels (Pandey, 2011). This increases the amount of organic matter in the soil and keeps phosphorus, potassium, and other macronutrients cycling, which is important for keeping the soil fertile and increasing crop output over time (Whalen et al., 2017). Co-digestion with animal manure improves the power to change the soil even more (Chandra et al., 2012). So, collecting residues in a sustainable way and managing nutrients help carbon-negative farming.

Comparison with fossil fuels and feedstocks

Biofuels see cost competitiveness compared to petroleum at oil prices above \$60-80/barrel currently (Shahi & Khajeh Mehrizi, 2021). But their primary benefit lies in delivering large

GHG cuts hard to achieve through emissions offsets in transportation (Gollakota & Shu, 2023). They also replace ozone-depleting SF6 in electric utilities with renewable biogas having zero global warming potential (Owens, 2016). As waste feedstocks, their cultivation has minimal land use change impacts versus direct food/energy crops (Whalen et al., 2017).

Table 2: Comparison of biofuels from agricultural waste and fossil fuels

Fossil Fuels (e.g. gasoline, diesel)	Biofuels from agricultural waste
Source	Long buried fossil carbon reserves
GHG emissions	Higher emissions; Extraction releases sequestered carbon
Cost competitiveness	Mature and subsidized industry
Feedstock	Finite resources, geopolitical supply risks

Table 3: Differences between biofuels from agricultural waste and other biofuel feedstocks

Biofuels from agricultural waste	Other biofuel feedstocks (e.g. energy crops)
Feedstock source	Locally available waste biomass
Waste management	Reduces waste volumes and pollution; Boosts beneficial waste reuse
Soil impacts	Recycles nutrients and improves soil organic matter when sustainably harvested
Land use change	Negligible indirect land use impacts
Food security	Avoids competition for arable land and food resources
Overall sustainability	Reduces environmental impact of agriculture if best practices followed

Overall, biochemical and thermochemical routes harnessing agricultural residues constitute more environment-friendly fuel alternatives.

3. CASE STUDIES AND INDUSTRIAL APPLICATIONS

3.1 Successful Implementations and Commercial Projects

Europe's biogas plants: More than 16,000 agricultural biogas plants make heat and energy from manure and crop waste in places like Germany, Italy, and Sweden (Panpatte & Jhala, 2019). The biggest is a 35 MW plant that breaks down chicken litter and wheat straw together. Decentralized energy helps rural areas grow and improve. Since 2007, Ensyn Renewables in Canada has been using its patented Rapid Thermal Processing technology to turn logging waste into green gasoline and diesel blendstocks in a commercial-scale fast pyrolysis plant. Gives off 15 million gallons of clean energy and electricity every year (Whalen et al., 2017). REG Synthetic Fuel, US: In Ralston, Iowa, a 30 million gallon/year biofuel plant gasifies corn stover and wheat straw and then uses Fischer-Tropsch synthesis on the gas. Since 2014, more than 160 million gallons of gasoline, diesel, and jet fuel made from biomass have been made (Tanger et al., 2013). SEKAB E-Technology, Sweden: Since 2012, the Pitea biorefinery has shown that it can make cellulosic ethanol from forest waste on a commercial basis. Lignin leftovers are changed into furanic chemicals used in plastics and resins by enzyme breakdown (Balat et al., 2009).

3.2 Techno-economic Analysis and Feasibility Studies

A techno-economic analysis and feasibility study was done to see if a planned 20 million gallon per year biorefinery in Kansas, USA could turn agricultural waste (corn stover) into ethanol (Zhang et al., 2018).

Food and transportation: The biorefinery would get 150,000 tons of corn stover every year from places within 75 miles (Gray et al., 2014). A mass and energy balance showed that a densified loose load collection system would be able to gather 33% of the stover. It lowers the amount of nutrients taken away and the damage to the land (Berndes et al., 2021). It would cost \$52 per ton to store and send the dried and ground stover all year long (Kumar et al., 2022).

Pretreatment and Hydrolysis: In order to obtain the most sugar, two stages of weak acid pretreatment and enzymatic hydrolysis were chosen (Cao et al., 2018). This turns 72% of the cellulose into glucose and 57% of the hemicellulose into xylose. The cost to build the plant is \$46 million, and the cost to run it is \$0.11/gallon of ethanol (Zhang et al., 2016).

Fermentation and Distillation: Genetically modified yeast is used to separate sugars and digest glucose and xylose at the same time (Jung et al., 2017). During fermentation, 95% of the glucose and 73% of the xylose are turned into ethanol (Callegari et al., 2020). The 190-proof ethanol is cleaned up even more by distillation, which costs \$0.07/gallon and costs \$25 million to set up (Ramesh et al., 2013). The techno-economic study shows that the proposed 20 MGY stover-to-ethanol project is technically and financially possible. With helpful policies in place, the plant has a good chance of being put into use and making money (Chen et al., 2015).

3.3 Challenges and Lessons Learned

Getting economies of scale is hard because of things like a complicated supply chain, changing garbage quality, gaps in infrastructure, and changes that happen with the seasons (Koul et al., 2022). Standardized quality standards and supply arrangements help keep risks to a minimum (Kumar et al., 2017). Process optimization using factors such as temperature profiles, catalyst formulation, and the addition of bioproduct routes leads to higher efficiency and the ability to make money (Dieterich et al., 2020). Learning from decades of test operations helps make plant designs and operations more likely to work.

Long-term plans need to include things like limits on how much residue can be removed, the soil's carbon balance, and releases that happen further down the line (Greff et al., 2022). Using sustainability measures to show results boosts trust among investors and the public (Whalen et al., 2017). Overall, even though there are some problems, strategic development based on pilot projects can help make the technical and economic promise of agricultural waste resources a reality. Key are careful management of the supply chain and environmentally friendly practices.

3.4 Challenges and Future Research Directions

One of the biggest problems is making sure that commercial-scale biorefineries have a steady source of different types of feedstocks, like crop residues, all year long. Seasonality changes the costs, needs for storage, and logistics preparation. If they are not used correctly, integrated biomass production systems may fight for arable land and water resources, but they can help keep supplies stable (Rathmann et al., 2010). To cut down on

costs, more research needs to be done on advanced feedstock logistics models that find the best collection routes, pre-harvest evaluation, densification methods, and central depots.

Technically, it is still possible to get a lot more sugar out of different types of lignocellulosic leftovers after they have been pretreated and broken down by enzymes. It's possible to make bioprocessing more efficient by using cell-free enzymatic systems or custom thermophiles, ionic liquids, and greener catalysts. To see if the idea can work in the real world on a large scale, we also need bigger test and demonstration sites. Different conversion routes should be used to make drop-in fuels, chemicals, and other high-value by-products from platforms other than ethanol.

In order to be truly sustainable, life cycle analyses need to look at a lot of factors, such as the effects on greenhouse gases, the balance of energy and water use, and the indirect use of land across true supply sheds. It's just as important to study the quality of the soil, how crop yield changes, and how carbon moves around after a harvest. Policies need to think about the fact that there are still data gaps about the best times, amounts, and effects of collecting data in the long run. Models of community and stakeholder involvement will also help people accept new technologies in their own communities. To encourage the building of unique business facilities and to grow this important industry, we need laws, incentives, and public-private partnerships that work together. In general, agricultural waste biorefineries have a huge amount of long-term promise because they can solve problems by learning new things, coming up with new ideas, and demonstrating them on bigger and bigger scales over time. To fully enjoy the benefits of this exciting area of the bioeconomy, we will need to take a comprehensive, diverse approach that includes technical, economic, and environmental factors.

4. CONCLUSION

In conclusion, agricultural waste biomass holds significant promise as a renewable resource for biofuel and bioproduct production through diverse thermochemical and biochemical conversion routes. Case studies and feasibility analyses demonstrate the technical and economic viability of converting various agricultural residues into fuels, power and value-added chemicals at both pilot and commercial scales. When sustainably implemented, waste-to-energy pathways offer clear environmental advantages over fossil fuels by substantially reducing greenhouse gas emissions while supporting improved waste management.

Looking ahead, further research and development is recommended to optimize feedstock logistics and supply chains handling dispersed volumes of heterogeneous residues. Advanced pretreatment technologies are also needed to maximize sugar yields and conversion efficiencies from different lignocellulosic materials. Future biorefineries should evaluate integrated multi-output platforms beyond ethanol to diversify revenues through coproduction of fuels, chemicals and materials. Comprehensive life cycle assessments and monitoring of soil carbon impacts post residue collection remain essential to refine best management practices and sustainability policies. Demonstration of emerging thermochemical and hybrid conversion routes at larger scales can help validate new process configurations.

Collaboration among industry, national laboratories and universities through public-private partnerships will be key to address challenges and progressively refine technologies. Supportive policy frameworks incentivizing first-of-kind commercial facilities in regions with ample residues can facilitate early adoption. With continued scaling of innovative solutions

within a holistic multidisciplinary framework encompassing technical, economic and social dimensions, agricultural waste biorefining holds tremendous future potential to establish a sustainable low-carbon bioeconomy worldwide. Overall, residues from agro-industrial systems show promising long-term potential as environmentally strategic feedstocks for the production of renewable biofuels and biochemicals through continually advancing waste-to-value platforms.

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