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Energy Utilization of Agricultural Waste: From Waste Management to Energy Production

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Abstract Agricultural waste management is a critical issue due to its environmental and economic implications. This study examines the transition from traditional waste management practices to innovative energy production technologies. Agricultural waste, including crop residues, animal manure, and agro-industrial by-products, varies in chemical and physical properties, and its production is influenced by seasonal and regional factors. Current waste management methods, such as burning and landfilling, have significant environmental and economic drawbacks, which are addressed by regulatory frameworks and policies. Advanced technologies like anaerobic digestion, pyrolysis, gasification, combustion, and biofuel production offer promising alternatives for converting waste into energy. Successful case studies from Europe, Asia, and North America demonstrate the practical implementation and benefits of these technologies. An economic analysis highlights the cost-effectiveness and market potential of energy products derived from agricultural waste, supported by government incentives. Environmental assessments reveal the sustainability and ecosystem benefits of these practices. Future research directions include emerging technologies, integration with other renewable sources, and policy recommendations to promote sustainable energy utilization of agricultural waste. This study underscores the importance of transitioning from waste management to energy production for enhanced environmental sustainability and economic viability.
Keywords Agricultural waste; Energy production; Waste management; Sustainability; Renewable energy

1 Introduction

Agricultural waste management has become a critical issue in recent years due to the increasing volume of waste generated by the agro-industrial sector. This waste, if not managed properly, can lead to significant environmental problems, including pollution and greenhouse gas emissions. The effective management of agricultural waste is essential not only for environmental protection but also for the sustainable development of the agricultural sector. In many countries, agricultural waste is being increasingly recognized as a valuable resource that can be converted into energy, thereby reducing the reliance on fossil fuels and contributing to energy security. For instance, in Ukraine, the potential for using agricultural waste as raw materials for biogas production has been highlighted, with significant energy generation capabilities already being realized1. Similarly, in China, the energy utilization of agricultural waste has been identified as a key area of development, with research focusing on various technologies and methods for converting waste into energy (Wei et al., 2020).

The transition from traditional waste management practices to energy production involves the adoption of innovative technologies and processes that can convert agricultural waste into various forms of energy. This shift is driven by the need to address the depletion of petroleum resources and the continuous deterioration of the ecological environment. Technologies such as biogas production, gasification, and microbial fuel cells are being explored and implemented to harness the energy potential of agricultural waste. For example, biogas plants in Ukraine have been successful in generating significant amounts of energy from agricultural waste, supported by favorable legislation (Tokarchuk, 2018). In addition, the development of multigeneration energy systems that utilize agricultural bio-waste for the production of electricity, heating, cooling, and freshwater demonstrates the versatility and efficiency of these technologies (Siddiqui and Dincer, 2021). The use of microbial fuel cells to generate electricity from organic waste further exemplifies the innovative approaches being taken to convert waste into energy.

The study is to provide a comprehensive overview of the current state of research and development in the field of energy utilization of agricultural waste. This includes an examination of the various technologies and methods being used to convert agricultural waste into energy, as well as an analysis of the benefits and challenges associated with these processes. The study aims to highlight the potential of agricultural waste as a sustainable energy resource and to identify the key factors that influence the efficiency and effectiveness of waste-to-energy conversion. By synthesizing the findings from multiple studies, this study seeks to offer insights into the best practices and future directions for the energy utilization of agricultural waste, thereby contributing to the broader goals of environmental sustainability and energy security.

2 Agricultural Waste: Types and Characteristics

2.1 Classification of agricultural waste (crop residues, animal manure, agro-industrial by-products)

Agricultural waste can be broadly classified into three main categories: crop residues, animal manure, and agro-industrial by-products. Crop residues include materials such as straw, husks, and stalks left in the field after harvesting crops. These residues are rich in lignocellulosic biomass, making them suitable for biofuel production. Animal manure, derived from livestock, is another significant type of agricultural waste. It is rich in organic matter and nutrients, making it a valuable resource for biogas production and soil amendment (Liu and Rajagopal, 2019). Agro-industrial by-products are generated from the processing of agricultural products and include materials such as bagasse, molasses, and fruit peels. These by-products can be utilized in biorefinery processes to produce biofuels, chemicals, and other value-added products (Yaashikaa et al., 2021).

2.2 Chemical and physical properties of different types of agricultural waste

The chemical and physical properties of agricultural waste vary significantly depending on the type of waste. Crop residues, for instance, are primarily composed of cellulose, hemicellulose, and lignin, which are complex carbohydrates that can be converted into biofuels through biochemical processes. Animal manure contains high levels of organic matter, nitrogen, phosphorus, and potassium, making it an excellent feedstock for anaerobic digestion to produce biogas. Agro-industrial by-products, such as bagasse, are rich in sugars and fibers, which can be fermented to produce bioethanol and other bio-based chemicals (Sadh et al., 2018). The physical properties, such as moisture content and particle size, also play a crucial role in determining the suitability of these wastes for various energy conversion technologies (Andreenko et al., 2022).

2.3 Seasonal and regional variations in agricultural waste production

The production of agricultural waste is subject to significant seasonal and regional variations. Crop residues are typically generated during the harvest season, which varies depending on the type of crop and the geographical location. For example, in regions where rice is a major crop, large quantities of rice straw are produced during the harvest season (Andreenko et al., 2022). Similarly, the production of animal manure is influenced by livestock farming practices, which can vary regionally. In areas with intensive livestock farming, such as certain parts of the United States and China, the generation of animal manure is substantial. Agro-industrial by-products are produced throughout the year but can vary based on the processing schedules of agricultural products. Regional factors, such as climate, soil type, and agricultural practices, also influence the quantity and type of agricultural waste produced (Wei et al., 2020). Understanding these variations is essential for optimizing the collection and utilization of agricultural waste for energy production. By comprehensively understanding the types, characteristics, and variations in agricultural waste production, we can better harness these resources for sustainable energy generation and waste management.

3 Current Waste Management Practices

3.1 Traditional waste disposal methods (burning, landfilling)

Traditional waste disposal methods such as burning and landfilling have been widely used for managing agricultural waste. Burning agricultural residues, such as straw and other crop residues, is a common practice in many regions. This method is often chosen for its simplicity and low cost. However, it has significant drawbacks, including the release of greenhouse gases and particulate matter, which contribute to air pollution and climate change (Bhatt et al., 2018). Landfilling, another prevalent method, involves the disposal of waste in designated landfill sites. While it is a straightforward approach, it poses environmental risks such as soil and groundwater contamination due to leachate formation and methane emissions, a potent greenhouse gas (Kaur et al., 2021).

3.2 Environmental and economic impacts of conventional practices

The environmental impacts of traditional waste disposal methods are profound. Burning agricultural waste releases large amounts of carbon dioxide, methane, and other pollutants into the atmosphere, exacerbating global warming and air quality issues. Landfilling, on the other hand, contributes to soil and water pollution through the leachate produced as waste decomposes. This leachate can carry harmful chemicals and pathogens into the surrounding environment, posing risks to human health and ecosystems (Kaur et al., 2021). Economically, these conventional practices are not sustainable. The costs associated with managing the environmental damage caused by burning and landfilling can be substantial. Additionally, these methods do not capitalize on the potential economic benefits of converting agricultural waste into valuable products such as biofuels, fertilizers, and other bioproducts (Kirilenko and Tokarchuk, 2020). The inefficiency of these traditional methods highlights the need for more sustainable and economically viable waste management practices.

3.3 Regulatory framework and policies governing agricultural waste management

The regulatory framework and policies governing agricultural waste management vary significantly across different regions. In many countries, there are stringent regulations aimed at reducing the environmental impact of waste disposal. For instance, policies may mandate the reduction of open burning of agricultural residues and promote the adoption of alternative waste management practices such as composting, anaerobic digestion, and bioenergy production (Wei et al., 2020). In China, for example, the government has implemented policies to encourage the recycling and utilization of agricultural waste, aiming to reduce pollution and promote sustainable agricultural practices. Similarly, in the European Union, regulations such as the Waste Framework Directive and the Renewable Energy Directive set targets for waste reduction and the use of renewable energy sources, including bioenergy from agricultural waste (Kirilenko and Tokarchuk, 2020).These regulatory frameworks are essential for driving the transition from traditional waste disposal methods to more sustainable practices. They provide the necessary guidelines and incentives for farmers and waste management companies to adopt environmentally friendly and economically beneficial waste management strategies.

4 Technologies for Energy Production from Agricultural Waste

4.1 Anaerobic digestion

4.1.1 Process description

Anaerobic digestion (AD) is a biological process that converts organic waste into biogas through the action of microorganisms in the absence of oxygen. This process involves several stages, including hydrolysis, acidogenesis, acetogenesis, and methanogenesis, which collectively break down complex organic materials into simpler compounds, ultimately producing methane (CH_4) and carbon dioxide (CO_2) as primary biogas components (Chew et al., 2021).

4.1.2 Types of digesters and biogas production

There are various types of anaerobic digesters, including batch, continuous, and semi-continuous systems. Portable biogas digesters, which are small-scale units designed for domestic use, have gained popularity for their ability to convert kitchen waste into biogas efficiently (Ajay et al., 2021). Co-digestion, which involves the simultaneous digestion of multiple types of organic waste, has been shown to enhance biogas production and process stability.

4.1.3 Factors affecting efficiency and yield

Several factors influence the efficiency and yield of anaerobic digestion, including temperature, pH, retention time, carbon-to-nitrogen ratio, and the presence of inhibitors. Pre-treatment methods such as thermal, chemical, and mechanical treatments can enhance the biodegradability of feedstock, thereby improving biogas yield (Bong et al., 2018). Additionally, the optimization of operational parameters and the use of additives can further enhance the performance of AD systems.

4.2 Pyrolysis

4.2.1 Process description

Pyrolysis is a thermochemical process that decomposes organic materials at high temperatures (300 °C~900 °C) in the absence of oxygen. This process results in the production of bio-oil, syngas, and biochar, which can be used as energy sources or soil amendments (Dutta et al., 2021).

4.2.2 Types of pyrolysis reactors

There are several types of pyrolysis reactors, including fixed-bed, fluidized-bed, and rotary kiln reactors. Each type has its own advantages and limitations in terms of efficiency, scalability, and product distribution (Yang et al., 2023).

4.2.3 Bio-oil, syngas, and biochar production

The pyrolysis process yields three main products: bio-oil, syngas, and biochar. The distribution of these products depends on the pyrolysis conditions, such as temperature and heating rate. Bio-oil can be used as a liquid fuel, syngas as a gaseous fuel, and biochar as a soil amendment or carbon sequestration agent (Dutta et al., 2021).

4.3 Gasification

4.3.1 Process description

Gasification is a thermochemical process that converts organic materials into syngas (a mixture of CO, H_2, and CO_2) by reacting the material at high temperatures (800 ℃~1200 ℃) with a controlled amount of oxygen or steam. This process is highly efficient in converting biomass into a versatile energy carrier (Ajay et al., 2021).

4.3.2 Syngas production and applications

Syngas produced from gasification can be used for various applications, including electricity generation, chemical synthesis, and as a fuel for internal combustion engines. The composition and quality of syngas depend on the feedstock and gasification conditions (Dutta et al., 2021).

4.3.3 Factors affecting gasification efficiency

The efficiency of gasification is influenced by factors such as feedstock properties, gasification temperature, and the type of gasifying agent used. Optimizing these parameters can enhance syngas yield and quality (Dutta et al., 2021).

4.4 Combustion

4.4.1 Direct combustion techniques

Direct combustion involves burning organic waste in the presence of excess air to produce heat, which can be used for electricity generation or industrial processes. This is the most straightforward method of energy recovery from biomass (Ajay et al., 2021).

4.4.2 Energy recovery systems

Energy recovery systems, such as combined heat and power (CHP) plants, can improve the overall efficiency of combustion processes by capturing and utilizing the heat generated during combustion (Ajay et al., 2021).

4.4.3 Emission control measures

Emission control measures, including the use of scrubbers, filters, and catalytic converters, are essential to minimize the release of pollutants such as particulate matter, NOx, and SOx during combustion(Ajay et al., 2021).

4.5 Bioethanol and biodiesel production

4.5.1 Fermentation processes

Bioethanol production involves the fermentation of sugars derived from biomass by microorganisms, typically yeast. This process converts sugars into ethanol and CO_2. Biodiesel production, on the other hand, involves the transesterification of fats and oils to produce fatty acid methyl esters (FAME) and glycerol (Ajay et al., 2021).

4.5.2 Feedstock selection and optimization

The selection of appropriate feedstock is crucial for efficient biofuel production. Common feedstocks for bioethanol include sugarcane, corn, and lignocellulosic biomass, while biodiesel feedstocks include vegetable oils, animal fats, and waste cooking oils. Optimization of feedstock processing and fermentation conditions can significantly enhance biofuel yield (Bhatt et al., 2018).

4.5.3 Challenges and advancements in biofuel production

Challenges in biofuel production include feedstock availability, process efficiency, and economic viability. Recent advancements, such as the development of genetically engineered microorganisms and the integration of advanced pretreatment technologies, have shown promise in overcoming these challenges and improving biofuel production efficiency(Bhatt et al., 2018).

5 Case Studies of Successful Implementations

5.1 Case study 1: biogas production from animal manure in europe

5.1.1 Overview of the project

Biogas production from animal manure has been a significant focus in Europe, particularly in countries like Poland and Germany. These countries have similar agricultural and municipal waste structures, making them ideal for biogas production projects. The biogas market in Poland is growing, while Germany continues to be a market leader despite a recent decline in installations. The primary goal of these projects is to reduce dependence on fossil fuels and increase the use of renewable energy sources, in line with EU policies (Vovk, 2022).

5.1.2 Technological setup and processes

The biogas production process involves anaerobic digestion (AD) of animal manure and other biodegradable waste. Advanced technologies in biogas plants include various digester technologies that optimize methane yield. Co-digestion and pre-treatments are employed to enhance biogas production. The selection of specific microorganisms and genetic manipulation of anaerobic bacteria are also explored to speed up the AD process (Caruso et al., 2019).

5.1.3 Economic and environmental benefits

Biogas production from animal manure offers significant economic and environmental benefits. It helps in waste management by reducing the amount of unmanaged waste. Economically, it provides an alternative to chemical fertilizers, which are becoming increasingly expensive. Environmentally, it contributes to greener crops and reduces greenhouse gas emissions. The pulp from biogas plants can be used as a sustainable alternative to chemical fertilizers (Figure 1), further enhancing its environmental benefits (Sobczak et al., 2022).

Sobczak et al. (2022) found that the prices of various fertilizers have exhibited significant fluctuations over recent years, with notable increases observed post-2020. The study highlights that ammonium hydrogen phosphate and urea fertilizers experienced the most pronounced price surges, reflecting changes in market dynamics, supply chain disruptions, and increased production costs. Conversely, triple superphosphate showed moderate price stability, suggesting more balanced supply and demand factors. Phosphorites displayed the least variation, indicating a relatively steady market. These trends underscore the complexities of the global fertilizer market and emphasize the need for strategic planning in agricultural practices to mitigate the impact of such price volatility on food production and security. The findings provide valuable insights for policymakers and stakeholders in the agricultural sector, promoting informed decision-making to address future challenges in fertilizer supply and cost management.

5.2 Case study 2: pyrolysis of crop residues in asia

5.2.1 Project background and objectives

Pyrolysis of crop residues is gaining traction in Asia as a method to convert agricultural waste into biofuel. The primary objective of these projects is to utilize renewable sources of energy and reduce the environmental impact of waste (Figure 2). Pyrolysis technology is seen as a revolutionary and straightforward process for converting waste into valuable products like bio-oil, biochar, and syngas (Dong et al., 2018).

Figure 1 Waste-to-energy technologies flowchart (Adopted from Sobczak et al., 2022)

Image capton: Different colored lines in the chart represent the price changes of various fertilizers: the blue line represents the price changes of diammonium phosphate, the orange line represents the price changes of urea, the gray line represents the price changes of NPK compound fertilizer, and the yellow line represents the price changes of phosphate rock. Both diammonium phosphate and urea prices saw a significant increase after 2020, while the price of NPK compound fertilizer remained relatively stable, and the price change of phosphate rock was relatively minor (Adopted from Sobczak et al., 2022)

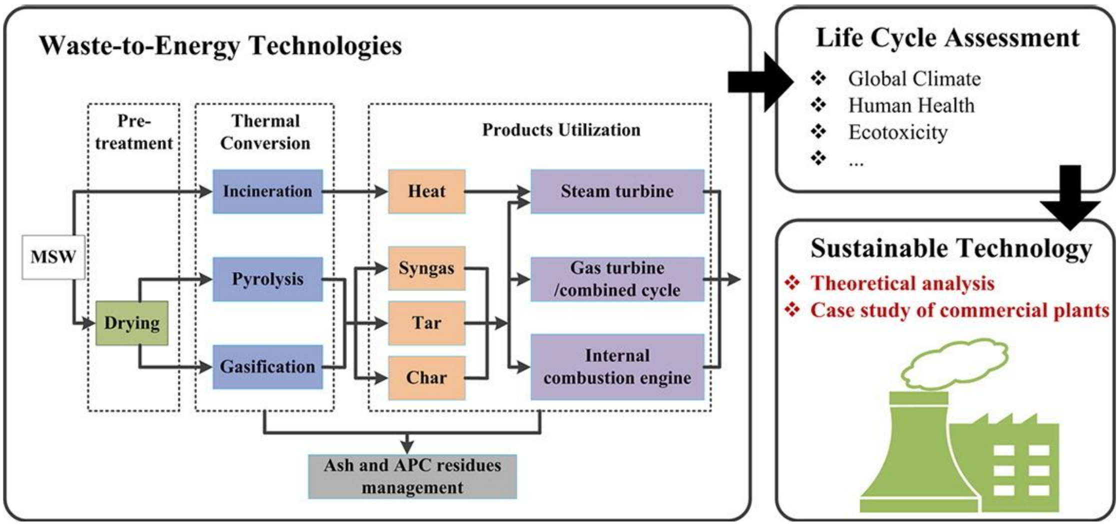

Figure 2 Waste-to-energy technologies flowchart (Adopted from Dong et al., 2018)

Image capton: Incineration: Generates heat; Pyrolysis and Gasification: Produce syngas, tar, and char. In the product utilization stage: Heat: Is used to generate electricity through a steam turbine. Syngas, Tar, and Char: Are used to generate electricity through gas turbines/combined cycle or internal combustion engines (Adopted from Dong et al., 2018)

Dong et al. (2018) found that waste-to-energy (WtE) technologies offer a comprehensive approach to managing municipal solid waste (MSW) while generating valuable energy products. Their study emphasizes the significance of pre-treatment processes, such as drying, to optimize the efficiency of subsequent thermal conversion methods, including incineration, pyrolysis, and gasification. Each method produces different energy carriers: heat, syngas, tar, and char, which can be utilized through various technologies like steam turbines, gas turbines, and internal combustion engines. The research highlights the importance of managing by-products, such as ash and APC residues, to minimize environmental impact. Additionally, the study underscores the need for lifecycle assessments to evaluate the global climate, human health, and ecotoxicity implications of WtE technologies. Theoretical analyses and case studies of commercial plants are essential for developing sustainable technologies that balance energy production with environmental protection.

5.2.2 Technological implementation

The most commonly used process for pyrolysis in these projects is rotary pyrolysis, which provides efficient heat transfer with relatively low energy consumption. Temperature control is crucial, as intermediate temperatures typically yield the maximum amount of bio-oil. Emission control systems are also integrated to ensure the process is environmentally friendly (Hasan et al., 2021).

5.2.3 Outcomes and scalability

The outcomes of pyrolysis projects in Asia have been promising, with significant yields of bio-oil, biochar, and syngas. These projects have demonstrated the potential for scalability, provided that challenges such as waste heterogeneity and syngas purification are addressed. The integration of emission control systems and optimization of process parameters are essential for scaling up these projects (Vovk, 2022).

5.3 Case study 3: gasification of agro-industrial waste in North America

5.3.1 Project overview

Gasification of agro-industrial waste is being explored in North America as a sustainable waste-to-energy (WtE) solution. These projects aim to convert waste into syngas, which can be used for energy production. The focus is on improving energy efficiency and reducing environmental loadings through advanced gasification technologies (Meggyes and Nagy, 2012).

5.3.2 Technology and processes used

The gasification process involves the thermal conversion of waste into syngas, which can then be used in various energy applications. Technologies such as gas turbines and combined cycles are employed to enhance energy efficiency. Syngas cleaning is a critical step to ensure the quality of the gas and reduce emissions.

5.3.3 Impact assessment and future prospects

The impact of gasification projects in North America has been positive, with significant improvements in energy efficiency and reductions in fossil-based energy consumption. Future prospects for these projects are promising, provided that advancements in syngas purification and waste quality management are achieved. The scalability of these projects will depend on continuous technological improvements and effective management of residues.

6 Economic Analysis and Market Potential

6.1 Cost-benefit analysis of different energy production technologies

The economic viability of energy production from agricultural waste is a critical factor in its adoption. Various technologies such as anaerobic digestion, gasification, and incineration have been evaluated for their cost-effectiveness. For instance, a study on an integrated multi-generation power plant using agricultural waste in Nigeria demonstrated a life cycle cost of $3.753 million, a breakeven point of 7.5 years, and a unit energy cost of $0.0109 per kWh, highlighting the economic feasibility of such projects (Ogorure et al., 2018). Additionally, the techno-economic model developed for China's iron and steel industry showed that practical potential for energy savings is less than 20% when considering technical implementation rates, emphasizing the need for efficient technology deployment (Zhang et al., 2017).

6.2 Market trends and potential for energy products derived from agricultural waste

The market for energy products derived from agricultural waste is expanding, driven by the need for sustainable energy solutions and waste management. In India, the valorization of agricultural waste for biogas production is gaining traction, supported by government initiatives and policy regulations (Kapoor et al., 2020). Similarly, the global trend towards renewable energy is evident in the increasing installed capacities for bioenergy, including waste-to-energy technologies. The potential for biogas production from agricultural waste in Ukraine is significant, with current capacities producing about 25 MW of energy, indicating a growing market for bioenergy (Tokarchuk, 2018).

6.3 Government incentives and funding opportunities

Government incentives and funding opportunities play a crucial role in promoting the adoption of energy production technologies from agricultural waste. In India, policy support is integral to the development of a biogas-based circular economy, which includes subsidies and financial incentives for biogas plants. In Ukraine, the adoption of the Law regarding competitive conditions for electricity production from alternative energy sources in 2015 has significantly boosted the development of biogas plants (Tokarchuk, 2018). These examples underscore the importance of government policies in facilitating the growth of the agricultural waste-to-energy sector.

6.4 Barriers to adoption and strategies to overcome them

Despite the promising potential, several barriers hinder the widespread adoption of energy production from agricultural waste. These include technological challenges, high initial investment costs, and regulatory hurdles. For instance, the heterogeneity and high moisture content of food waste pose significant challenges for its conversion to energy (Pham et al., 2015). Additionally, the lack of comprehensive waste management policies in some regions complicates the effective use of agricultural waste for energy production. Strategies to overcome these barriers include technological advancements to improve efficiency, government incentives to reduce financial risks, and the development of robust waste management frameworks.

7 Environmental Impact and Sustainability

7.1 Life cycle assessment of energy production from agricultural waste

Life Cycle Assessment (LCA) is a crucial tool for evaluating the environmental impacts of energy production from agricultural waste. Various studies have demonstrated the benefits and challenges associated with different waste-to-energy (WtE) systems. For instance, a comparative LCA of food waste management scenarios in Singapore revealed that anaerobic digestion followed by gasification (ADgas) had the best global warming score due to high electricity output and carbon sequestration of biochar (Tong et al., 2018). Similarly, an LCA study in Turkey highlighted that biogas production from agricultural and animal waste through anaerobic digestion significantly reduced the environmental impact compared to traditional energy sources like coal. Another study of over fifty LCA studies on WtE systems found that most WtE processes have lower greenhouse gas emissions compared to fossil fuels, although some processes may increase impacts like acidification and eutrophication due to agricultural chemicals (Hermann et al, 2011).

7.2 Comparative analysis of carbon footprints

The carbon footprint of different waste management strategies varies significantly. For example, a study comparing incineration and landfill scenarios in Tehran found that incineration led to a substantial reduction in greenhouse gas emissions compared to landfilling (Nabavi Pelesaraei et al., 2017). Another study focusing on biodegradable materials' waste treatment showed that anaerobic digestion had the lowest carbon footprint, while incineration could become more favorable with improved energy efficiency. Additionally, the application of biochar in agricultural soils has been shown to neutralize greenhouse gas emissions from agricultural production and serve as a carbon capture method, further reducing the overall carbon footprint (Matuštík et al., 2020).

7.3 Soil health and fertility implications of biochar application

Biochar application in agriculture has been extensively studied for its benefits to soil health and fertility. Research conducted in the Czech Republic on various biomass wastes demonstrated that biochar produced from these wastes could restore carbon deposits in the soil, enhancing soil fertility (Kwoczynski and Čmelík, 2021),. Field interventions in South Asia showed that using crop residue as biochar improved soil organic carbon, moisture, nutrients, and biological activity, leading to a significant increase in agricultural production (Dey et al., 2020). These findings underscore the potential of biochar to improve soil health while simultaneously managing agricultural waste.

7.4 Long-term sustainability and ecosystem benefits

The long-term sustainability of energy production from agricultural waste hinges on its environmental and economic viability. Studies have shown that biochar-to-soil systems offer significant benefits, including carbon sequestration and energy production, which often outweigh the greenhouse gas emissions from feedstock production and handling. However, the economic sustainability of these projects must also be considered. For instance, the environmental assessment of biogas production in Turkey highlighted the need to mitigate emissions from digestate application to enhance sustainability further (Nayal et al., 2016). Additionally, the adoption of alternative crop residue management practices in South Asia has led to reduced CO_2 emissions and improved agricultural yields, demonstrating the ecosystem benefits of sustainable waste management practices. In conclusion, the environmental impact and sustainability of energy production from agricultural waste are multifaceted, involving careful consideration of life cycle assessments, carbon footprints, soil health, and long-term ecosystem benefits. The integration of biochar and other sustainable practices can significantly enhance the overall environmental performance of these systems.

8 Future Prospects and Research Directions

8.1 Emerging technologies and innovations in agricultural waste-to-energy conversion

The field of agricultural waste-to-energy conversion is rapidly evolving with several emerging technologies and innovations. One promising area is the development of thermocatalytic reforming (TCR) processes, which have shown potential in converting various agricultural wastes into valuable energy products such as syngas, bio-oil, and bio-char. The environmental and economic sustainability of these processes is highly dependent on the characteristics of the biomass waste and the utilization of the product fractions obtained from the TCR process (Moreno et al., 2019). Additionally, advancements in anaerobic digestion (AD) technologies are being explored to enhance the treatment and reuse of agricultural and food wastes. Novel methods such as composting, algae culture, and struvite crystallization are being investigated to improve the efficiency of AD effluent treatment and reuse. Furthermore, the integration of gasification processes with other subsystems for multigeneration of electricity, heating, cooling, and freshwater from agricultural bio-waste is another innovative approach that has demonstrated high energetic and exergetic efficiencies.

8.2 Integration with other renewable energy sources

Integrating agricultural waste-to-energy conversion with other renewable energy sources can enhance the overall sustainability and efficiency of energy systems. For instance, combining bioenergy production from agricultural residues and livestock manure with solar and wind energy can create a more resilient and reliable energy network. This integration can help in balancing the intermittent nature of solar and wind energy while providing a continuous supply of bioenergy (Bijarchiyan et al., 2020). Additionally, the use of biochar produced from agricultural waste in soil amendment can improve soil health and carbon sequestration, further contributing to the sustainability of agricultural practices. The development of sustainable biomass network models that incorporate multiple renewable energy sources can optimize the supply chain and maximize the economic and social benefits of bioenergy production (Figure 3).

Bijarchiyan et al. (2020) found that utilizing agricultural waste, cattle manure, and chicken manure for anaerobic digestion and combined heat and power (CHP) generation offers a sustainable approach to waste management and energy production. Their study emphasizes the efficiency of storing organic waste in warehouses before processing it in anaerobic digestion facilities, which convert waste into biogas. The biogas is then used to generate electricity, which can be fed into the electrical grid or exported. This method not only reduces the environmental impact of waste but also provides a renewable energy source, contributing to energy security and reducing reliance on fossil fuels. The research highlights the potential for integrating such systems into agricultural practices to enhance sustainability, improve waste utilization, and support rural economies by providing additional revenue streams through energy production.

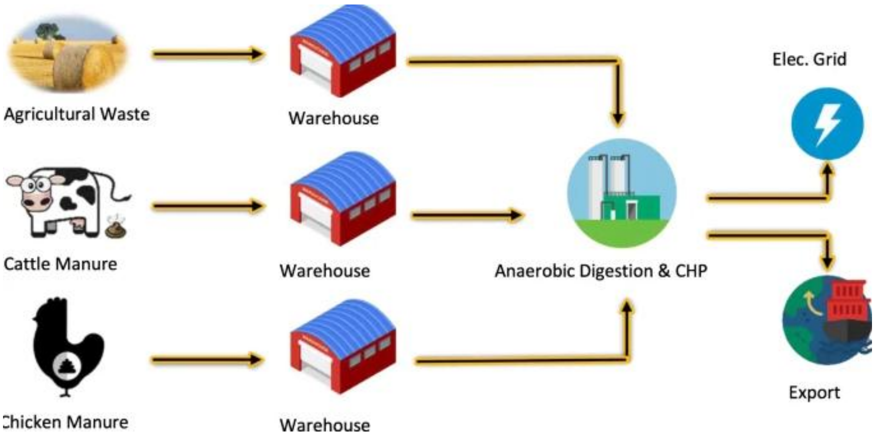

Figure 3 Structure of the sustainable BSCN for bioenergy generation through anaerobic digestion process (Adopted from Bijarchiyan et al., 2020)

Image capton: The processing of agricultural waste, cow dung and chicken manure. The waste is first stored in a warehouse and then processed through anaerobic digestion and combined heat and power (CHP) process to generate electricity. The generated electricity is fed into the grid or exported (Adopted from Bijarchiyan et al., 2020)

8.3 Policy recommendations for promoting sustainable energy utilization of agricultural waste

To promote the sustainable energy utilization of agricultural waste, several policy recommendations can be made. Firstly, governments should provide financial incentives and subsidies to support the development and deployment of advanced waste-to-energy technologies. This can include tax credits, grants, and low-interest loans for projects that demonstrate significant environmental and economic benefits. Secondly, policies should encourage the integration of agricultural waste-to-energy systems with other renewable energy sources to create a more diversified and resilient energy mix (Bijarchiyan et al., 2020). Thirdly, regulations should be established to ensure the safe and sustainable management of agricultural waste, including guidelines for the treatment and reuse of AD effluent and other by-products. Finally, international collaboration and knowledge sharing should be promoted to accelerate the adoption of best practices and innovative technologies in the field of agricultural waste-to-energy conversion (Wei et al., 2020).

8.4 Potential areas for future research and development

Several potential areas for future research and development in the field of agricultural waste-to-energy conversion can be identified. One key area is the optimization of existing technologies to improve their efficiency and scalability. This includes enhancing the performance of AD processes, developing more efficient thermocatalytic reforming methods, and exploring new pathways for biohydrogen production. Another important area is the investigation of the environmental and economic impacts of different waste-to-energy conversion pathways through comprehensive life-cycle assessments (Liu and Rajagopal, 2019). Additionally, research should focus on the development of integrated systems that combine multiple renewable energy sources and waste-to-energy technologies to maximize resource utilization and minimize environmental impacts. Finally, there is a need for interdisciplinary research that addresses the social, economic, and policy dimensions of agricultural waste-to-energy conversion to ensure its sustainable and equitable implementation (Tokarchuk, 2018). By addressing these future prospects and research directions, the field of agricultural waste-to-energy conversion can make significant strides towards achieving sustainable energy production and waste management.

9 Concluding Remarks

The systematic study of the literature on the energy utilization of agricultural waste reveals several critical insights. Firstly, agricultural waste, including crop residues, livestock manure, and agro-industrial by-products, holds significant potential for biogas and biofuel production, which can substantially reduce energy dependence and greenhouse gas emissions. The studies highlight the growing trend of utilizing agricultural waste for renewable energy, with notable examples from countries like Germany, Denmark, and Ukraine, which have implemented successful models for biogas production from agricultural waste. Additionally, the potential energy yield from agricultural waste is substantial, with estimates indicating that regions like Piedmont in Italy could produce enough biomethane to power local agricultural machinery and significantly reduce CO2 emissions. The study also underscores the importance of a holistic assessment of energy recovery pathways to maximize net energy gain and minimize life-cycle emissions.

The findings from this study have several implications for policy and practice. Policymakers should consider creating supportive frameworks and incentives to promote the use of agricultural waste for energy production. This includes implementing competitive conditions for renewable energy production, as seen in Ukraine, and integrating GHG taxes or life cycle emissions-based performance standards to optimize biomass resource utilization. Additionally, there is a need for comprehensive management strategies that address the entire supply chain of agricultural waste, from collection to conversion, to ensure efficient and sustainable energy production. The transition to renewable energy from agricultural waste also requires investment in technology and infrastructure to support biogas plants and other conversion facilities.

The transition from traditional waste management to energy production using agricultural waste represents a significant step towards achieving energy sustainability and reducing environmental impact. The studyed literature demonstrates that agricultural waste is not merely a disposal problem but a valuable resource for renewable energy generation. By adopting integrated and systemic approaches to waste valorization, it is possible to create a circular bioeconomy that not only addresses waste management challenges but also contributes to energy security and climate change mitigation. The successful implementation of such strategies requires coordinated efforts from governments, industry stakeholders, and the scientific community to develop and deploy effective technologies and policies that support the sustainable use of agricultural waste for energy production.

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Conflict of Interest Disclosure

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