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Enhancing the Efficiency of Converting Agricultural Waste into Biomethane Using Anaerobic Digestion Technology

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Abstract This study's focus is on integrating various innovative techniques and process optimizations to improve biomethane yield and overall system performance. The study highlights several key advancements in anaerobic digestion technology. Integrating pyrolysis with anaerobic digestion has shown a significant increase in biomethane production, achieving an overall efficiency of 67% compared to 52% for stand-alone systems. The use of biochar as an additive has been found to enhance hydrolysis, acidogenesis, and methanogenesis, thereby stabilizing the microbial community and increasing methane yield. Co-digestion of food waste with other substrates has also been identified as an effective method to boost biogas production, with yields ranging from 0.272 to 0.859 m³ CH_4/kg VS. Additionally, emerging technologies such as membrane separation and chemical looping for biogas upgrading have been discussed, showing potential for further enhancing biomethane quality and production rates. The integration of advanced techniques such as pyrolysis, biochar addition, and co-digestion, along with innovative biogas upgrading methods, significantly enhances the efficiency of converting agricultural waste into biomethane. These advancements not only improve biomethane yield but also contribute to the sustainability and economic viability of anaerobic digestion technology.

Keywords Anaerobic digestion; Biomethane; Agricultural waste; Pyrolysis; Biochar

1 Introduction

The global energy landscape is undergoing a significant transformation, driven by the urgent need to mitigate climate change and reduce dependency on fossil fuels. Renewable energy sources, such as solar, wind, and bioenergy, are increasingly recognized for their potential to provide sustainable and environmentally friendly alternatives to conventional energy sources. Among these, bioenergy stands out due to its ability to convert organic waste into valuable energy, thereby addressing both energy production and waste management challenges simultaneously (Salman et al., 2017; Verbeeck et al., 2018; Nguyen et al., 2020).

Biomethane, a renewable form of natural gas, is produced through the anaerobic digestion of organic materials, including agricultural waste. Agricultural waste, such as crop residues, animal manure, and food waste, represents a significant and underutilized resource for biomethane production. The anaerobic digestion process involves the microbial breakdown of organic matter in the absence of oxygen, resulting in the production of biogas, which primarily consists of methane (CH_4) and carbon dioxide (CO_2). This biogas can be upgraded to biomethane by removing CO_2 and other impurities, making it suitable for use as a fuel or for injection into the natural gas grid (Meng et al., 2015; Beegle and Borole, 2018; Bong et al., 2018).

Anaerobic digestion (AD) technology plays a crucial role in sustainable waste management by converting organic waste into renewable energy and valuable by-products. The process not only reduces the volume of waste destined for landfills but also mitigates greenhouse gas emissions by capturing methane that would otherwise be released into the atmosphere. Additionally, the digestate produced during anaerobic digestion can be used as a nutrient-rich fertilizer, contributing to a circular economy and enhancing soil health (Lin et al., 2017; Antoniou et al., 2019; Neri et al., 2023). Innovations in AD technology, such as the integration of pyrolysis and the use of conductive materials like graphene, have shown promise in further enhancing biomethane yields and process efficiency (Lin et al., 2017; Salman et al., 2017).

This systematic study aims to provide a comprehensive overview of the current advancements and challenges in enhancing the efficiency of converting agricultural waste into biomethane using anaerobic digestion technology. The specific objectives are to evaluate the latest innovations and process configurations that improve biomethane production efficiency, to assess the economic and environmental benefits of integrating anaerobic digestion with other technologies, to identify the key factors influencing the performance and stability of anaerobic digestion systems, and to highlight future research directions and potential policy implications for promoting the adoption of anaerobic digestion technology in agricultural waste management.

By synthesizing findings from recent studies, this study seeks to inform researchers, policymakers, and industry stakeholders about the potential of anaerobic digestion technology to contribute to sustainable energy production and waste management.

2 Agricultural Waste as a Feedstock for Biomethane Production

2.1 Types of agricultural waste suitable for anaerobic digestion

Agricultural waste encompasses a variety of materials that can be effectively utilized as feedstock for anaerobic digestion to produce biomethane. The primary types of agricultural waste include:

Crop Residues: These are the remnants of crops after the harvest, such as straw, stalks, and husks. Crop residues are rich in lignocellulosic materials, which can be challenging to break down but offer significant potential for biomethane production when pretreated appropriately (Salman et al., 2017; Noor et al., 2021).

Animal Manure: Manure from livestock such as cattle, swine, and poultry is a common feedstock for anaerobic digestion. Co-digestion of animal manure with other organic wastes has been shown to significantly enhance methane yields (Muscolo et al., 2017; Ma et al., 2020).

Food Processing Waste: This includes waste generated from the processing of agricultural products, such as fruit and vegetable peels, pulp, and other organic residues. Food processing waste is often rich in easily degradable organic matter, making it an excellent candidate for anaerobic digestion (Bong et al., 2018; Neri et al., 2023).

2.2 Characteristics and composition of agricultural waste

The efficiency of anaerobic digestion largely depends on the characteristics and composition of the agricultural waste used. Key factors include:

Carbon to Nitrogen (C/N) Ratio: An optimal C/N ratio is crucial for maintaining microbial activity and enhancing methane production. For instance, co-digestion studies have shown that a C/N ratio ranging from 26 to 34 is ideal for maximizing methane yields (Ma et al., 2020; Pan et al., 2021).

Volatile Solids (VS): The amount of organic matter available for microbial degradation is indicated by the volatile solids content. Higher VS content generally correlates with higher biogas production potential (Meng et al., 2015; Ma et al., 2020).

Particle Size and Pretreatment: Smaller particle sizes and appropriate pretreatment methods, such as mechanical, thermal, or chemical treatments, can enhance the digestibility of lignocellulosic materials, thereby improving biomethane yields (Salman et al., 2017; Bong et al., 2018).

pH and Temperature: Maintaining optimal pH (around 7.0-7.5) and temperature (mesophilic: 30℃-40℃, thermophilic: 40℃-50℃) conditions is essential for the stability and efficiency of the anaerobic digestion process (Noor et al., 2021; Neri et al., 2023).

2.3 Challenges associated with using agricultural waste as feedstock

Despite the potential benefits, several challenges are associated with using agricultural waste as feedstock for biomethane production:

Variability in Composition: Agricultural waste composition can vary significantly depending on the type of crop, animal diet, and seasonal factors, leading to inconsistent biogas yields (Meng et al., 2015; Bong et al., 2018).

High Lignocellulosic Content: Many agricultural residues, such as straw and stalks, have high lignocellulosic content, which is resistant to microbial degradation. Effective pretreatment methods are required to enhance their digestibility (Salman et al., 2017; Xiao et al., 2021).

Inhibitory Compounds: Certain agricultural wastes may contain inhibitory compounds, such as phenols or high levels of ammonia, which can negatively impact the anaerobic digestion process. Managing these inhibitors is crucial for maintaining process stability (Muscolo et al., 2017; Neri et al., 2023).

Logistics and Collection: The decentralized nature of agricultural waste production poses logistical challenges in terms of collection, transportation, and storage, which can affect the overall feasibility and cost-effectiveness of biomethane production (Verbeeck et al., 2018; Pan et al., 2021).

By addressing these challenges through optimized feedstock management, pretreatment technologies, and process control, the efficiency of converting agricultural waste into biomethane can be significantly enhanced, contributing to sustainable energy production and waste management.

3 Anaerobic Digestion Technology

3.1 Basic principles and process of anaerobic digestion

Anaerobic digestion (AD) is a biological process that converts organic waste into biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2), through the action of microorganisms in the absence of oxygen. This technology is gaining attention due to its dual benefits of waste management and renewable energy production (Li et al., 2019). The process involves the breakdown of complex organic materials into simpler compounds, which are then converted into biogas through a series of biochemical reactions facilitated by different microbial communities (Figure 1) (Mlaik et al., 2019; Neri et al., 2023).

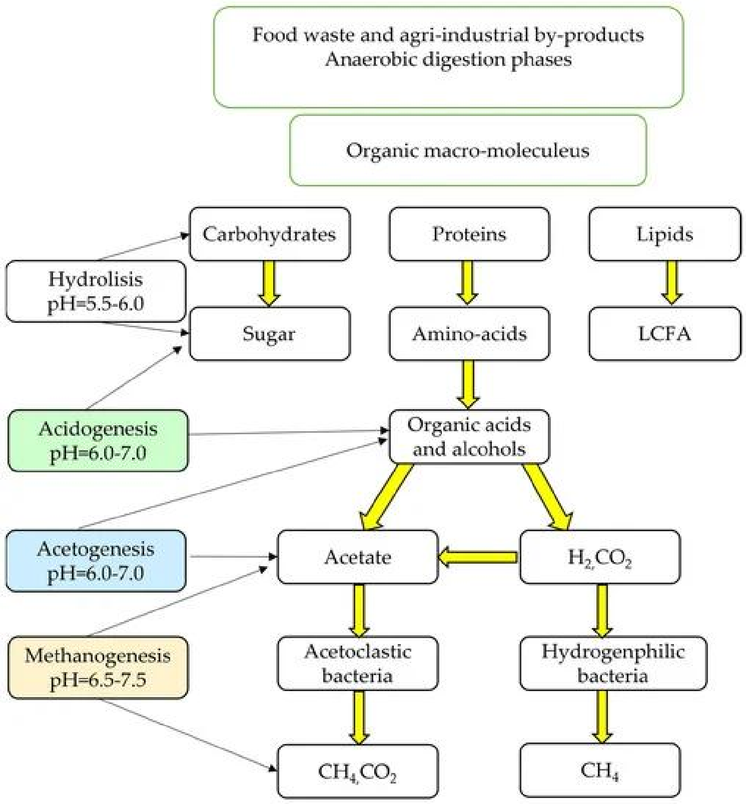

Figure 1 Flow chart of anaerobic digestion (Adopted from Neri et al., 2023)

3.2 Stages of anaerobic digestion

The anaerobic digestion process can be divided into four main stages:

Hydrolysis: In this initial stage, complex organic polymers such as carbohydrates, proteins, and fats are broken down into simpler monomers like sugars, amino acids, and fatty acids by hydrolytic enzymes (Mlaik et al., 2019). Enzymatic pretreatment has been shown to enhance this stage significantly, improving the solubilization of organic matter (Mlaik et al., 2019).

Acidogenesis: The monomers produced during hydrolysis are further broken down by acidogenic bacteria into volatile fatty acids (VFAs), alcohols, hydrogen, and carbon dioxide (Li et al., 2019).

Acetogenesis: In this stage, the VFAs and alcohols are converted into acetic acid, hydrogen, and carbon dioxide by acetogenic bacteria (Li et al., 2019).

Methanogenesis: The final stage involves methanogenic archaea converting acetic acid, hydrogen, and carbon dioxide into methane and water. This stage is crucial for the production of biogas and can be enhanced by improving enzyme activity and electron transfer processes (Salman et al., 2017; Li et al., 2019).

3.3 Types of anaerobic digesters

There are several types of anaerobic digesters, each suited to different types of feedstock and operational conditions:

Batch Digesters: These operate in a fill-and-draw mode, where the digester is filled, sealed, and left to digest the material for a set period before being emptied (Li et al., 2019).

Continuous Digesters: These systems continuously feed organic material into the digester and continuously remove digested material, allowing for a steady production of biogas (Li et al., 2019).

Plug Flow Digesters: These are designed for high-solids content feedstocks and operate by pushing the material through the digester in a plug flow manner, ensuring that the material moves as a unit through the system (Li et al., 2019).

3.4 Parameters influencing the anaerobic digestion process

Several parameters significantly influence the efficiency and stability of the anaerobic digestion process:

Temperature: The process can be operated under mesophilic (30℃-40℃) or thermophilic (50℃-60℃) conditions. Thermophilic digestion generally results in higher biogas yields but requires more energy input (Li et al., 2019).

pH: The optimal pH range for anaerobic digestion is between 6.8 and 7.2. Deviations from this range can inhibit microbial activity and reduce biogas production (Li et al., 2019).

C/N Ratio: The carbon to nitrogen (C/N) ratio is crucial for maintaining microbial balance. An optimal C/N ratio of around 20-30:1 is recommended for efficient digestion (Li et al., 2019).

Hydraulic Retention Time (HRT): This is the average time the feedstock remains in the digester. Longer HRTs generally improve biogas yields but require larger digester volumes (Li et al., 2019).

Organic Loading Rate (OLR): This parameter refers to the amount of organic material fed into the digester per unit volume per day. Optimizing OLR is essential to prevent overloading and ensure stable operation (Li et al., 2019).

By understanding and optimizing these parameters, the efficiency of converting agricultural waste into biomethane using anaerobic digestion technology can be significantly enhanced.

4 Pre-treatment Methods to Enhance Biomethane Production

4.1 Physical pre-treatments

Physical pre-treatments such as grinding, milling, and thermal treatment are commonly used to enhance the efficiency of anaerobic digestion by increasing the surface area of the substrate and making it more accessible to microbial action. Thermal pre-treatment, in particular, has shown significant promise. For instance, heating food waste at 50℃ for 6-12 hours or at 80℃ for 1.5 hours can increase biomethane production by 44%-46% (Ariunbaatar et al., 2015). Similarly, mechanical treatments like grinding and milling can break down complex organic materials, making them more digestible and thus improving biogas yields (Bong et al., 2018).

4.2 Chemical pre-treatments

Chemical pre-treatments involve the use of acids, alkalis, or oxidative agents to break down complex organic materials into simpler compounds that are more easily digested by anaerobic microbes. Acid pre-treatment is particularly effective for lignocellulosic materials, enhancing hydrolysis and subsequent biomethane production (Rawoof et al., 2020). Alkaline treatments, such as the use of $NaHCO_3$, have also been shown to improve methane yields by reducing lignin, cellulose, and hemicellulose content in agricultural waste, thereby increasing the cumulative methane production by 11.2%-29.7% (Figure 2) (Almomani and Bhosale, 2020). Ozonation is another chemical pre-treatment that has been found to enhance biomethane production, although its energy requirements may offset some of the gains (Ariunbaatar et al., 2014).

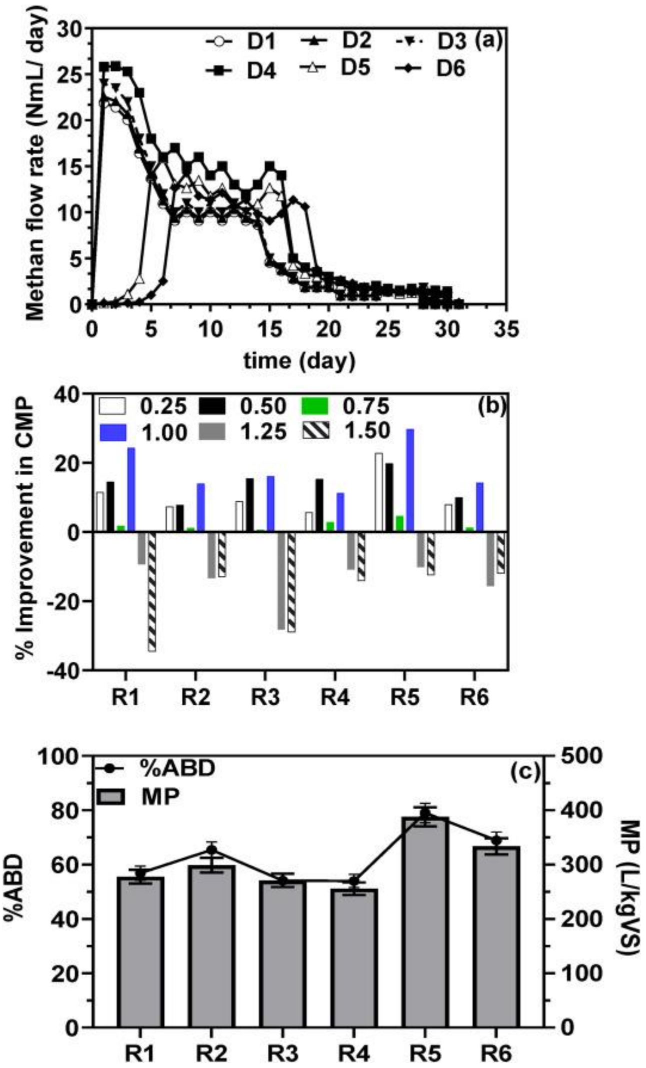

Figure 2 (a) Methane flow rate in the studied reactors under different alkalinity doses, (b) improvement in CMP for all studied reactors under different NaHCO3 doses and (c) maximum MP potential and %ADE under D4 (Adopted from Almomani and Bhosale, 2020)

4.3 Biological pre-treatments

Biological pre-treatments involve the use of enzymes or microbial consortia to break down complex organic materials. Enzyme addition can significantly enhance the hydrolysis of lignocellulosic materials, leading to higher biomethane yields (Rawoof et al., 2020). The use of microbial consortia can also improve the efficiency of anaerobic digestion by synergizing the effects on microbial communities, balancing nutrients, and reducing inhibitory effects (Neri et al., 2023). Co-digestion, which involves the simultaneous digestion of multiple types of organic waste, has been shown to enhance biogas production by 25%-400% compared to mono-digestion (Rawoof et al., 2020).

4.4 Impact of pre-treatment methods on the efficiency of anaerobic digestion

The impact of pre-treatment methods on the efficiency of anaerobic digestion is substantial. Physical, chemical, and biological pre-treatments can significantly enhance the breakdown of complex organic materials, making them more accessible to anaerobic microbes and thus increasing biogas yields. For example, thermal pre-treatment at lower temperatures can accelerate the kinetics of the anaerobic digestion process, leading to higher biomethane production (Salman et al., 2017). Chemical pre-treatments like acid and alkaline treatments can improve the hydrolysis of lignocellulosic materials, resulting in higher methane yields (Almomani and Bhosale, 2020). Biological pre-treatments, including enzyme addition and co-digestion, can synergize microbial activity and improve nutrient balance, further enhancing biogas production (Rawoof et al., 2020; Neri et al., 2023).

In summary, the integration of various pre-treatment methods can significantly improve the efficiency of converting agricultural waste into biomethane using anaerobic digestion technology. Each method has its advantages and can be selected based on the specific characteristics of the feedstock and the desired outcomes.

5 Optimization Strategies for Anaerobic Digestion

5.1 Co-digestion of agricultural waste with other organic materials

Co-digestion involves the simultaneous digestion of multiple organic substrates, which can enhance the efficiency and stability of the anaerobic digestion process. Studies have shown that co-digestion of agricultural waste with other organic materials, such as food waste, floatable oil, and bioplastics, can significantly improve biomethane production. For instance, co-digestion of food waste and floatable oil resulted in higher biomethane yields and better system stability compared to mono-digestion (Meng et al., 2015). Additionally, co-digestion of bioplastics with biowastes has been found to efficiently degrade bioplastics and improve biogas production (Abraham et al., 2020). The synergistic effects of co-digestion help balance nutrient content, reduce inhibitory effects, and enhance microbial community interactions, leading to increased biomethane yields (Rawoof et al., 2020; Pan et al., 2021).

5.2 Optimization of process parameters (temperature, pH, HRT, OLR)

Optimizing process parameters such as temperature, pH, hydraulic retention time (HRT), and organic loading rate (OLR) is crucial for maximizing biomethane production. The optimal temperature range for anaerobic digestion is typically mesophilic (30℃-40℃) or thermophilic (40℃-50℃), with higher methane yields observed in the thermophilic range (Noor et al., 2021). Maintaining an optimal pH range of 6.8-7.2 is essential for stable methane production (Rawoof et al., 2020). Adjusting HRT and OLR can also significantly impact the efficiency of the digestion process. For example, reducing the retention time from 72 to 20 hours improved hydrogen yield, while an optimal C/N ratio of 16-27 enhanced methane productivity (Rawoof et al., 2020). Proper control of these parameters ensures a stable and efficient anaerobic digestion process (Rawoof et al., 2020; Noor et al., 2021; Pan et al., 2021).

5.3 Use of additives and supplements (trace elements, biochar, etc.)

The addition of various additives and supplements can enhance the anaerobic digestion process. Trace elements such as iron, nickel, and cobalt are known to improve microbial activity and methane production. Biochar, a byproduct of pyrolysis, has been shown to increase biomethane content and support the development of a stable microbial community when added to the digester (Salman et al., 2017). Other additives, such as enzymes and micronutrients, can also enhance the breakdown of complex organic materials and improve overall process efficiency (Zhang et al., 2019; Rawoof et al., 2020). The strategic use of these additives can lead to higher biomethane yields and more stable digestion processes (Salman et al., 2017; Zhang et al., 2019; Rawoof et al., 2020).

5.4 Innovations in digester design and operation

5.4.1 Advanced digester configurations

Innovative digester configurations, such as two-stage anaerobic digestion systems, have been developed to enhance biomethane production. Two-stage systems separate the hydrolysis and acidogenesis phases from the methanogenesis phase, allowing for better control of each stage and improved overall efficiency. For example, a two-stage co-digestion system using pretreated organic wastes and animal manure resulted in significantly higher methane production compared to single-stage systems (Noor et al., 2021). Advanced configurations can also include integrated processes that combine anaerobic digestion with other technologies, such as pyrolysis, to further enhance biomethane yields (Salman et al., 2017).

5.4.2 Improved mixing and gas collection systems

Effective mixing and gas collection systems are essential for optimizing anaerobic digestion. Improved mixing ensures uniform distribution of substrates and microorganisms, enhancing the breakdown of organic materials and preventing the formation of inhibitory zones. Advanced gas collection systems can efficiently capture and store the produced biogas, reducing losses and increasing the overall yield. Studies have shown that proper mixing and efficient gas collection can significantly improve the performance of anaerobic digesters (Verbeeck et al., 2018; Rawoof et al., 2020). Innovations in these areas contribute to more efficient and reliable biomethane production processes (Verbeeck et al., 2018; Rawoof et al., 2020).

By implementing these optimization strategies, the efficiency of converting agricultural waste into biomethane using anaerobic digestion technology can be significantly enhanced, leading to higher energy yields and more sustainable waste management practices.

6 Advances in Anaerobic Digestion Technology

6.1 Integration with other renewable energy technologies

The integration of anaerobic digestion (AD) with other renewable energy technologies, such as solar and wind, has shown significant potential in enhancing the efficiency and sustainability of biomethane production. By combining AD with solar energy, for instance, the heat generated from solar panels can be used to maintain the optimal temperature for the digestion process, thereby improving the overall efficiency of biogas production. Similarly, wind energy can be harnessed to power the mechanical components of AD systems, reducing reliance on non-renewable energy sources and lowering operational costs (Labatut and Pronto, 2018; Verbeeck et al., 2018; Neri et al., 2023).

6.2 Development of hybrid systems

Hybrid systems that combine anaerobic digestion with other processes, such as pyrolysis, have been developed to maximize the conversion of agricultural waste into biomethane. One notable approach involves coupling AD with the pyrolysis of lignocellulosic or green waste. The biochar produced from pyrolysis can be added to the digester to enhance microbial activity and increase biomethane yield. Additionally, the bio-oil and syngas generated from pyrolysis can be reformed into syngas and subsequently converted to biomethane via methanation. This integrated process has demonstrated a significant increase in biomethane production and overall system efficiency compared to standalone AD systems (Sheets et al., 2015; Salman et al., 2017; Zhang et al., 2019).

6.3 Application of real-time monitoring and control systems

The application of real-time monitoring and control systems in anaerobic digestion technology has revolutionized the management and optimization of the digestion process. Advanced sensors and control algorithms enable continuous monitoring of critical parameters such as pH, temperature, and biogas composition. This real-time data allows for immediate adjustments to be made, ensuring optimal conditions for microbial activity and maximizing biogas production. The implementation of these systems has been shown to prevent process upsets, enhance stability, and improve the overall efficiency of AD plants (Fan et al., 2018; Labatut and Pronto, 2018; Abraham et al., 2020).

6.4 Use of computational models and simulations for process optimization

Computational models and simulations have become invaluable tools for optimizing the anaerobic digestion process. These models can simulate various scenarios and predict the outcomes of different operational strategies, allowing for the identification of optimal conditions for biogas production. By incorporating factors such as feedstock composition, loading rates, and environmental conditions, these models provide insights into the complex interactions within the digester. The use of computational models has led to significant improvements in the design and operation of AD systems, resulting in higher biomethane yields and more efficient waste-to-energy conversion (Muscolo et al., 2017; Salman et al., 2017; Nguyen et al., 2020; Neri et al., 2023).

In conclusion, the advancements in anaerobic digestion technology, including the integration with other renewable energy sources, development of hybrid systems, application of real-time monitoring and control systems, and the use of computational models, have significantly enhanced the efficiency and sustainability of converting agricultural waste into biomethane. These innovations not only improve biogas production but also contribute to the broader goals of renewable energy generation and waste management.

7 Environmental and Economic Benefits

7.1 Reduction of greenhouse gas emissions

Anaerobic digestion (AD) of agricultural waste significantly reduces greenhouse gas (GHG) emissions by capturing methane that would otherwise be released into the atmosphere from decomposing organic matter. The process of converting organic waste into biogas, primarily composed of methane (CH_4) and carbon dioxide (CO_2), helps mitigate the release of these potent GHGs. Studies have shown that AD can effectively reduce GHG emissions by diverting organic waste from landfills and utilizing it for energy production (Muscolo et al., 2017; Zhang et al., 2019; Dutta et al., 2021). Additionally, the integration of AD with other technologies, such as pyrolysis, can further enhance the reduction of carbon emissions by converting digestate into biochar, which sequesters carbon (Salman et al., 2017; Dutta et al., 2021).

7.2 Resource recovery and nutrient recycling

AD not only produces biogas but also generates nutrient-rich digestate, which can be used as a biofertilizer. This digestate contains essential nutrients such as nitrogen, phosphorus, and potassium, which are beneficial for soil health and crop production. The application of digestate to agricultural lands can improve soil organic matter, enhance microbial activity, and promote sustainable farming practices (Sheets et al., 2015; Stoknes et al., 2016; Muscolo et al., 2017). Moreover, emerging technologies are being developed to further treat and reuse AD effluent, ensuring that both the liquid and solid fractions are effectively utilized, thereby closing the resource loop and supporting a circular economy (Sheets et al., 2015; Dutta et al., 2021).

7.3 Energy production and potential for grid integration

The biogas produced through AD can be used for various energy applications, including electricity generation, heating, and as a vehicular fuel. Upgrading biogas to biomethane allows for its injection into the natural gas grid, providing a renewable energy source that can be distributed and used widely (Molino et al., 2013; Verbeeck et al., 2018; Kassem et al., 2020). This integration with the gas grid not only enhances energy security but also supports the decarbonization of the energy sector. For instance, a study demonstrated the feasibility of producing renewable natural gas (RNG) from dairy waste and injecting it into the gas pipeline, contributing to grid decarbonization and reducing reliance on fossil fuels (Kassem et al., 2020).

7.4 Economic feasibility and cost-benefit analysis

The economic viability of AD technology is influenced by several factors, including the cost of feedstock, operational expenses, and the market value of biogas and digestate. Government incentives and carbon credit mechanisms play a crucial role in making AD projects financially attractive. For example, the Low Carbon Fuel Standard (LCFS) and Renewable Fuel Standard (RFS) can significantly enhance the net present value (NPV) of AD projects, making them economically feasible (Kassem et al., 2020). Additionally, integrating AD with other processes, such as pyrolysis, can increase the overall efficiency and revenue of the system, as demonstrated by a study that showed a 1.2-fold increase in biomethane production and higher annual revenue compared to traditional waste treatment methods (Salman et al., 2017). The economic benefits of AD extend beyond energy production, as the use of digestate as a biofertilizer can reduce the need for synthetic fertilizers, leading to cost savings for farmers (Stoknes et al., 2016; Muscolo et al., 2017).

8 Case Studies and Practical Applications

8.1 Successful case studies of anaerobic digestion plants using agricultural waste

Several successful case studies highlight the effectiveness of anaerobic digestion (AD) plants in converting agricultural waste into biomethane. For instance, the integration of pyrolysis and anaerobic digestion processes has shown promising results. By coupling the anaerobic digestion of biodegradable waste with the pyrolysis of lignocellulosic or green waste, a significant increase in biomethane production was achieved. The biochar produced from pyrolysis was used as an adsorbent in the digester, enhancing the biomethane content and supporting a stable microbial community. This integrated process demonstrated an approximately 1.2-fold increase in biomethane volume and an overall efficiency of 67%, compared to 52% for a stand-alone anaerobic digestion system (Salman et al., 2017).

Another notable case is the anaerobic co-digestion of agricultural wastes and waste-activated sludge, which has been shown to produce bioenergy and biochemicals, contributing to a circular bioeconomy. This process has been optimized by adjusting feedstock compositions and operating conditions, resulting in enhanced biomethane production (Pan et al., 2021).

8.2 Lessons learned from pilot and commercial-scale projects

Pilot and commercial-scale projects have provided valuable insights into the practical applications of anaerobic digestion technology. For example, the anaerobic digestion of orange peel in a semi-continuous pilot plant demonstrated the potential for biomethane production from citrus waste. The study found that under mesophilic conditions, the highest daily specific methane yield was achieved at an organic loading rate (OLR) of 1.0 gTVS L^{-1} d^{-1} and an essential oil supply rate (EOsr) of 47.6 mg L^{-1} d^{-1}. However, partial inhibition occurred at higher OLR and EOsr values, highlighting the importance of optimizing these parameters for successful operation (Zema et al., 2018).

Additionally, the use of hydrothermal carbonization (HTC) coupled with anaerobic digestion for the treatment of municipal solid waste has shown significant improvements in biomethane production. The HTC process increased methane production by up to 363% compared to untreated waste, demonstrating the effectiveness of this combined approach (Lucian et al., 2020).

8.3 Regional and global perspectives on the adoption of anaerobic digestion technology

The adoption of anaerobic digestion technology varies regionally and globally, influenced by factors such as regulatory support, economic incentives, and technological advancements. In Europe, for instance, the upgrading of biogas to biomethane and its injection into the gas grid has been explored as a means to connect decentralized biomass production to a centralized gas grid. This approach has been economically viable even without subsidies, promoting anaerobic digestion as a key driver for a new bio-industry (Verbeeck et al., 2018).

Globally, the interest in enhancing anaerobic digestion efficiency through the application of biochar has been growing. Biochar has been shown to enhance hydrolysis, acidogenesis-acetogenesis, and methanogenesis, as well as alleviate inhibitor stress, thereby promoting stable and efficient biomethane production (Pan et al., 2019).

In summary, the successful implementation of anaerobic digestion technology in various case studies and pilot projects, along with regional and global perspectives, underscores its potential in converting agricultural waste into valuable biomethane. The lessons learned from these projects provide a roadmap for optimizing and scaling up anaerobic digestion processes to achieve sustainable and efficient waste management solutions.

9 Policy and Regulatory Framework

9.1 Overview of policies supporting anaerobic digestion and biomethane production

The promotion of anaerobic digestion (AD) and biomethane production is supported by various policies aimed at enhancing renewable energy sources and reducing greenhouse gas emissions. In Europe, regulatory support schemes incentivize the conversion of biomass to biogas, which can be upgraded to biomethane and injected into the gas grid. These policies provide financial incentives, such as feed-in tariffs and subsidies, to make investments in AD technology economically viable (Verbeeck et al., 2018). Additionally, the use of biogas for electricity and heat generation is encouraged through government support, which helps in connecting decentralized biomass production to centralized energy systems (Verbeeck et al., 2018).

9.2 Regulatory challenges and incentives for agricultural waste utilization

Despite the supportive policies, several regulatory challenges hinder the widespread adoption of AD for agricultural waste utilization. One major challenge is the economic and environmental concerns associated with the land application of AD effluent, which can limit the use of AD for treating agricultural and food wastes (Sheets et al., 2015). To address these issues, emerging technologies for the treatment and reuse of AD effluent are being developed, but their application is often limited by regulatory constraints and the composition of the effluent (Sheets et al., 2015). Furthermore, the variation in food waste characteristics and the lack of standardized regulations can affect the efficiency of AD processes and the consistency of biogas production (Bong et al., 2018).

Incentives for agricultural waste utilization include financial support for biogas upgrading techniques, such as water scrubbing, pressure swing adsorption, and membrane separation, which are essential for producing pipeline-quality biomethane (Nguyen et al., 2020). These incentives help wastewater treatment plants (WWTPs) become net energy producers by utilizing spare digestion capacity and generating surplus biogas (Nguyen et al., 2020).

9.3 Role of government and industry in promoting sustainable practices

The government plays a crucial role in promoting sustainable practices by providing regulatory frameworks and financial incentives that support the development and adoption of AD technology. Policies that encourage the use of renewable energy sources and the reduction of greenhouse gas emissions are essential for driving the growth of the AD industry (Verbeeck et al., 2018; Nguyen et al., 2020). Additionally, government support for research and development can lead to innovations in biogas upgrading techniques and the efficient treatment of AD effluent (Sheets et al., 2015; Nguyen et al., 2020).

The industry also has a significant role in promoting sustainable practices by investing in advanced AD technologies and optimizing the AD process. For instance, the integration of pyrolysis with AD can enhance biomethane production and improve the overall efficiency of the process (Salman et al., 2017). Moreover, the use of conductive carbon materials, such as graphene, can boost biomethane yield and production rate by facilitating direct interspecies electron transfer (Lin et al., 2017). By adopting these innovative approaches, the industry can contribute to the sustainable management of agricultural waste and the production of renewable energy.

In conclusion, the collaboration between government and industry is vital for overcoming regulatory challenges and promoting the efficient utilization of agricultural waste through AD technology. By providing supportive policies and investing in advanced technologies, both entities can drive the growth of the biomethane industry and contribute to a more sustainable future.

10 Future Prospects and Research Directions

10.1 Emerging Trends and Technologies in Anaerobic Digestion

Recent advancements in anaerobic digestion (AD) technology have focused on integrating various processes to enhance biomethane production. One notable trend is the coupling of anaerobic digestion with pyrolysis, where biochar produced from pyrolysis is used as an adsorbent in the digester to increase biomethane yield and stabilize the microbial community (Salman et al., 2017). Additionally, the use of co-digestion strategies, such as combining shrimp chaff with agricultural biomass, has shown significant improvements in biomethane production and system stability (Ali et al., 2021). The development of two-stage anaerobic co-digestion processes, which involve pretreating organic wastes before digestion, has also been highlighted as a promising approach to enhance biomethane yields (Noor et al., 2021).

10.2 Potential for scaling up and commercialization

The potential for scaling up and commercializing anaerobic digestion technology is substantial, particularly with the integration of biogas upgrading systems that convert biogas to pipeline-quality biomethane. This biomethane can be injected into the gas grid, providing a decentralized solution for biomass feedstocks and reducing the need for biomass transportation (Verbeeck et al., 2018). The economic feasibility of such systems has been demonstrated, with studies showing positive net return values and reasonable payback times (Noor et al., 2021). Furthermore, the use of anaerobic digestion for the treatment of solid organic wastes (SOWs) and food waste has been recognized as an effective method for waste management and energy production, with various performance-enhancing strategies being explored to promote industrial applications (Ren et al., 2018; Zhang et al., 2019).

10.3 Gaps in current research and areas for future investigation

Despite the advancements in anaerobic digestion technology, several gaps remain in current research. One major area that requires further investigation is the optimization of feedstock compositions and operating conditions to maximize biomethane production. The effects of different feedstock characteristics, such as particle size and carbon-to-nitrogen ratio, on the anaerobic digestion process need to be critically explored (Pan et al., 2021). Additionally, there is a need for more research on the genetic engineering of enzymes and microbial strains to enhance the efficiency of the digestion process (Zhang et al., 2019). The development of novel pretreatment methods and the integration of multiple enhancing techniques also present opportunities for future research (Neri et al., 2023).

10.4 Collaborative efforts and partnerships for advancing anaerobic digestion technology

Advancing anaerobic digestion technology will require collaborative efforts and partnerships between academia, industry, and government. Collaborative research initiatives can help address the technical challenges associated with anaerobic digestion and promote the development of innovative solutions. Partnerships with industry can facilitate the commercialization of new technologies and the scaling up of anaerobic digestion systems. Government support, in the form of regulatory incentives and funding, will be crucial in promoting the adoption of anaerobic digestion technology and achieving sustainability goals (Molino et al., 2013; Verbeeck et al., 2018). By fostering collaboration and leveraging the expertise of various stakeholders, the potential of anaerobic digestion technology can be fully realized, contributing to a circular bioeconomy and sustainable energy future.

11 Concluding Remarks

The systematic study of recent advancements in anaerobic digestion (AD) technology for converting agricultural waste into biomethane has highlighted several key findings. Integrating pyrolysis with AD has shown a significant increase in biomethane production, achieving an overall efficiency of 67% compared to 52% for standalone AD systems. The use of biochar as an additive in AD processes has been found to enhance hydrolysis, acidogenesis-acetogenesis, and methanogenesis, thereby stabilizing digester performance and increasing methane yield. Additionally, the application of conductive materials like graphene has demonstrated potential in boosting biomethane yield and production rate through direct interspecies electron transfer. Co-digestion strategies, particularly at wastewater treatment plants, have also been effective in generating surplus biogas, which can be upgraded to biomethane for use as fuel or town gas. Furthermore, pretreatment of lignocellulosic waste with microbial consortia has significantly improved biogas and methane yields.

The findings from this study have significant implications for sustainable waste management and renewable energy production. The integration of pyrolysis and AD not only enhances biomethane production but also provides a viable solution for managing different fractions of agricultural waste, thereby reducing the environmental impact of waste disposal. The use of biochar and other additives in AD processes can lead to more stable and efficient biogas production, making it a more attractive option for waste management. The potential of co-digestion and biogas upgrading at wastewater treatment plants to produce surplus biomethane underscores the role of AD in decentralized renewable energy production and its integration into existing energy infrastructures. Moreover, the development of novel pretreatment methods for lignocellulosic waste can further optimize the AD process, making it more cost-effective and efficient.

The future of anaerobic digestion technology looks promising, with ongoing research and innovations continually enhancing its efficiency and applicability. The integration of advanced pretreatment methods, such as the use of microbial consortia and conductive materials, is likely to play a crucial role in overcoming current limitations and maximizing biomethane yields. Additionally, the coupling of AD with other technologies, such as pyrolysis and biogas upgrading, offers a comprehensive approach to waste management and renewable energy production. As the demand for sustainable energy solutions grows, further advancements in AD technology will be essential in meeting these needs while addressing environmental concerns associated with agricultural waste. Continued research and development, along with supportive regulatory frameworks, will be key to realizing the full potential of anaerobic digestion in the renewable energy landscape.

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Conflict of Interest Disclosure
The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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