

1

Agricultural Waste as a Feedstock for Bioenergy

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1.1 Introduction

1.1.1 Global Energy Demand and Sustainability Challenges

The global energy landscape is undergoing a dramatic transformation as humanity grapples with the dual challenge of meeting rising energy demand while mitigating environmental pressures. Over the past five decades, global energy consumption has increased nearly threefold, reflecting rapid industrialization, urban expansion, and improvements in living standards. According to recent international energy projections, demand is expected to increase by another 25–30% by 2040, particularly in emerging economies in Asia and Africa [1]. Fossil fuels such as coal, oil, and natural gas still account for more than 80% of the global energy input, making the sector one of the largest contributors to greenhouse gas (GHG) emissions [2].

The consequences of this dependency are becoming increasingly serious. The combustion of fossil fuels releases vast amounts of carbon dioxide, methane, and nitrous oxide, intensifying global warming and triggering more frequent extreme weather events. Moreover, air pollution from fossil energy systems is linked to millions of premature deaths annually, while resource depletion raises concerns about long-term energy security. Therefore, the need for clean, affordable, and accessible energy is not just an environmental imperative but also a socioeconomic necessity.

In recent years, different types of renewable energy sources such as solar, wind, hydropower, and biomass have gained global prominence. Each of these resources offers unique advantages, but biomass occupies a distinctive position because of its ability to simultaneously provide energy and manage waste. Unlike intermittent renewables, biomass can deliver dispatchable energy, making it a valuable complement in diversified energy systems. Within the biomass sector, agricultural residues represent one of the most available, promising, yet underexploited resources for sustainable energy development.

1.1.2 Role of Agricultural Residues in Renewable Energy

Agriculture is an essential pillar of the global economy and human survival, but it is also a sector that produces huge quantities of biomass waste. Every stage of crop cultivation, harvesting, and processing produces by-products such as straw, stalks, husks, shells, cobs, bagasse, and oilseed cakes. In addition, animal husbandry contributes manure, bedding materials, and other organic residues. Estimates suggest that the world produces more than five billion tons of agricultural residues annually, with Asia alone accounting for more than 40% due to the intensity of rice, wheat, and maize cultivation [3].

In many regions, these residues are either left unused, openly burned in fields, or disposed of through landfilling and uncontrolled dumping. Such practices create significant environmental and social problems, including air pollution, soil degradation, and the release of GHGs during decomposition. The burning of rice straw in South and East Asia, for example, contributes heavily to seasonal smog episodes that impact public health and regional climate [4]. Yet, these residues possess high concentrations of lignocellulosic biomass, which consists mainly of cellulose, hemicellulose, and lignin, making them suitable for conversion into diverse bioenergy products.

Value-added conversion of agricultural residues for bioenergy provides several advantages. First, these materials are by-products rather than primary crops, meaning they do not directly compete with food production. This is an important distinction compared with dedicated bioenergy crops such as maize or sugarcane, which can exacerbate food–fuel conflicts. Second, agricultural residues are often locally available in large quantities, reducing transport costs and enabling decentralized energy solutions in rural areas. Third, their valorization contributes to a circular economy by converting waste streams into useful products, simultaneously improving waste management and generating economic opportunities for farmers.

Several conversion pathways already exist and are still being updated. For example, residues can be anaerobically digested to produce biogas, which serves as a direct substitute for natural gas in heat and power generation. Alternatively, pyrolysis and gasification processes transform them into biochar, syngas, or liquid fuels. Even simple densification into pellets or briquettes offers a renewable replacement for coal in residential heating or industrial boilers. Beyond energy, agricultural residues also hold potential for producing advanced materials such as bio-based carbon catalysts, electrodes, biodegradable plastics, and soil amendments, linking energy recovery to broader sustainability benefits. Thus, agricultural residues are more than an agricultural by-product; they represent a renewable energy feedstock that aligns with climate goals, rural development, and sustainable waste management strategies.

1.1.3 Chapter Objectives

The aim of this chapter is to provide a comprehensive exploration of agricultural waste as a feedstock for bioenergy. The discussion is structured to reflect the

multifaceted nature of this topic, covering technical, environmental, and policy dimensions. The specific objectives are as follows: (i) To review the diversity and global availability of agricultural residues. This involves mapping the types of wastes, from crop residues like straw and husks to processing by-products such as bagasse, and assessing their regional distribution. Understanding availability is crucial for determining both local and global bioenergy potential. (ii) To evaluate the physicochemical characteristics that influence bioenergy applications. Agricultural residues vary significantly in cellulose, hemicellulose, lignin, and ash content, all of which affect energy potential and conversion efficiency. This chapter will outline these compositional features and highlight their relevance in different bioenergy pathways. (iii) To assess environmental and policy considerations.

Residues play a role in reducing GHG emissions, improving soil health, and mitigating pollution when properly managed. At the same time, their utilization is shaped by national and regional policies, economic incentives, and competing uses. These aspects will be critically examined to provide a holistic perspective. Moreover, the chapter will highlight ongoing challenges and limitations, such as seasonal availability, storage, and logistics, while pointing toward future prospects including digitalized biorefineries, integrated waste valorization, and artificial intelligence-driven optimization of waste-to-energy systems.

As the world searches for solutions for the urgent need for decarbonization and resource efficiency, agricultural residues emerge as both a challenge and an opportunity. Left unmanaged, they pose environmental burdens and economic losses. When harnessed effectively, however, they provide a renewable, carbon-neutral energy resource that contributes to climate mitigation, rural livelihoods, and circular economy strategies. This introduction sets the stage for the subsequent sections, which will delve deeper into the types of agricultural wastes, their characteristics, current applications, challenges, and policy frameworks. Collectively, these discussions aim to provide a robust foundation for understanding how agricultural residues can be strategically mobilized in the global effort toward sustainable energy and material recovery.

1.2 Types, Sources, and Availability of Agricultural Wastes

Agricultural wastes are the residues obtained from the production and processing of agricultural products such as crop residues, processing residues, livestock-related biomass, and food waste. Employing agricultural residues for energy purposes contributes to the valorization of crop systems and supports a more sustainable agricultural framework.

1.2.1 Crop Residues

Crop residues include lignocellulosic biomass obtained from field remnants after harvesting the crops and comprise the bulk portion of primary agricultural waste.

Cereal straws such as rice, wheat, and barley, husks like groundnut shells, rice hulls, and cobs, and stalks such as maize stover and sorghum stalks are the most commonly available crop residues. The generation of crop residues usually varies depending on the type of crop, harvesting technique, and regional agricultural practices [5]. As the waste residues are collected directly from crop farming at fields, these are considered the most inexpensive organic waste, and a variety of carbon-based value-added products can be easily obtained by utilizing these crop residues. These residues are categorized into primary and secondary type residues. Primary residues are those usually generated while harvesting crops in fields, and the residues that are produced by further processing of main products are known as secondary residues, also referred to as process-based residues. These are heterogeneous wastes, which vary in bulk density, moisture content, particle size, and distribution. Improper management of crop residues can exacerbate environmental problems, such as air pollution, and simultaneously lead to nutrient depletion and a decline in soil fertility by disrupting beneficial soil organisms [6]. Beyond these challenges, crop residues are increasingly recognized as valuable resources that contribute to soil organic matter maintenance, nutrient recycling, livestock feeding, and as renewable feedstock for bioenergy and bio-based products.

Globally, three primary crop residues are commonly used for bioethanol production: rice straw, wheat straw, and corn stover. These residues are produced throughout the year, but only a small fraction is used for fodder or biofuel, while the majority is often burned, leading to significant environmental issues. Rice straw is one of the most abundant and promising biomass sources globally, with an annual production of 731 million tons, primarily in Asia. Wheat straw, the by-product of wheat harvesting, yields approximately 1–3 tons per acre, with a total global annual production of 354.34 million tons. Corn stover, also called corn straw, is considered a highly promising feedstock for lignocellulosic ethanol, with an estimated yield of 4.0 tons per acre and a global annual production of 128.02 million tons [7]. Additionally, residues from crops like barley, sorghum, and oats also contribute to agricultural wastes.

1.2.2 Crop Processing Residues

While primary crops undergo agro-industrial processing, the by-products generated are known as processing residues, which can also be referred to as secondary agricultural wastes. Processing residues are usually produced by different industrial operations such as sugar mills, rice mills, and oil mills, while crop residues are typically scattered throughout the harvest fields. The increasing global demand for renewable energy has highlighted the importance of processing residues from agricultural and industrial activities as valuable feedstocks for bioenergy. Processing residues, often considered low-value by-products, possess a significant content of lignocellulosic biomass that can be effectively converted into biofuels, biogas, and other forms of bioenergy. Utilizing these resources not only contributes to sustainable energy production but also minimizes the environmental impact of waste disposal.

The advantages of using processing residues include their wide availability, low cost, and potential to reduce GHG emissions. Moreover, integrating bioenergy production into existing agro-industrial processes enhances resource efficiency and creates additional revenue streams. However, several challenges must be addressed, including the variability in residue composition, seasonality of agricultural by-products, and the need for pretreatment technologies to improve the conversion efficiency. High lignin content and structural complexity often require energy-intensive pretreatment methods before conversion [8]. The incorporation of agricultural and industrial residues into bioenergy supply chains represents a sustainable pathway to meet energy demands while addressing waste management issues. Future advancements should focus on developing cost-effective pretreatment methods and establishing regional supply networks that ensure the continuous availability of biomass. By promoting bioenergy from processing residues, industries and policymakers can significantly contribute to the transition toward a low-carbon and sustainable energy future.

1.2.3 Livestock-related Biomass

Livestock-related biomass offers one of the most promising, locally available, renewable feedstocks for bioenergy with significant potential in regions of intensive livestock farming where its collection and utilization are most feasible. Livestock biomass refers to various organic residues derived from livestock production, including manure, bedding, animal by-products (e.g., offal, bone, and fat), slurries, and urine, and sometimes even wasted feed, plus residues associated with livestock operations (e.g., straw used in bedding). A study proposed steam pretreatment of animal bedding, consisting of a mixture of straw and cow manure, to enhance ethanol yields. The results suggest that steam pretreatment could unlock the bioenergy potential of bedding materials, achieving conversion efficiencies comparable to higher-quality feedstocks [9]. These materials can be converted into bioenergy through different biological or thermal processes. For example, the abundance, reusability, and enriched organic matter content of these wastes make them potential feedstock for biogas generation. When suitably collected, treated, and converted, it can generate heat, electricity, reduce GHG emissions, and improve waste management.

Livestock operations in the United States produce an estimated 35 million dry tons of manure-based biomass each year, representing nearly 18% of the sustainable biomass potential from agricultural lands [10]. The application of waste-to-bioenergy technologies in livestock systems can transform waste management from an economic burden into a revenue-generating process, offering opportunities for steady annual income, reduced dependence on commodity price fluctuations, and enhanced diversification of farm revenues. The selection of an appropriate biomass conversion pathway is primarily influenced by economic feasibility, the quantity, and characteristics of the feedstock. The outputs from these processes are broadly categorized into three groups: heat and power, transportation fuels, and chemical intermediates.

1.2.4 Food Waste Biomass

Food waste includes food items that are thrown away or left uneaten, available in abundance throughout the food supply chain from households to restaurants, retail sectors, food processing industries, and so on. The main objective is to develop the most effective processing techniques that should be cost-effective and eco-friendly, mitigate the worldwide-expanded release of GHGs, and enhance the yield of energy to a great extent. For example, noodles are excessively consumed, and cheap food and its processing industries usually generate an abundance of solid and liquid waste like rice in starch, lignin, cellulose, oil, and so on. Modern technologies like anaerobic digestion, gasification, transesterification, fermentation, and pyrolysis can transform these generated noodle residues into sustainable fuels such as bioethanol, biodiesel, biogas, and bio-oil [11]. Almost 20% oil content of noodle residues might contribute to valuable biodiesel generation, and the remaining starch portion can be processed by enzymatic hydrolysis and fermentation to produce ethanol. Fish by-products are considered another valuable resource. Up to 80% of the fish parts, like heads, fins, skin, shells, and tails, are discarded while processing. These residues are loaded with important macro and micronutrients like proteins, lipids, collagen, gelatin, chitin, and essential minerals that make them highly potential as a source for biorefineries, transformation into biofuels, as well as a variety of valuable products. For instance, wastewater from fish processing has been effectively utilized for biogas production through anaerobic digestion [12].

1.2.5 Regional and Global Availability

The idea of employing agricultural biomass as an energy resource can be traced back to the early 1800s. In 1830, biofuel production in Ethiopia was reported using the plant *Euphorbia abyssinica*, marking one of the earliest documented examples of biomass conversion for energy. Sixty percent of this energy is used for traditional heating and cooking, while the remainder is used in modern conversion technologies to produce heat, transport fuels, and electricity. One of the earliest large-scale demonstrations of cellulosic ethanol production was launched in Italy in 2012, operated by Beta Renewables Crescentino, producing about 60,000 metric tons annually from giant reed (*Arundo donax*) and wheat straw. By 2014, three major US facilities followed: DuPont's 30 million gallon per year plant in Nevada, Iowa, using corn stover, Poet-DSM's Emmetsburg, Iowa, facility producing 7–12 million gallons, relying on corn cobs and stover, and Abengoa's Hugoton, Kansas plant with a capacity of 25 million gallons primarily from corn stover. In Canada, progress has focused more on chemicals than fuels, exemplified by Comet Biorefining's planned 23,000-ton cellulosic sugar facility in Sarnia, with animal feed coproducts. The Atikokan Generating Station in Northern Ontario operates entirely on wood pellets, chosen because their energy content closely matches that of lignite coal, the plant's original fuel. This similarity enabled straightforward adaptation of much of the existing infrastructure. Pellet procurement follows a competitive process that mandates sourcing from sustainably managed forests. In Denmark, around 1.4 million tons of straw

Table 1.1 Classification and availability of agricultural wastes worldwide.

Waste type	Example source(s)	Annual generation (Mt/yr)	Major producing regions
Crop residues	Cereal (corn, rice, wheat, barley), legumes (soybeans chickpeas), tuber crops (potato)	5280	China, Vietnam, Thailand, India, United States, Brazil, EU, Southeast Asia
Processing residues	Sugarcane bagasse, oilseed cake, fruit pomace, milling bran, brewery, spent grain	~279–467	Brazil, India, China, Thailand, Pakistan, Mexico, Colombia, Indonesia, Philippines, United States
Livestock-related biomass	Cattle, pig, poultry manure (slurry, solid, droppings)	~125	China, EU, United States, Brazil, India, Africa, South America, Central Asia
On-farm food waste (post-harvest losses)	Spoiled fruits/vegetables, tubers lost during harvest/handling	10–50% of production lost for some commodities; aggregate hundreds of Mt/yr	Sub-Saharan Africa, South/Southeast Asia, Latin America, China, India

Source: Data from [13, 14].

are consumed annually for heat and power, representing roughly 16% of renewable energy and 2–3% of total national energy production. Table 1.1 provides an overview of agricultural waste types and their availability across the world.

Recent assessments indicate that biomass resource production across 62 countries amounts to a combined total of 2.83 billion dry metric tons [15]. Currently, Brazil and the United States are the leading biomass producers. Within the European Union, the primary current feedstock is lipids (fats and greases derived from crops), which are mainly used for biodiesel production. In most other regions, forest residues are the most significant biomass feedstock, and the main applications are for heat and cooking.

1.3 Characteristics of Agricultural Waste Relevant to Bioenergy

Agricultural residues represent one of the largest streams of biomass available for renewable energy production, with annual generation surpassing 140 billion metric tons worldwide. While often treated as waste through practices such as open burning or landfilling, these materials carry significant energy potential [16]. Their utilization, however, depends on more than just availability; the physicochemical characteristics of the residue determine how effectively they can be converted into bioenergy. The lignocellulosic composition, moisture content, ash fraction, and

nutrient profile directly influence conversion pathways and efficiency [17]. Understanding these properties is therefore essential to designing sustainable valorization strategies that reduce environmental impacts and support the transition toward a circular bioeconomy.

1.3.1 Physical and Chemical Composition (Lignin, Cellulose, Hemicellulose, Ash)

Agricultural waste is largely lignocellulosic, mainly consisting of cellulose, hemicellulose, and lignin, with proportions varying by crop species, growth conditions, and residue type. These compositional differences determine whether biochemical routes (e.g., anaerobic digestion and fermentation) or thermochemical routes (e.g., pyrolysis and gasification) are most appropriate. Cellulose is the most abundant fraction, comprising 30–60% of residues. It is a crystalline polymer of glucose linked by β -1,4-glycosidic bonds, resistant to enzymatic hydrolysis yet valuable as a source of fermentable glucose [18]. Hemicellulose, by contrast, is a heterogeneous and amorphous polymer of pentoses and hexoses, accounting for 15–50% of residues. Its relative ease of hydrolysis is offset by the risk of producing inhibitory compounds such as furfurals during harsh pretreatment [19]. Lignin, an aromatic and highly recalcitrant polymer, provides rigidity but restricts access to cellulose and hemicellulose. It contributes 8–40% of residue composition, hindering biochemical conversion but offering high calorific value for thermochemical pathways [20]. In addition to these major fractions, agricultural residues may also contain starch, typically present as amylose and amylopectin granules, along with minor organic constituents such as proteins (up to 10%), lipids (2–40%), acetyls, uronic acids, and inorganic minerals [18]. Moisture content is another important index of biomass quality, ranging from 10 to 60%, and in some cases such as food waste, exceeding 80%. High moisture levels significantly affect handling, storage, and the energy potential of the biomass [21]. Ash content, particularly in silica-rich feedstocks such as rice husk, may exceed 16%, reducing energy density, promoting slagging, and interfering with catalysts [22]. These compositional differences strongly influence conversion pathways: while cellulose and hemicellulose favor biochemical routes like fermentation or anaerobic digestion, lignin and high-ash residues are better suited for thermochemical processes such as pyrolysis and gasification. Representative analyses show that agricultural residues vary widely in cellulose, hemicellulose, lignin, starch, and ash, affecting their calorific value. Rice straw contains 20–40% cellulose, 20–50% hemicellulose, and up to 16% ash, yielding 15 MJ/kg, while groundnut shells, richer in lignin, reach about 18 MJ/kg. Table 1.2 summarizes the physicochemical properties of agricultural wastes, highlighting that silica-rich rice husk has lower energy density and operational issues, whereas lignin-rich groundnut shells are more suitable for thermochemical conversion [30].

1.3.2 Energy Potential (Calorific Value, Biodegradability)

Agricultural residues are valuable feedstocks for renewable energy due to their calorific value, biodegradability, and ability to generate multiple forms of biofuels.

Table 1.2 Physicochemical properties of representative agricultural wastes.

Biomass type	Cellulose (%)	Hemicellulose (%)	Lignin (%)	Ash content (%)	Heating value (MJ/kg)	References
Rice straw	20–40	20–50	8–10	10–20	~12.0	[23]
Wheat straw	30–50	20–25	10–25	4–8	~15.7	[24]
Maize stalk	35–40	15–45	7–10	2–5	~18.7	[25]
Sugarcane bagasse	40–50	25–35	15–20	2–6	~18.0	[26]
Peanut shell	30–40	5–20	20–40	2–6	~21.0	[27]
Sunflower stalk	30–45	30–35	15–30	6–16	~14.0	[28]
Soybean stover	40–50	10–25	15–20	4–6	~19.0	[29]

Their heating values typically range from 15 to 19 MJ/kg, making them suitable for combustion and thermochemical processes such as pyrolysis and gasification [17]. Lignin-rich residues achieve higher calorific values, while high ash and moisture contents reduce energy recovery. Thermochemical conversion can yield products like syngas, a mixture of H₂, CO, and CO₂, or bio-oil, both of which serve as intermediates for further fuel production [31]. In biochemical pathways, biodegradability plays a central role. Cellulose and hemicellulose are digestible, but lignin restricts their accessibility. Residues with low lignin fractions, such as vegetable wastes, are well suited for anaerobic digestion, producing biogas—a clean, low-cost mixture of methane and carbon dioxide. Moisture-rich residues, though unsuitable for direct combustion, are advantageous for fermentation-based pathways, enabling the production of liquid fuels like bioethanol, biobutanol, and biodiesel [32].

1.3.3 Pretreatment Requirements and Variability Across Feedstocks

Pretreatment is a critical step for both thermochemical and biochemical conversion of agricultural biomass. Lignocellulosic materials are naturally recalcitrant, and pretreatment enhances enzymatic or microbial accessibility by reducing cellulose crystallinity, solubilizing or disrupting lignin, and increasing surface area. The specific requirements for pretreatment vary across feedstocks. For example, rice and wheat straw, which contain high levels of silica and lignin, often require intensive chemical or thermal pretreatment, whereas residues like soybean stover or fruit waste can be effectively treated using biological or mild physical methods. Pretreatment also significantly impacts sugar yield, fuel quality, and downstream process efficiency, and can account for over 40% of the total cost of producing second-generation biofuels, highlighting its role as a major techno-economic bottleneck [17, 33].

1.3.3.1 Conventional Pretreatment Approaches

Conventional pretreatment methods include physical, chemical, biological, thermal, and mechanical processes that modify biomass to improve digestibility and conversion efficiency. Physical pretreatment reduces particle size and increases surface area through milling, grinding, or chipping. These modifications improve enzymatic accessibility for biochemical conversion and facilitate heat transfer in thermochemical processes like torrefaction or pelletization. While physical methods reduce cellulose crystallinity and polymerization degree, they generally preserve chemical integrity. Method selection depends on biomass type and intended application [34]. Chemical pretreatment involves acids, alkalis, organic solvents, or ionic liquids to break polymeric bonds, depolymerize hemicellulose, and solubilize lignin. This approach enhances cellulose accessibility, reduces crystallinity, and improves hydrolysis efficiency [35]. Even diluted acids can achieve high treatment efficiency, making chemical methods widely used due to their scalability and cost-effectiveness, though careful control is required to minimize inhibitor formation. Biological pretreatment relies on microbes, primarily fungi, to selectively degrade lignin and hemicellulose while leaving cellulose largely intact. This energy-efficient and environmentally friendly method avoids toxic by-products but is slow, requires controlled growth conditions, and occupies significant space. Microbial residence times are often around two weeks, with efficiency dependent on organism type and feedstock characteristics [36]. Thermal pretreatment includes hydrothermal processing, steam explosion, and microwave heating. Operating typically between 50 and 300 °C, these methods accelerate depolymerization, improve anaerobic digestion rates, and reduce microbial load. Steam explosions are particularly effective for lignocellulosic residues, using high-pressure steam followed by rapid depressurization to mechanically disrupt fibers and solubilize lignin. Process parameters must be optimized to avoid the formation of inhibitory recalcitrant compounds. Mechanical pretreatment, such as milling, grinding, or shearing, reduces particle size and enhances porosity, improving hydrolysis efficiency and digestibility. Smaller particles allow better enzyme access, accelerating conversion rates, while fiber disruption further exposes cellulose and hemicellulose for subsequent processing [37, 38].

1.3.3.2 Advanced and Emerging Pretreatment Techniques

Advanced pretreatment methods provide alternative or complementary solutions, particularly for highly recalcitrant biomass. Ionic liquid-based pretreatment uses low-melting, nonvolatile solvents to disrupt hydrogen bonding in lignocellulosic biomass, effectively solubilizing lignin and increasing cellulose accessibility. This approach is particularly effective for wheat straw, corn stover, and woody residues. Combining ionic liquids with additives such as ammonia improves cellulose recovery and reduces processing time and cost. Rice straw treated with 1-N-butyl-imidazolium chloride achieved over 95% conversion, demonstrating the potential for ethanol and other biorefinery applications. Electrical pretreatment techniques, including pulsed electric fields and electron beam irradiation, modify biomass at the structural and chemical levels. These treatments increase porosity,

enhance surface area, and improve enzymatic hydrolysis efficiency. These pretreatments increase porosity, enhance surface area, and improve enzymatic hydrolysis efficiency in various feedstocks such as vegetable and fruit waste, wood chips, and lignocellulosic residues like rice straw and switchgrass, though lignin remains partially resistant to these methods [17, 39].

1.3.4 Biomass Characterization Methods

Detailed characterization of biomass composition and properties is essential for selecting and optimizing conversion processes. Basic characterization often begins with proximate analysis, which determines moisture, volatile matter, fixed carbon, and ash content, providing insights into combustion performance and energy potential. Ultimate analysis complements this by measuring elemental composition (C, H, O, N, S), which is closely correlated with calorific value and emission characteristics. While proximate and ultimate analyses are useful for general fuel properties, advanced methods are necessary to explore structural, compositional, and thermal behavior in greater detail [40]. Compositional analysis is crucial for understanding biomass reactivity, degradation mechanisms, and suitability for producing biofuels and value-added chemicals. The typical procedure involves first removing moisture and soluble extractives, followed by specific chemical treatments to isolate each component. Cellulose is commonly measured through strong acid hydrolysis, hemicellulose through sequential alkaline extraction, and lignin using Klason analysis with concentrated sulfuric acid. More recently, spectroscopic and hybrid analytical techniques have been developed to increase precision and reduce processing time. These methods provide reliable compositional data that support advancements in bioenergy, material science, and environmental applications [41].

1.3.4.1 Organic Compounds Characterization

Analysis of organic compounds provides quantitative and qualitative information about the chemical constituents of biomass. This is particularly important for detecting modifications caused by pretreatment and for identifying functional groups that influence conversion behavior. Fourier transform infrared spectroscopy (FTIR) is widely applied for this purpose. It works on the principle that organic compounds absorb infrared radiation in the 400–4000 cm^{-1} region, producing spectra that reveal functional groups and chemical bonds. FTIR has been extensively used to monitor the removal of lignin and hemicellulose during pretreatment and to assess reactive components that affect thermochemical and biochemical pathways. Because it is rapid, non-destructive, and versatile, FTIR remains a standard tool for biomass characterization in both thermochemical and biochemical applications [42].

1.3.4.2 Structural Characterization

The structural organization of biomass plays a central role in its reactivity and conversion efficiency. A combination of analytical tools is typically required to capture information on crystallinity, chemical composition, and morphology. X-ray diffraction (XRD) provides information on crystalline versus amorphous

phases, crystal size, and molecular orientation. These data are critical for evaluating the hydrolysis efficiency of pretreated biomass, since cellulose crystallinity is directly linked to enzymatic hydrolysis rates. Nuclear magnetic resonance (NMR) spectroscopy adds complementary detail by revealing chemical and structural orientation in lignocellulosic biomass. It allows researchers to assess cellulose crystallinity, hemicellulose distribution, and overall chemical bonding within the solid-state matrix. This makes NMR particularly valuable for designing efficient processes aimed at biofuel and value-added product generation. Scanning electron microscopy (SEM) provides direct visual evidence of surface morphology and particle structure. It produces high-resolution images of pore development, fiber disruption, and other morphological features that result from pretreatment. Such information helps in assessing pretreatment efficiency and predicting susceptibility to further thermochemical or biochemical conversion. Since SEM requires moisture-free samples, biomass must be thoroughly dried before analysis to avoid imaging distortions [17, 43]. X-ray photoelectron spectroscopy (XPS) is a useful technique for examining the surface composition and chemical states of agricultural biomass materials. When the sample is exposed to X-rays, electrons are ejected from its surface. By measuring the energy of these electrons, researchers can identify the elements present and determine their oxidation states. XPS is particularly effective for studying surface functional groups and chemical modifications. For example, this information helps explain how biomass-derived materials interact with contaminants during adsorption [44].

1.3.4.3 Thermochemical Characterization

Thermal characterization methods evaluate the behavior of biomass under heating conditions, which is crucial for thermochemical systems such as combustion, pyrolysis, and gasification. Thermogravimetric analysis (TGA) measures changes in biomass mass as a function of temperature under controlled heating. It provides information on volatile content, fixed carbon, ash yield, and thermal degradation kinetics. By simulating conditions similar to thermal energy production units, TGA delivers essential data for designing and optimizing conversion processes. Differential scanning calorimetry (DSC) complements TGA by monitoring heat flow during heating or cooling cycles. It identifies phase transitions, endothermic and exothermic reactions, and activation energy, making it highly relevant for optimizing thermal conversion efficiency. Gas chromatography–mass spectrometry (GC–MS) is employed to analyze volatile and semi-volatile compounds generated during pyrolysis or hydrothermal liquefaction. By separating and identifying these compounds, GC–MS helps map degradation pathways and quantify biofuel and value-added chemical products. Given the structural variability of biomass, GC–MS is critical for tailoring pyrolysis and liquefaction processes to maximize desired outputs [36, 45].

1.4 Environmental and Sustainability Benefits

1.4.1 Reducing GHG Emissions

One of the most compelling environmental advantages of utilizing agricultural residues for bioenergy is the potential to significantly reduce GHG emissions. Open-field burning and unmanaged decomposition of crop residues release large quantities of carbon dioxide, methane, and nitrous oxides. By utilizing residues in controlled bioenergy conversion processes such as anaerobic digestion, pyrolysis, or combustion in efficient systems, emissions can be mitigated substantially. For example, biogas capture from livestock manure not only displaces fossil-derived natural gas but also prevents the uncontrolled release of methane, a GHG over 25 times more potent than carbon dioxide on a 100-year timescale [46].

1.4.2 Improving Soil Health

Agricultural residues are considered part of the short-term carbon cycle because the carbon they contain originates from atmospheric CO₂ fixed by crops during photosynthesis. When residues are converted into bioenergy, the CO₂ released is largely offset by future crop growth, contributing to carbon neutrality. However, the sustainability of residue removal depends on balanced management practices. Excessive extraction of crop residues can deplete soil organic carbon, reduce soil fertility, and increase erosion risk. Conversely, partial retention of residues or the application of biochar (a co-product of pyrolysis) can enhance soil structure, water retention, and nutrient cycling. Such integrated approaches not only preserve long-term soil productivity but also sequester carbon in stable forms, offering additional climate benefits.

1.4.3 Waste Management and Pollution Reduction

Improper disposal of agricultural residues, particularly through open burning, remains a significant source of air pollution in many regions. Fine particulate matter (PM_{2.5}) from residue burning is linked to severe respiratory and cardiovascular diseases. Transitioning residues into bioenergy pathways reduces such localized air pollution burdens. In addition, waste-to-energy approaches offer an alternative to landfilling or uncontrolled dumping, minimizing leachate formation and the associated risk of groundwater contamination. Bioenergy valorization also encourages circular economy practices by converting what would otherwise be an environmental liability into a renewable energy resource and, in some cases, valuable coproducts like biofertilizers or soil amendments. This not only mitigates pollution but also improves rural waste management infrastructure, potentially leading to more sustainable agricultural landscapes and projects.

1.5 Current Applications in Bioenergy Production

There are multiple current applications of bioenergy production that contribute to renewable energy transitions. These include biogas and biomethane generation, solid biofuels, biohydrogen and syngas production, bio-jet fuels, biocarbon-based energy storage materials, and biochar-based catalysts.

1.5.1 Biogas and Biomethane Generation

Biogas, also referred to as biomethane, is a valuable gaseous biofuel that can be considered as a sustainable substitute for conventional fossil fuels. Biogas offers several key advantages over natural gas, including its production from sustainable and renewable resources, its role in reducing environmental pollution caused by organic waste, and its lower net contribution to GHG emissions. The enrichment of macromolecules such as carbs, protein, cellulose, hemicellulose, and lignin within the agricultural residues makes these highly potential for biogas generation especially because of their high methane content. Different crop residues exhibit varying amounts of biomethane content such as rice straw, wheat straw, and corn stover usually produce 302, 290, and 338 L/kg of volatile solids (VS), respectively. Animal manure is considered a highly promising feedstock for biogas production because of its enriched organic matter, high moisture content, and a reduced C/N ratio, which is highly suitable for anaerobic combining. Under optimal conditions, this manure can be utilized as a single substrate. For instance, pig manure can yield 495 mL of biogas per gram of VS with methane content in between 70 and 80%, while cattle manure was reported to generate 398 mL/g VS with a methane fraction of 55–75% [47]. Residual microalgae biomass can be transformed into biogas via anaerobic digestion, generating primarily CH_4 and CO_2 with a very insignificant amount of H_2S . The energy content of generated biogas has a very low heating value (LHV) of only 20–40% of biomass. This process can also be performed with very wet biomass containing 90% of moisture [48]. The yield and energy content of biogas are generally influenced by nutrient constitutes of biomass, process temperature and pH, loading rate, and hydraulic and solid retention times.

The key factors responsible for inhibiting the process of anaerobic digestion include the accumulation of free ammonia, sulfides, metal ions, and other organic compounds. Ammonia inhibition can be overcome by maintaining an optimal C/N ratio and pH, as well as by using a higher organic loading rate [49]. Excess ammonia can also be eliminated through air stripping using inert materials such as zeolite, activated carbon, or clay [50]. Sulfide inhibition can be prevented by keeping an optimal C/S ratio in the substrate. Acid and thermal pretreatment of biomass can generate hydroxymethylfurfural and furfural, which increase nitrogen content and reduce the C/N ratio, thereby inhibiting anaerobic digestion; hydrothermal pretreatment offers a potential solution [50]. Recent advances suggest separating anaerobic digestion into two stages—hydrolysis/acidogenesis and acetogenesis/methanation or using multistage processes to improve organic loading, adjust temperature conditions, and enhance the conversion efficiency of organic substrates [51].

1.5.2 Solid Biofuels

Solid biofuels produced from agricultural biomass include densified products (pellets, briquettes) and thermochemical residues such as biochar. Biomass solid fuels (BSFs), such as briquettes and pellets, are manufactured from compressed biomass feedstock, including agricultural residues, sawdust, and forest waste. Depending on the feedstock characteristics, biomass densification can be achieved with or without binders. Research has shown that while certain residues, such as sugarcane bagasse and rice husk, can form stable pellets without significant morphological changes, other materials, like coffee husk, benefit from binder addition to enhance pellet quality and strength [52]. Biochar is the carbon-rich solid product of pyrolysis (thermal decomposition under oxygen-limited conditions). Pyrolysis temperature, heating rate, and residence time determine biochar yield, fixed carbon content, porosity, and higher heating value (HHV). Biochar often has higher energy density and greater thermal stability than the original biomass and can be used as a direct solid fuel, co-fired with coal, or upgraded for improved handling.

Other processing methods, such as adjusting the moisture content of feedstock or using binders, can also be used to improve the properties of solid fuels. The BSFs made through a combination of binders and biomass usually display better mechanical properties and higher calorific value than non-composite BSFs without any binding agent [53]. The BSF has a lesser carbon footprint than fossil fuels and can help minimize the utilization of nonrenewable energy products. Moreover, BSF can be manufactured locally, which supports local economies and can create jobs. Life-cycle analyses and IEA/IEA-Bioenergy assessments emphasize the need for sustainable feedstock sourcing to avoid adverse land-use impacts and to ensure that bioenergy contributes to climate mitigation and sustainable development goals.

1.5.3 Biohydrogen

When hydrogen (H_2) is produced from renewable sources such as organic matter, biomass, or microorganisms, it is referred to as biohydrogen. In its molecular form, H_2 possesses the highest energy density and is entirely carbon-free, producing only water as a clean by-product during combustion [54]. Biohydrogen serves huge advantages over all other renewable fuels as an alternative clean energy source, addressing global environmental problems like acid rain, ozone layer depletion, and excessive GHG emissions [54]. It has such potential to be directly used as a fuel in combustion engines as well as electricity production through fuel cells [55]. In industrial-scale applications, biohydrogen is employed in synthesizing alcohols, aldehydes, and ammonia, along with the hydrogenation of petroleum, edible oils, coal, and shale oil [55]. Using biological substrates, biohydrogen production occurs through autotrophic or heterotrophic mechanisms. In autotrophic processes, photosynthetic microorganisms like microalgae, bacteria, and protists transform sunlight directly into hydrogen. Heterotrophic processes, in contrast, include anaerobic transformation of biomolecules, mainly carbohydrates, to generate H_2 through dark or photosynthetic fermentation [56].

The generation of H_2 can be enhanced significantly with the pretreatment of corn stalk. Biohydrogen production can be enhanced up to 57 mL H_2 /g VS (19-fold) with 0.5% NaOH pretreatment and up to 150 mL H_2 /g VS (50-fold) with 0.2% HCl with heat treatment, compared to untreated biomass. Thermal, steam explosion, and microwave methods have similarly shown effectiveness [57]. In contrast, livestock waste does not possess high efficiency for hydrogen production owing to its abundance in nitrogen content that inhibits microbial activity by releasing ammonia during the process of fermentation. Fruit and vegetable wastes (FVWs), along with carbohydrate-rich industrial residues such as starch-processing by-products, potato and sugar beet waste, brewery whey, and cheese whey, are abundant in simple sugars, making them suitable feedstocks for biohydrogen production, with yields ranging from 50 to 290 mL H_2 /g VS [58, 59].

1.5.4 Bio-jet Fuel

Bio-jet fuels produced from renewable biomass have gained considerable attention due to their potential to reduce GHG emissions while meeting strict aviation performance standards, including low freezing points, high thermal stability, and favorable cold flow properties. Unlike biodiesel, which suffers from poor low-temperature behavior and limited shelf stability, bio-jet fuels are designed to be fully compatible with aviation turbines, enabling their blending with conventional kerosene without requiring modifications to existing aircraft infrastructure [60].

Multiple technological pathways have been developed for bio-jet fuel production, generally classified as thermochemical or biochemical processes. Among these, four routes, namely hydroprocessed esters and fatty acids (HEFA), Fischer–Tropsch synthesis (FTS), direct sugars to hydrocarbons (DSHC), and alcohol-to-jet (ATJ), have been certified by the American Society for Testing Materials (ASTM) for aviation use. HEFA, derived from oils and fats such as camelina, jatropha, and waste cooking oils, is currently the most commercially mature option, while lignocellulosic biomass conversion via FTS or pyrolysis offers greater feedstock availability but faces economic and technical challenges due to its complex structure [61]. Additionally, sugar-based pathways, including fermentation to alcohol and subsequent oligomerization, provide further flexibility but remain at early stages of commercialization. These diverse strategies highlight both the promise and challenges of establishing bio-jet fuels as a large-scale, sustainable alternative to fossil-derived aviation fuels.

1.5.5 Biocarbon-based Functional Materials

Biocarbon refers to carbonaceous materials obtained through thermochemical conversion processes of biomass. Such materials derived from agricultural biomass waste have emerged as a versatile and environmentally benign candidate for supercapacitors, batteries, and hybrid energy storage systems. Different processes were used to convert biomass into carbon-based substances and give them their unique structural characteristics (like permeability and a substantial specific surface area).

Pyrolysis of biomass yields biocarbon having a higher potential for electrochemical energy storage, especially in batteries and supercapacitors. Pyrolysis under oxygen-limited conditions produces a carbon-rich framework, while subsequent activation (KOH, ZnCl_2 , and FeCl_3) develops micro and mesopores, increasing surface area and electrolyte accessibility. Heteroatom doping, particularly with nitrogen, oxygen, sulfur, or phosphorus, introduces additional redox-active sites and enhances electronic conductivity. For example, dual activation of bio-tar using KOH and urea yields nitrogen-doped carbons with hierarchical porosity, which significantly improves capacitance and energy density [62].

Biocarbon fibers are a type of carbon fiber derived from biomass, typically sourced from lignocellulosic materials such as wood, agricultural residues, or other organic matter. The cellulose or lignin components are refined and converted into fibers, often through spinning techniques. Biocarbon fibers can serve as conductive components when carbonized and used in electrodes for energy storage devices. For example, Li et al. (2022) synthesized lignocellulosic biomass-derived carbon electrodes that showed high-performance supercapacitor behavior thanks to their porous structure and large surface area [63]. Another study on sawdust-based carbon nanofibers (CNFs) prepared via electrospinning and carbonization revealed initial capacities of up to $\sim 798 \text{ mAh/g}$ at 100 mA/g and good cycling stability when used as anodes in Li-ion batteries [64]. Another important energy storage material is biocarbon aerogels produced using renewable biomass materials, such as cellulose, lignin, or other plant-based polymers, to create lightweight, highly porous structures. In order to produce composite aerogels for use in supercapacitors, Guo et al. [65] developed a simple, effective method for fabricating composite aerogels intended for supercapacitor applications by incorporating carbonized nanocellulose fibers (CNFs) with mixed-valent MnO_x , enhancing the material's electrochemical performance and structural stability. For the synthesis of carbon dots (CDs), biomass waste offers an accessible, reliable, renewable, and environmentally benign carbon source. Additionally, biocarbon can function as an anode material in lithium-ion batteries, facilitating the intercalation and deintercalation of lithium ions between carbon layers during charge and discharge cycles. To enhance conductivity, capacitance, and cycling stability, hybrid systems are designed by integrating pseudocapacitive materials with biomass-derived activated carbons, thereby improving both the efficiency and longevity of energy storage.

1.5.6 Biochar-based Catalysts for Renewable Energy Production

Biochar-based catalysts have recently attracted considerable attention in thermochemical energy production processes such as biomass pyrolysis, catalytic reforming of pyrolysis vapors, and gasification. In pyrolysis coupled with catalytic reforming, engineered biochar (i.e., physically or chemically activated, metal-doped, or heteroatom-doped) can significantly enhance syngas ($\text{H}_2 + \text{CO}$) yields while reducing tar formation. For example, Yang et al. demonstrated that Ni-doped biochar catalysts achieve high hydrogen yield ($26 \text{ mmol H}_2/\text{g biomass}$) and good gas energy conversion efficiency (73%) in a biomass pyrolysis plus catalytic reforming

process without added steam [66]. Similarly, rice husk biochar activated via KOH produced up to 91.75% tar decomposition and gas yields of about 704.85 mL/g biomass at 800 °C with a catalyst:feedstock ratio of 2:1, illustrating the role of high surface area, microporosity, and appropriate activation in achieving catalytic effectiveness in pyrolysis environments [67].

In hydrothermal liquefaction (HTL) and biomass steam gasification techniques, biochar serves as both a catalyst and a catalytic support. Metal-supported biochars (notably Ni or Ni/Fe on biochar) have shown strong performance in the steam reforming of biomass. For instance, hydrogen production from biomass steam gasification, Yao et al. reported that cotton-stalk biochar-supported Ni resulted in hydrogen contents up to 64 vol% (92 mg/g H₂) in a two-stage fixed bed reactor; the performance was linked to both the higher content of alkali/alkaline earth metallic species and the biochar's external surface area [68]. Biochar produced from agricultural residues has been shown to act both as a catalyst and as a sacrificial carbon source, improving H₂/CO ratios and reducing coke deposition on metal surfaces during reforming. Figure 1.1 presents the pathways of biomass feedstock transformation into usable energy through densification, direct use, and thermal conversion.

1.6 Challenges and Limitations

1.6.1 Seasonal and Logistical Issues in Biomass Harvesting

While the utilization of agricultural feedstock as a source of energy shows a significant potential for sustainable energy production, its implementation faces systematic and practical barriers that can vary across different regions, climates, and infrastructures. Commonly, a continuous and stable supply of feedstock (in our case, agricultural waste) is required for conversion facilities to produce bioenergy, which mismatches the seasonal generation of agricultural waste. For example, straw, husk, corn stover, and many other crop productions are limited to specific seasons. This issue creates complexity in logistics and storage costs. Furthermore, agricultural waste collection is another major challenge due to the high dispersity of residues across large areas of fields, necessitating labor and fuel-intensive collections. Additionally, in less developed regions or rural infrastructures, poor road access remains a challenge for residue collection [70].

1.6.2 Competing Uses

Agricultural residues are not always regarded as waste; on the contrary, they play an important role in soil fertility, improving soil organic matter, preventing erosion, and retaining moisture when incorporated into the soil. In addition, these residues often serve as an important feed source for livestock. Diversion of all the residues toward bioenergy may create a trade-off, potentially weakening soil fertility, reducing livestock productivity, and negatively impacting farm income. Policymakers and

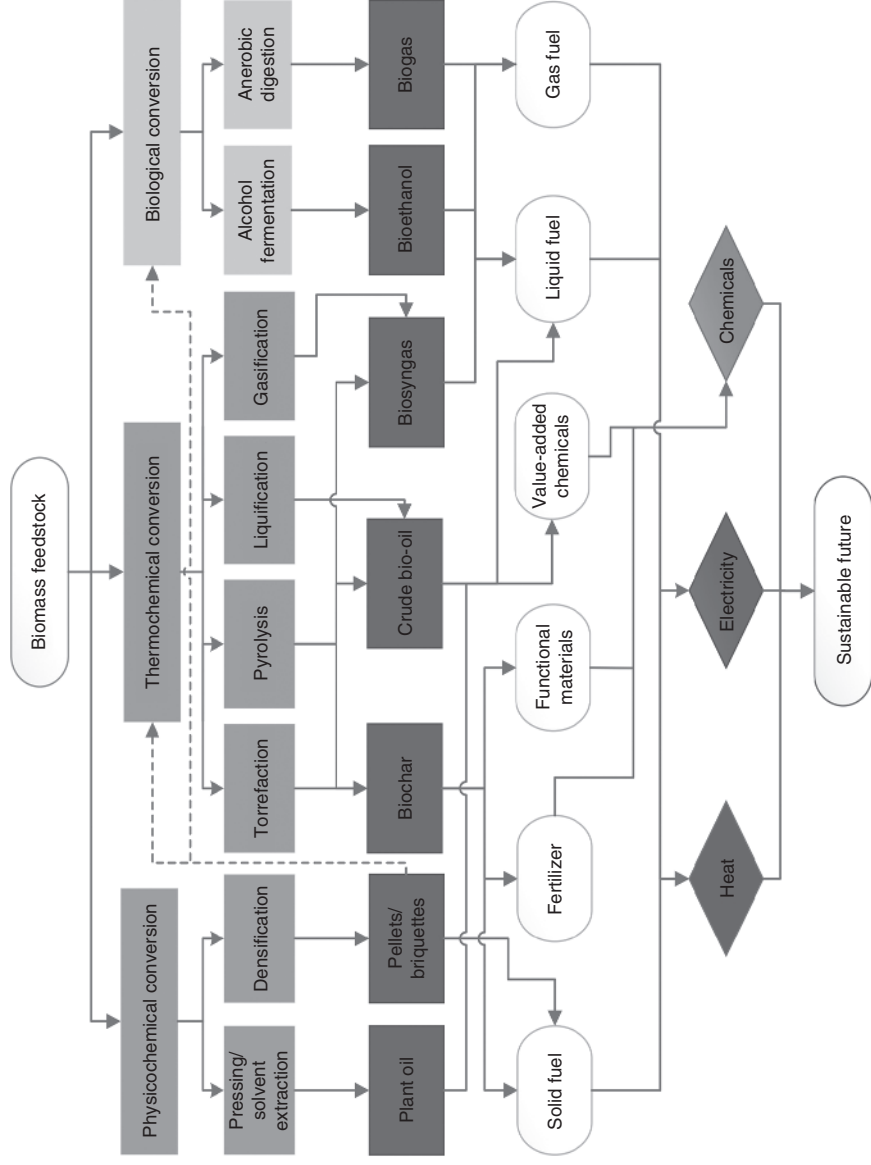


Figure 1.1 Schematic overview of agricultural waste streams and their conversion pathways into bioenergy products. *Source:* [69] / with permission of Elsevier.

project developers, therefore, face the challenge of balancing bioenergy expansion with the preservation of these traditional and ecologically important uses [71].

1.6.3 Storage, Handling, and Contamination Concerns

Once collected, agricultural waste is often bulky with high moisture content and heterogeneous, making storage, transport, and processing of residues difficult, and any poor management of the mentioned tasks can lead to contamination, decomposition, or fire hazards, reducing the quality of the biomass and the efficiency of conversion processes. Agricultural waste conversion to bioenergy requires different types of pretreatments, such as biological, chemical, and mechanical. The need for pretreatment is an important drawback in this matter, as reportedly 33% of the whole conversion process costs belong to the pretreatment processes [17]. Furthermore, agricultural wastes are mostly lignocellulosic biomass, which also contains lignin as one of its components, thus making the conversion a challenge, as lignin breakage is a problematic process and requires further pretreatment [72].

Due to the diverse nature of agricultural waste and residues, each type will have different chemical or physical characteristics, such as different ratios of lignin, hemicellulose, cellulose, moisture content, and particle size that require a specific pretreatment process, making it challenging to follow a standard process or uniform procedure across different wastes. Moreover, certain feedstocks may need specialized pretreatments or the addition of chemical or biological additives to enhance quality and yield. Factors such as the type, sequence, and intensity of pretreatment operations play an important role in reaction pathways during thermochemical or biochemical conversions [70].

1.7 Policy, Regulation, and Incentives

1.7.1 National and Regional Frameworks Supporting Bioenergy Production from Agricultural Waste

The development of bioenergy systems using agricultural leftovers is strongly reliant on favorable legislative conditions. Governments across the world have implemented legislative frameworks, financial incentives, and sustainability standards to encourage bioenergy while addressing environmental and social issues. A diverse set of policy tools in different countries contributed to the shift to bioenergy from agricultural wastes. Countries including the United States, India, Brazil, and part of the European Union have implemented frameworks that combine legislative mandates with financial incentives to encourage biofuel production and consumption. These policies aim not only to enhance energy security but also to meet emission reduction targets that align with national and international climate commitments. While much of the early focus was on road transportation, there is currently a growing interest in advanced biofuels generated from agricultural residues, particularly for complicated industries like aviation and maritime transport [73].

1.7.2 Subsidies, Carbon Credits, and Sustainability Standards and Examples

To achieve the widespread adoption of biofuels and promote sustainable energy from agricultural residues internationally, governments employ a variety of policies that are designed to create market stability, encourage investment, and ensure environmental performance. Examples of such key policies are listed below.

1.7.2.1 Mandatory Blending Percentage

Many governments set requirements for incorporating a certain percentage of biofuels into the national fuel supply. These blending guidelines help make a stable demand for biofuels and encourage industries to invest in this field. For example, India has set progressive ethanol blending targets under its Ethanol Blended Petrol (EBP) Program, aiming to reach 20% blending by the year 2025–2026, and Brazil has also made biodiesel blending in diesel fuel mandatory, which differs by state and feedstock availability and accessibility, and has been increasing over the recent years [74, 75]. The EU countries set minimum renewable fuel incorporation targets under the Renewable Energy Directive III (RED III), encouraging member states to adopt advanced biofuels derived from residues and wastes. Blending guidelines are not only important for domestic biofuel production but also help promote innovation in feedstock processing and logistics [76].

1.7.2.2 Tax Incentives and Subsidies

Financial measures, such as tax credits, investment grants, and preferential loan schemes, reduce the cost of production and attract private sector investments in biofuel development. In the United States, the *Inflation Reduction Act* (IRA) introduced the Section 45Z, Clean Fuel Production Credit, which ties financial support to verified GHG reductions achieved by the fuel [76, 77]. Other examples include production incentives for cellulosic ethanol, capital investment tax credits for advanced biofuel plants, and grants for developing decentralized waste-to-energy facilities. By lowering production costs and improving return on investment, these measures enhance the adoption of low-carbon fuels across different sectors, including road transportation and aviation.

1.7.2.3 Carbon Intensity-based Policies

Frameworks like the US IRA and Brazil's RenovaBio program exemplify this approach: both assign credits or incentives based on the lifecycle GHG emissions of the fuel compared to conventional fossil fuels [74]. These mechanisms promote the development of low-carbon fuels, including those derived from agricultural residues. Similarly, Canada's Clean Fuel Regulations set mandatory reductions in fuel carbon intensity over time, incentivizing producers to adopt low-carbon biofuels, including those from agricultural residues, waste, and lignocellulosic biomass [78]. These mechanisms encourage innovation in feedstock processing, improve sustainability, and ensure that biofuel deployment contributes meaningfully to climate change mitigation on a global scale.

Overall, the above-mentioned policies illustrate a collaborative approach for advancing the production and use of bioenergy from agricultural waste and residues. By combining clear targets in production and process requirements, financial and economic incentives, and carbon intensity-based regulatory frameworks, governments create stable markets, motivate technological innovations, and encourage private sectors to invest more.

1.8 Future Prospects and Research Directions

1.8.1 Integrated Biorefinery

The future of agricultural waste valorization lies in integrated biorefinery systems, where multiple conversion pathways are combined within a single platform. Instead of focusing on one product, advanced biorefineries will simultaneously produce bioenergy, bio-based chemicals, and high-value materials. For example, lignocellulosic residues could be fractionated into cellulose for bioethanol, hemicellulose for biogas, and lignin for bio-based carbon products. Such holistic utilization maximizes resource efficiency, reduces waste streams, and improves economic viability. Research is increasingly directed toward modular and decentralized biorefineries that can be adapted to local feedstock availability, thereby promoting rural development and reducing transportation costs.

1.8.2 Co-valorization of Mixed Agro-industrial Waste Streams

Agricultural residues rarely exist in isolation; they are often co-located with other organic wastes such as food processing by-products, municipal solid waste fractions, and forestry residues. Co-processing these mixed feedstocks presents opportunities to enhance yield, balance nutrient composition, and achieve synergies in conversion efficiency. For instance, co-digestion of livestock manure with crop residues improves methane recovery while stabilizing the digestion process. Similarly, blending agro-industrial by-products with field residues may enable more flexible feedstock supply chains and reduce seasonal bottlenecks. Future research should focus on optimizing feedstock pretreatment strategies, understanding potential inhibitory interactions, and developing robust multi-feedstock conversion technologies.

1.8.3 Digitalization and Artificial Intelligence

Emerging digital technologies are expected to revolutionize waste-to-energy operations. Artificial intelligence (AI), machine learning, and Internet of Things (IoT)-enabled monitoring can optimize feedstock logistics, predict system performance, and reduce operational risks. For example, AI-driven models can forecast seasonal residue availability and match it to energy demand, while smart sensors embedded in digesters or pyrolysis reactors can provide real-time process data to enhance efficiency and stability. Digital platforms also enable traceability and

certification of bioenergy products, strengthening consumer and policy confidence. Investment in such smart infrastructures will accelerate the transition toward adaptive and resilient bioenergy systems.

1.8.4 Advancing Global Adoption

The applicability of agricultural waste-to-energy systems will vary across different regions, depending on policy support, infrastructure readiness, and socioeconomic drivers. Developed economies may prioritize advanced and digitalized biorefineries, while emerging economies could focus on decentralized systems that provide local energy access and reduce open-field residue combustion. International collaboration, knowledge transfer, and supportive policy frameworks will be crucial in scaling up global adoption. As carbon markets expand and sustainability standards tighten, agricultural residues are poised to become a mainstream component of renewable energy portfolios. Looking ahead, the convergence of circular economy principles, technological innovation, and policy incentives suggests a promising future where agricultural waste plays a central role in sustainable energy transitions.

1.9 Conclusion

Agricultural waste, once regarded primarily as a waste management and disposal challenge, is increasingly recognized as a critical renewable feedstock for sustainable bioenergy systems. Its diverse forms, from crop residues and processing by-products to livestock biomass and food waste, offer abundant and regionally distributed resources that can help reduce GHG emissions, improve soil health, and advance circular economy practices. Despite challenges related to seasonal availability, logistics, competing uses, and pretreatment requirements, continued policy support, technological innovation, and integrated biorefinery approaches are unlocking its potential. Looking forward, the convergence of digitalization, co-valorization strategies, and supportive regulatory frameworks positions agricultural residues not only as a substitute for fossil fuels but also as a driver of rural development, energy security, and global decarbonization.

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