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Review Article

# Cost-Effective Production of Methane from Commonly Available Food wastes in China: A Comprehensive Review and Comparative Analysis

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## ABSTRACT

Anaerobic digestion or biogas technology represents a viable approach to addressing existing problems with the disposal and treatment of organic waste where organic substances are converted to methane, a source of renewable energy. The quarterly review paper covers all facets of methane generation from organic waste, especially the functional model and performance of AD systems in China’s diversified industries. In the paper, the author divides AD systems into four sections: batch, continuous, single-stage, and multi-stage, and explains the best practices of each for large-scale operations as well as for certain types of waste. Technical problems, high moisture content, foaming, and the problem of acidification are described along with their influence on the effectiveness of the process and with reference to ways to avoid these problems. Economic challenges are also addressed, with an emphasis on the costs associated with scaling up AD systems from pilot to full-scale operations, the economic viability of these systems, and the barriers to technology adoption. Case studies from various regions in China are examined to demonstrate the practical applications and the potential of these systems to contribute to energy sustainability and waste reduction. The paper concludes with recommendations for future research and development to enhance the efficiency and cost-effectiveness of methane production from organic waste, underscoring the need for technological innovations and supportive policies.

**Keywords:** Anaerobic digestion, methane production, organic waste, renewable energy, biogas technology, sustainability, operational challenges, economic challenges, China, technology adoption.

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## INTRODUCTION

Agricultural waste, organic waste, and livestock manure constitute a significant proportion of the content of each landfill; its degradation releases approximately 18% of the methane emissions, causing global warming 25 times more potent than CO2 within 100 years (Mirzabaev et al., 2021). it is bad news for the world's second-largest producer of organic waste, given its large population and rapidly expanding agricultural sector. Data from the Ministry of Ecology and Environment reveal that China today alone produces 60 million tons of organic waste every year. This waste was simply considered a disposal issue in the past, but it is actually a potential source of methane through AD (Alzate et al., 2023). Expected methane emission reduction, together with the capture and use of organic waste for energy production, is a successful solution to address the greenhouse effect since it also supplements China's energy sources.

The country has plans to extend its biogas generation from agricultural waste as it targets to achieve net zero emissions by 2060. Maxima methane recovery from organic waste is EPA's responsive approach from an environmental perspective as well as to the country's energy security and sustainability – making it a research and developmental necessity (Rashama et al., 2019).

**Problem Statement**

The potential to get renewable energy through methane exists in China, as there is much organic waste, and its organic component is vast. The potential of current management and processing practices for organic waste has not been well optimized, which has led to considerable environmental impact. The AD process that converts organic waste to methane is considered a potential technological fix for this (Singh et al., 2023). Several critical difficulties compound it. These include low biogas production rates, fluctuating digestion process, and low biogas generating capability, mainly due to the diverse composition of organic waste. Such inefficiencies not only constrain methane generation but also slow the advancement of the overall AD technology as a biogas and waste solution to China's push toward a green economy.

**Significance of the Study**

This research is crucial, covering waste management as well as sustainable energy generation, which are considered to be significant problems in China. This study focuses on methane production from easily accessible organic wastes, which will be immensely helpful in augmenting cost-effective and sustainable biotechnological methods. The results are envisaged to reduce the various environmental impacts associated with organic waste through improved energy recovery mechanisms (Harish et al., 2022). This study seeks to develop a replicable and scalable model for renewable energy projects that can be adopted in both urban and rural settings across China. The research benefits greater national objectives of decreasing the emissions of greenhouse gases and increasing the utilization of renewable energy sources to work towards worldwide environment stability goals and further enhancing China's effort in protecting ecology and energy development (Turap et al., 2023).

**Objectives**

To assess the biochemical methane potential (BMP) of common organic wastes in China.

To evaluate the efficiency of different anaerobic digestion configurations and technologies.

To identify and propose solutions to the challenges associated with the anaerobic digestion of organic waste.

## ORGANIC WASTE AS A RESOURCE FOR METHANE PRODUCTION

### Types of Organic Wastes Commonly Available in China

The quantities and types of organic waste generated in China are numerous and huge due to large population and diverse food preferences (Li et al., 2022). This waste primarily originates from three critical sectors: and the proportion of organic waste that they produce continues to be a point of discussion, residential, commercial, and agricultural are some of the sectors that make up the national total.

**Residential Organic waste**

What has been revealed by the Chinese study is the duality of the organic waste situation in urban and rural houses, which shows that managing organic waste is not quite as simple for the purpose of methane production. Metropolitan regions, mainly driven by high consumption of manufactured foods, produce waste with higher biochemical oxygen demand (BOD), making it a promising route for AD. Similarly, richer nutrients herein result in faster decomposition, which may cause hindrances in the storage and preprocessing stages in relation to Methane extraction, albeit once addressed, may affect the efficiency of the whole process as described by (Sprouse, 2024). Rural organic waste, which is mainly comprised of raw agricultural outputs, points toward an altogether different issue. However, it has many variations in composition, such as high cellulose; this may prove to need other pretreatment methods to enhance AD. This country's waste cannot degrade as fast as it can, but it may produce less biogas per ton of urban waste unless technological intervention is used. These differences in the characteristics of urban and rural waste streams highlight the requirement of region-based technology that can take the parameter of input solid waste with regard to the evaluation of efficient methane generation through AD (Ding et al., 2021).

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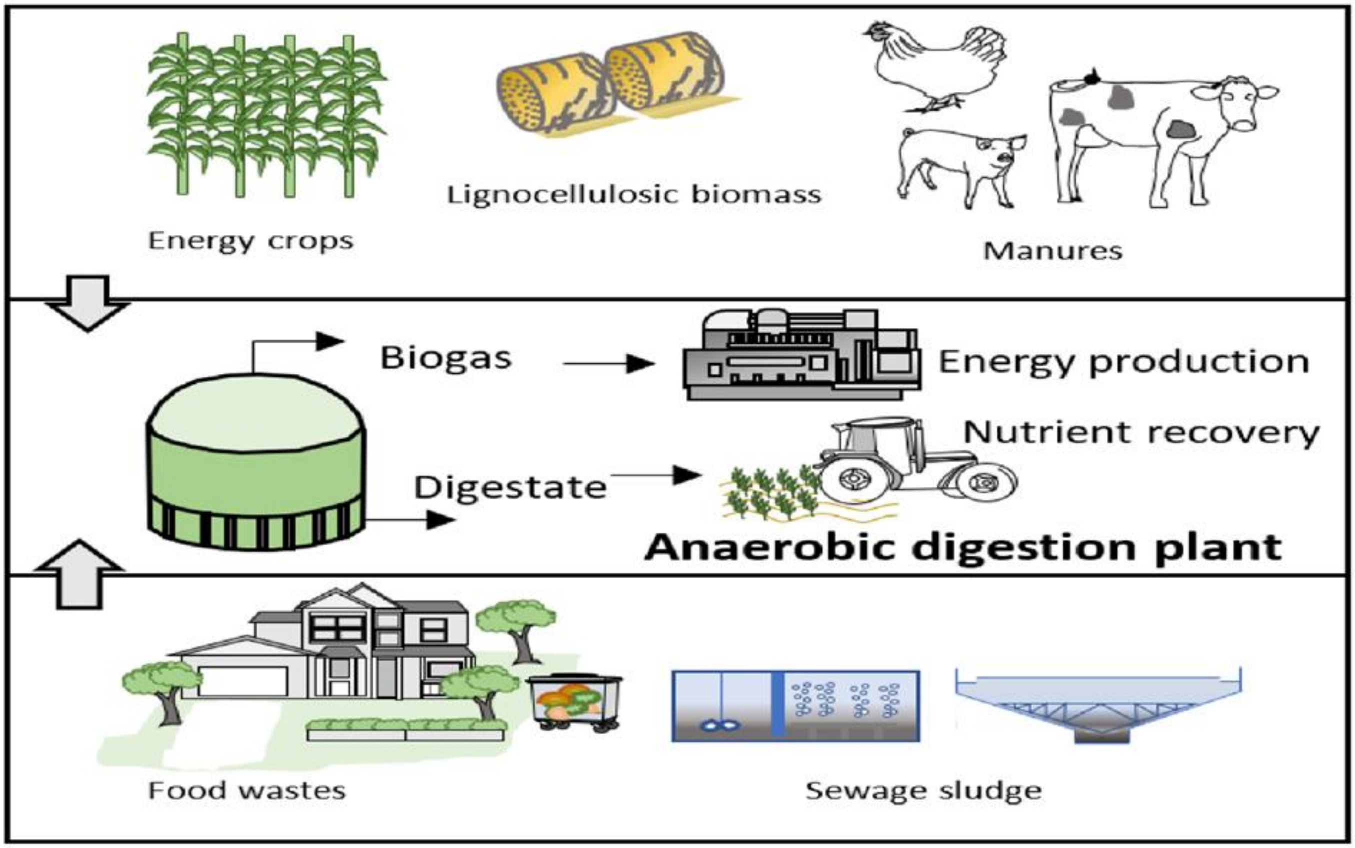


Figure 1: Residential and Agricultural Waste into Biogas (Source: Han, 2023)

**Commercial Organic waste**

To some extent, restaurant organic waste and some other types of organic waste, such as canteen and hotels, are different and pose some sort of challenge or prospect for methane production through AD. This waste normally contains some degree of oils and fats, which, while undesirable due to the detrimental impact they have on microbial activity within AD processes, if well handled through appropriate pretreatment, contains high methane potential (Lee et al., 2024). Since the nature and character of waste in food operations are variable due to the type of cuisine that is offered and the scale of operations of the business, there is a need to adopt differential approaches in waste management. Superior food service providers may use a system that generates less waste per quantity of food served and hence may have a reduced amount of AD volume and hence less treatment needed. Waste generated in food joints located in or near tourist attraction centers and busy areas is relatively high, and there is a need to identify and capitalize on this potent resource through efficient waste processing facilities. Solving these problems calls for advanced pretreatment techniques that will be effective in the high lipid content with the community and the variability of the organic load that characterizes commercial organic waste to boost biogas production in the overall advancement of sustainable urban waste management (Thonar, 2024).

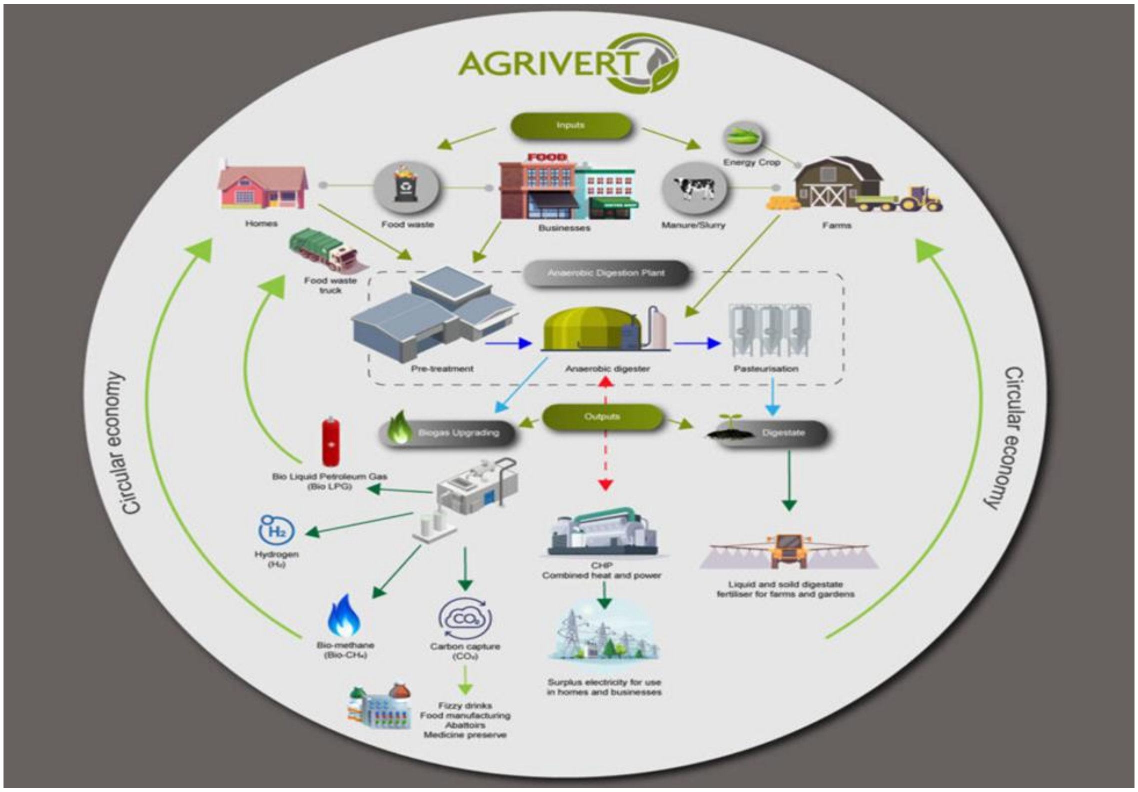


Figure 2: Experimental Setup for Ethanol Pre-Fermentation of Food Waste and Carbon Isotope Analysis

**Agricultural Organic waste**

Plant residues, spoiled vegetables and fruits, and by-products of animal husbandry present some peculiarities in AD because of the variability of their composition and the availability of the material throughout the year (Vogel, 2022). This waste type is virtually symbiotic with the farming schedule and, as such, experiences drastic shifts in volume and types of feedstocks amenable to digestion. Such variations require appropriate and adaptable waste management solutions to accommodate the processes of the post-harvest season at which there is congestion and, in consequence, a display of a high generation rate of waste. Agricultural waste normally has a higher percentage of cellulose and comparatively low moisture content and hence differs typically from domestic or commercial organic waste that undergoes AD (Chen et al., 2023).


Figure 3. Agricultural Waste Types (Sharma et al., 2022).

This requires the implementation of specific pre-treatment measures that will improve the degree of biodiesel feedstock biodegradability, which increases cost and technological implications. Such processes should thus be well integrated following biochemical characteristics of agricultural waste that maximize methane production efficiency and other aspects of the overall AD system economics and energetics.

Biochemical Methane Potential (BMP) of Organic wastes

**Types of Organic Waste**

Organic waste, encompassing a diverse range of biodegradable materials, significantly contributes to global methane emissions when not managed properly. This waste primarily originates from three main sectors: residential, commercial, and agricultural, with their respective organic composition and the potential for, and method of, methane production by anaerobic digestion (AD).

Residential organic waste It is usually derived from families' activities, such as residues from meals, fruits, vegetables, and garden wastes. These materials are quite variable and composed of chemically complex organic matter that is high in moisture and biodegradable activity. Residential waste is heterogeneous and unique in characteristics that present several complexities regarding AD, including the need to pretreat the waste to optimize methane production and reactor stability.

Commercial organic waste, it comprises remains from food service establishments, markets, and retailers, expired foods and scarp meals, food packaging materials, etc. This kind of waste is usually laden with fats, oil, and protein—compounds that are likely to slow down microbial activity during AD, consequently reducing gas yields and system fluctuations if not well pre-treated. The highly enriched energy source of commercial waste, once harnessed, can augment substantial amounts of biogas but entails highly viable handling management to address the impact of high lipid values.

Agricultural waste it includes plant wastes, animal droppings, other farm offal products, and all kinds of other renewable farm inputs. Due to conditions, such as high cellulose content and seasonal variation in agricultural waste production, specific AD processes are needed. Plant materials are largely fibrous, and the use of plant based materials can thus present bioavailability issues with the organic matter, and often needs mechanical or enzymatic pre-treatment.

The discrete characteristics of these waste types and the corresponding challenges that exist in their handling must be fully appreciated to effectively and efficiently enhance functional AD processes. Danilčenko et al. (2022) stress the importance of developing new complex processing technologies that can work with the fluorogenic properties of organic wastes, such as improving the overall performance of methane production systems. From this knowledge, the further more efficient and, at the same time, more suitable for the planned biogas plants designed and adapted to the specific type of waste will contribute to the further improvement of the waste management and energy recovery processes.

**Material Characteristics of Each Waste Type**

It is widely appreciated in the scientific literature that the factors impacting on the efficiency and effectiveness of the AD processes can be strongly and directly influenced by the nature of the organic materials fed to the system. Stable biogas production and outcome can also be enhanced by or hampered through these characteristics present in the feedstock.

Residential Organic Waste Most often include used food, food remains, and remnants, as well as grass clippings and plant trimmings. This kind of waste is generally laden with moisture, which, though effective in promoting the microbial action required for AD, water thins down the nutrient density, thereby reducing the total energy content. Due to the significant levels of carbohydrates and proteins, the biodegradability level of the residential waste is also high. The inorganics and non-degradable materials may pose some difficulties in the preprocessing steps, which include sorting and tearing, which is significant in the balance of the AD.

Commercial Organic Waste, another potential pathogen source is the dirty water produced by restaurants, markets, and food processing companies; this water is frequently laden with oils and proteins. Some of these components are undesirable because they can cause the accumulation of ammonia and long-chain fatty acids during digestion, and these substances are lethal to methanogenic bacteria required for AD. According to Pelagalli et al. (2024), the deposition of lipids and proteins slows down the process of biogas production and also poses a threat of upsets such as foaming and acidification of the system. Hence, commercial organic wastes must undergo strict pretreatment to eliminate such risks through methods such as degreasing or mixing with other feeds.

Agricultural Organic Waste is in fact mainly made of plant residues like crop residues, such as stubble, husks, and manure, which are rich cellulose and hemicellulose. These fibrous materials are not as easily biodegradable and require physical or enzymatic treatments to degrade high polymerization complexes into more manageable polymer forms that can be broken down by microorganisms. Another aspect of the variability discussed by Mohd Sabri et al (2022) is based on (BMP) of agricultural wastes, specifically their high cellulose content, and seasonal production of agricultural wastes. This volatility translates in the management of AD processes to address the unstable nature and source of feedstock.

**Biochemical Methane Potential (BMP) of Organic Wastes**

The maximum chemical energy that can be produced as a result of the anaerobic digestion of organic materials under the best possible conditions is defined as Biochemical Methane Potential (BMP). As described by Danilčenko et al. (2022), BMP allows a quantifiable figure that helps engineer scientists assess the viability and energetically profitability of biogas projects. It enables a comparative analysis of different substrates by their ability to produce methane, which is essential for planning and designing AD plants.

BMP of the organic wastes differs from one another due to variations in the biochemical characteristics of wastes. For example, vegetable waste usually has a high BMP of (450-500 mL $CH_4$/g VS) because of its high contents of easily degradable carbohydrates, particularly for short-term methane generation. On the other hand, meat bones with relatively small amounts of easily degradable substances present BMP values that are comparatively low (350-400 mL $CH_4$/g VS), showing a slow and less efficient biogas-generating process. This pattern of BMP is relevant for identifying the most suitable organic waste streams for the AD processes because BMP plays a critical role in determining the overall energy yield and process efficiency.

Improvements in the technologies for pretreatment have the potential to increase the BMP of the organic waste, which would have been difficult for the BMP of the organic wastes. Dikshit et al. (2023) acknowledge that enhanced biodegradability of recalcitrant substances by means of mechanical, thermal, and enzymatic methods enhances BMP. These technologies decompose large and complex organic structures into simpler structures that are easily utilizable to the anaerobic bacteria in the creation of methane.

Knowledge on BMP is crucial for enhancing the AD process, defining how individual waste streams should be combined, and modifying the working conditions for the highest yield of biogas. This approach guarantees that intended AD facilities can run more efficiently, thus aiding in the achievement of waste management and renewable energy provision.

Table 1. Biochemical Methane Potential (BMP) of Various Organic Wastes.

| Organic Waste Category | Description | BMP (mL $CH_4$/g VS) | Comments |
|---|---|---|---|
| Vegetable Waste | High in easily digestible carbohydrates | 450-500 | Highly suited for short-duration production of methane |
| Fruit Waste | Rich in sugars and easily digestible nutrients | 430-480 | High potential because it contains natural sugars. |
| Meat Bones | Less digestible materials | 350-400 | May take long time to digest, not so effective for methane |
| Expired Bakery Goods | High in carbohydrates and fats | 480-500 | High BMP because of high energy density is one of the reasons. |
| Grease Trap Waste | Contains fats, oils, and greases | 470-500 | Needs to be pretreated so it can be broken down to be used. |
| Dairy Products | High in lipids and proteins | 450-490 | Some pretreatments are needed in order to make the material more biodegradable. |
| Commercial Organic Waste | A mix of various food remains from eateries | 400-450 | Due to different types of food, it is above the moyen BMP is above. |
| Residential Organic Waste | Mix of organic and inorganic components | 350-400 | Lower BMP due to presence of non-digestible material |

**Anaerobic Digestion Process Specific to Organic Wastes**

Anaerobic digestion (AD) is a complex biochemical process that converts organic waste into methane through the activities of diverse microbial consortia, proceeding through four main stages: The treatment processes include;

Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis.
Hydrolysis: The first stage involves the reduction of large and more structured molecule such as carbohydrates proteins and fats into simpler structured molecules such as sugars amino acids and fatty acids. This process is effected by hydrolytic bacteria.
Acidogenesis: To this, the acidogenic bacteria ferment the more basic polymers into volatile fatty acids (VFAs), alcohols, hydrogen and carbon dioxide.
Acetogenesis: During this stage, acetogenic bacteria oxidatively anaerobically convert products from acidogenesis to: acetate, more hydrogen, and carbon dioxide which are important inputs to the final stage.
Methanogenesis: AD is a four-stage process the final of which is accomplished by methanogens that reduce acetic acid, hydrogen and carbon dioxide to methane and water. This has been found to be highly volatile to any changes within the specified AD environment.
Challenges in AD: The organic waste character has a direct impact on the efficiency of the AD process due to the high variability in its composition, as seen in Figure 1 below. Protein, fats, and complex carbohydrates create certain difficulties; proteins and fats cause the building up of ammonia and long-chain fatty acids that are toxic to methanogens. These substances make up the digester's content and can induce acidosis, which suppresses methanogenesis. As rightly stated by Singh et al. (2024), solving these problems is subject to a delicate equilibrium of microbial community. It calls for the adjustment of basic working parameters such as pH and temperature.
Recent Advances: There has been a major improvement in the AD techniques with the latest technological developments to increase productivity. However, one of the most important innovations is the integration of (AnMBRs) into the anaerobic digestion process. AnMBRs combine membrane filtration with conventional AD processes, which significantly addresses the issue of digestate biogas separation and the quality and volume of methane produced. Singh et al. (2024) point out that in addition to immobilizing key microbial consortia for the stabilization of the digestion process, AnMBRs also decrease hydraulic retention time, thus enhancing the overall capacity of AD systems. This innovation is especially useful in treating wastes that contain a high amount of inhibition, such as fats and proteins, and in producing enhanced and sustainable biogas.2.2.5 Integration and Optimization of AD Technology
The AD, connecting the advanced pretreatment methods, is essential in order to improve the biodegradability of non-degradable organic substrates. Another method of waste preparation is thermal pretreatment, which entails heating the waste with the aim of getting rid of complex polymers and, hence, enhancing the accessibility of organics to compaction by microbial action. In chemical pretreatment, materials like alkalis or acids are also applied in order to dissolve compounds like lignin in waste materials from plants. One of the mechanical pretreatment processes, which involves grinding and shredding of the feed, lowers the particle size and hence provides a large surface area to the microbes. The application of advanced technology in AD is well illustrated in the integration of technological tools like the AnMBRs, which may be considered an innovation in the AD field. AnMBRs integrate the traditional anaerobic digestion process with a membrane filtration step that further optimizes the process of solid separation from the biogas and enhances both the efficiency and yield of methane production. The authors Domguia et al. (2024) have further highlighted that the incorporation of AnMBRs helps overcome the matter of variation in waste type as well as provides the economic and ecological advantages that include stabilization of the digestion process and lesser space required for the treatment plants. State-of-the-art AD processes enhance energy efficiency, enabling an efficient conversion of numerous organic wastes into useful methane assets for energy sustainability and circular economy. For this reason, as pointed out by Singh et al. (2024), incremental improvement and modification of AD technologies are critical to increasing their effectiveness and sustainability.

## METHODS FOR METHANE PRODUCTION FROM ORGANIC WASTE

### Overview of Anaerobic Digestion Processes

AD is widely appreciated owing to its ability to reduce organic waste and produce biogas, a renewable energy source. However, to examine the process critically the following drawbacks and challenges are pointed out especially when the substrate contains heterogeneous material such as organic waste as discussed by Kumar et al., 2021. The fluctuations in the composition of organic waste are the main concern for AD systems as shown below. Although the fundamental processes of AD have been determined, which include hydrolysis, acetogenesis and methanogens the efficiency of these processes will be considerably diminished by the presence of heterogeneous and varying organic compounds. For example, high fat and protein content, which are typical for the organic waste, reduce microbial activity and thereby affect the lower methane generation and system fluctuations (Catarino et al., 2018).

In the cases of batch or continuous processes, single or multi-stage operating modes of AD systems require strict regulation of the microbial environment and the highest yields of biogas. However, multi-stage systems are superior, since they enable fine-tuning of the conditions in each stage of the process; on the other hand, the construction of such systems implies higher costs, which sometimes hinders their implementation (Pratap et al., 2024). Further complication arises when AD processes are scaled up from laboratory or pilot scale to industrial scale. These are some of the correlates of the system such as accumulation of inhibitory substances, system scaling, as well as microbial balance all of which become magnified with larger systems. These threats require daily fine-tuning and optimization, and they make the processes more cumbersome and expensive (Mahmood et al., 2023).

From a sustainability perspective, while AD significantly reduces the volume of organic waste and converts it into biogas, the digestate produced must be managed properly to avoid environmental pollution. Nutrient runoff, particularly nitrogen and phosphorus, can lead to eutrophication in water bodies, posing significant environmental risks. Although AD presents a promising technology for managing organic waste and producing renewable energy, its application, particularly in the treatment of organic waste, requires careful consideration of biological, technical, and environmental factors. Future research and development are essential to address these challenges, enhance system efficiencies, and reduce the environmental footprint of AD systems.

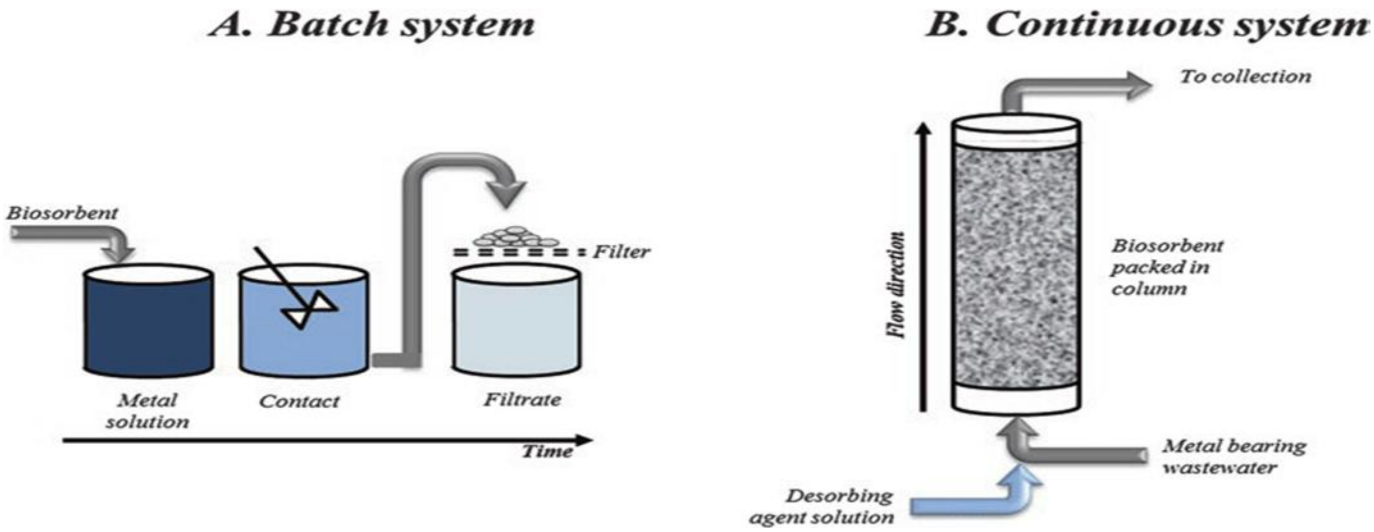


Figure 4. Batch Vs Continuous AD System (Papirio et al., 2017).

**Comparitive Analysis of Traditional Vs Advanced Technique**

AD technology alone has significantly been improved such that the first- and second-generation technology differ largely in their performance characteristics and efficiency. It is therefore important to distinguish between these methods in order to achieve maximum levels of methane production from organic waste, based on cost, efficiency and impact factors (Nexus, 2023).

## Traditional Techniques

Conventional AD systems typically work at mesophilic temperature of around 35 to 37°C and can be either batch or continuous fed processes. These systems are considered easy to use and the systems have been applied widely for the treatment of the sewage sludge and agricultural waste (Singh et al., 2023). When used in organic waste, established systems have some issues concerning process constancy as a result of the high load of organic matter and inhibitors like fats and proteins, which cause the fabrication of acids that inactivate functioning microorganisms. In traditional configurations, the operational parameters include; pH control, temperature maintenance, and hydraulic retention time of the system are critical in avoiding system failure. Although such systems are comparatively cheaper to establish, and easier to manage, they typically have lower rates of methane production and slower digestion periods especially for feeds with high solid loadings such as waste food products (Rabehi et al., 2024).

## Advanced Techniques

Modern AD technologies have been worked out to overcome the defects of the conventional methods and to improve the performance and sustainability of methane generation. Key innovations include:

Anaerobic Membrane Bioreactors (AnMBRs): The about systems integrate the anaerobic biological digestion with the membrane filtration, the aspect that provide the enhanced biological solid liquid separation, thus the quality of the effluent is high and the microbial consortia are not lost. Unlike any other microbial reactors, AnMBRs are capable of handling relatively higher values of the F/M ratio thereby increasing both the methane yield and the overall stability of the process (Hasan et al., 2021).
Thermophilic Digestion: Working at higher temperatures, that is temperatures around 50-60°C, thermophilic digestion provides for faster digestion of the organic substrate and a consequent increase in the speed of digestion cycles and the amount of biogas produced. It takes more energy to heat as well as more power to monitor the system balance.
Co-digestion Strategies: The comments have it that decomposition of the organic waste can be enhanced if the wastes are mixed with other forms of organic wastes, which will balance the nutrient composition of the organic wastes, dilutes toxic substances and enhance the biogas output levels. Co-digestion is carried out with an aim of enhancing the breakdown of several feed components in a single process, the production of gas and stability of the process (Sahoo & Mani, 2019).

## Comparative Metrics

When comparing traditional and advanced AD techniques, several metrics are considered:
Efficiency: Sophisticated process tend to exhibit higher conversion rates of the organic matter to methane due better control of the system and improved metabolic activity (Feng & Rosa, 2024).
Cost-effectiveness: Adopted systems can have higher initial cost compared with the more developed systems but the latter are more beneficial in the long-run since it yields more biogas and have shorter processing period.
Scalability: Complex methodologies are likely to be more scalable because they are stronger in quantity, and have the ability to handle various forms of waste (Sharma et al., 2024).
Environmental Impact: Both systems have an equivalent effect of minimizing the volume of waste that is deposited in the ground; advanced systems are often more compact and produce comparatively minimal impact on the environment because they are resource-efficient.

Table 2: Comparative Analysis of Traditional vs. Advanced AD Techniques for Organic waste

| Metric | Traditional Techniques | Advanced Techniques | Notes |
|---|---|---|---|
| Efficiency | Moderate | High | These are AnMBRs and thermophilic digestion which offer higher methane yields since microorganisms work better, and the rate at which organic matter is degraded is faster. |
| Cost-Effectiveness | Lower initial cost but higher operational costs | Higher initial cost but lower long-term costs | High investment contributes to low efficiency in the short term but, sophisticated systems are capable of generating more biogas and faster throughput in the long run. |
| Scalability | Limited | High | Applied techniques are more versatile compared to the size and kinds of waste thus allowing for the easier scalability and duplication of AD projects. |
| Environmental Impact | Higher | Lower | The advanced systems are generally less invasive to the environment, the waste reduction is enhanced as well as energy recovery with a small footprint. |

**Integration of BMP Analysis with Material Processing**

Biochemical Methane Potential (BMP) of substrates is among the essential parameters guiding the choice and optimization of the AD processes. Large BMP data suffices for the assessment of methane production capacity of different Organic substrates that from the basis of enhancing the overall performance of Biogas plants (Abreu et al., 2023). The BMP data are very significant in providing the right design of AD systems since they contribute to the definition of operational strategies in the process to support efficiency and stability. Understanding of the BMP of a substrate enables engineers to determine and adjust temperature, pH and hydraulic retention time which is contributing to the MH (Raj et al., 2023). Substrates with higher BMP values might be expected to have different optimal temperature to enhance the rate of digestion as well as to avert build-up of intermediate that may hinder this phase of methane production process.PH level may also need to be adjusted to create a favorable microbial environment to promote the action necessary for the production of methane (Ahmad et al., 2018). These BMPs are important because they provide data which are customized for feedstock type accurate BMP data help to achieve the maximum energy yield and the optimal productivity of AD facilities.

The BMP data is not just used solely to develop the basic design of the process but is also used in the decision making of the preprocessing and postprocessing steps. From BMP data, mechanical, thermal or chemical pre-treatment methods to improve the biodegradability of feedstocks can be determined (Zhou et al., 2021). Studies with high-BMP substrates that include lignocellulosic materials will be helped by the splitting of polymers into smaller molecules through heat using thermal precursors prior to anaerobic digestion. During the post processing stage, knowledge of the BMP can be useful in the application of methods directed at improving methane separation and recovery. It might include implementing of gas scrubbing systems to enhance on purity of methane that leads to efficiency in energy conversion. Use of BMP data where actual AD projects are being implemented showcase the usefulness of BMP data (Peng et al., n.d.). A record example of using BMP is the optimization of processes at the municipal waste treatment plant in Beijing where adjustment of the parameters based on BMP data contributed to the increase in methane production by 20%. The facility receives both organic waste and yard waste; this is where the BMP data helped to devise a co-digestion plan that optimized biogas yield but also system stability. Another example is a commercial AD plant in Shanghai where BMP data was used in designing the SBR installed in the plant (Thonar, 10, 2024). This configuration made it easier to vary the feedstock loading rates and the retention time because the different BMP values of the wastes allowed efficient plant variation and methane production.

## CHALLENGES IN METHANE PRODUCTION FROM ORGANIC WASTE

### Technical Challenges

The treatment of organic waste in AD comes across several technical problems that may affect the rate at which the process occurs and therefore the yield of the process. These include include issues such as moisture content, foaming and acidification all of which are factors that cause operational problems in different ways.

### High Moisture Content

Organic waste generally has a high initial moisture content: while this is essential for microbial action in anaerobic digestion, it has some problems. Microorganisms require certain nutrient concentrations for their metabolism, and high moisture can wash out such nutrients hence decreasing the biogas yield (Lynd et al., 2022). This phase includes the cost impacts of high water content in the digestate as it hampers the ease and efficiency of physical separation of solid and liquid phase. High moisture content can take more energy to heat the digestate to the right temperature for the microbes lowering the energy value of this process (de, 2023). Inability to control the moisture content can be offset by pre-treatment processes such as dewatering or by adding drier organic source to the organic waste, to achieve the right moisture content that would enhance the efficiencies of the AD process.

### Foaming

Digesters is foaming, which is usually shaped by proteins, fats and detergents present in organic waste (Cataldo et al., 2021). Foaming can minimize the working volume of digesters, bring about mechanical failures, and often results in overflows that can interrupt the process and require expensive washings. Foaming can lead to entrapment of gases, this will in turn lead to low yields of biogas collected besides they can explode if not controlled. The problem can be minimized by use of anti-foaming agents although the problem usually requires resolution through feedstock and process control involving regulation of loading rate as well as mixing intensit (Ashokkumar et al., 2022).

### Acidification

Organic matter decomposition in the organic waste decomposes them into volatile fatty acids (VFAs) as the intermediate product. High levels of VFAs pose a danger because they lower pH rapidly when it occurs it is referred to as acidification. This environment depresses the activity of methanogenic archaea that are involved with the final stage of the conversion of acetic acid to methane, which they directly decrease. Acidification can kill microbial culture, which makes the process unstable and leads to failure (Taleyarkhan, 2020). Specific measures to prevent acidification have to be employed in AD systems, and pH levels have to be especially carefully controlled. Some of these include the use of buffering agents to counteract any overproduction of acids in the system and to control the transition from one phase to the other so as to maintain the optimum stages of acidogenesis, and methanogenesis respectively in order to increase methane yield (Harirchi et al., 2022).

Table 3. Technical Challenges in AD of Organic waste and Their Impact on Process Efficiency.

| Challenge | Description | Impact on Biogas Yield (%) | Solution Implemented |
|---|---|---|---|
| High Moisture Content | High levels of water in organic waste dilute nutrients and require more energy for heating. | Decrease up to 20-30% | Dewatering, mixing with drier materials |
| Foaming | Caused by proteins, fats, and detergents, leading to reduced digester volume and potential overflows. | Decrease up to 15-25% | Use of anti-foaming agents, operational adjustments like controlled loading and mixing |
| Acidification | Accumulation of volatile fatty acids drops pH, inhibiting methanogens crucial for methane conversion. | Decrease up to 25-35% | pH monitoring, addition of buffering agents, optimizing process stages |

**Economic Challenges**

One of the economic limitations that arise when moving from pilot scale to large scale AD systems is discussed below (Meena et al., 2020). Some of these issues include; that AD is often expensive leading to increased costs, logistics is challenging, and maintaining process constancy can be a nightmare, all of which act as barriers to investment and the resultant rolling out of AD technologies.

**Scale-Up Challenges**

Scaling up from pilot scale project creates a new problem whereby the technology advances to full scale AD plants, meaning that the technology is capable of managing much more waste. On this scale-up, there is likelihood to cause higher costs since larger and more complex equipment and infrastructure may be required and occupies relatively larger land area (Mazlan, n.d.). There are also other practical problems that include complexities in enhancing the feedstock supply chains and other challenges in addressing with larger volume of output digestate. It becomes significantly problematic to control the temperature, pH, and other significant factors whenever the scale increases at the industrial level cheers to routine fluctuation in the process (Rout et al., 2024). All the mentioned factors can result in low operational effectiveness and frequent shut-downs, which, in turn, reduce the feasibility of undertaking massive plant AD projects.

**Cost-Effectiveness**

The technical, economic and market feasibility of biomethane from organic waste by incorporating CC trend depends on the capital cost, operational cost, and income from biogas recovery and sale (Mikulčić et al., 2021). The cost incurred in setting up AD systems at an initial stage can be fairly high based on construction cost, engineering cost and other costs related to the environment. Some of the other costs that hinder effective implementation of the digesters include energy used to heat and mix the digesters, maintenance and labor costs (Zhanga et al., n.d.). These costs are recoverable by income earned from the sale of biogas and depending on the quality of the end product, digestate as a fertilizer. Economic evaluations necessarily have to take long-term gains and rates of return into account, which in turn depend on constant and sustainable generation of biogas, and the continued marketability of the energy produced.

**Technology Adoption**

The fundamental constraints to the implementation of greater AD technologies are mostly linked to money risks and the requirement for technologies to demonstrate their workability in the real world. Industry investors and operators will typically not risk committing to new technologies without robust information to support the effectiveness of these new methods, and the corresponding cost savings compared to conventional methods (Choi et al., 2021). The initial financial expenditures and unsaturated revenues present potential barriers towards some investors willing to invest in CSP in areas where the clear policies and available subsidies cannot cover the costs of CSP installations. New technological trends for integrated waste management and energy need more than just capital investment but uptake of new policies and legislations (Bedoić et al., 2019).

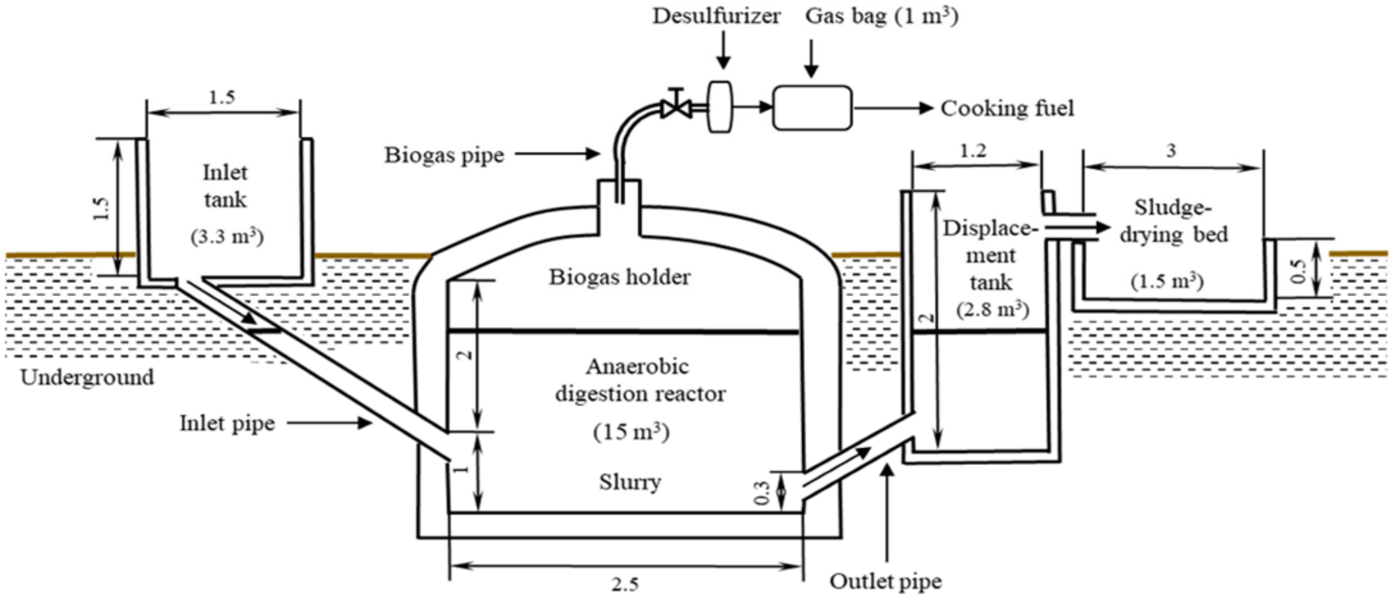


Figure 5. Anaerobic Digestion System Scale-Up (Hanum et al., 2023).

**Environmental Impacts**

Anaerobic digestion or AD is a process that is normally promoted as an environmentally friendly solution for combating greenhouse gas emissions through the production of energy from waste. AD processes themselves may turn out to be sources of pollution to the environment (Weerakoon et al., 2023). Environmental issues that are associated with AD are balanced by several disadvantageous issues; key among them being methane slippage. Methane which is the main component of the produced biogas is a more effective greenhouse gas than carbon dioxide, its effect being 25 times as much in the first one hundred years. Lack of efficiency in containment and management in the said digestion and storage phases can result in what is known as slip, generally meaning methane that goes up in the atmosphere unfixed. The control of containment leakages is highly challenging when it occurs in older or even poorly maintained structures where seals, valves, and pipes tend to be more susceptible to leaks as noted by Vangala et al (2023). These features involve metal shutters capable of achieving high capture efficiencies and frequent inspection and maintenance of the systems do not allow leakage of methane into the atmosphere, which will counter the gains of biogas production on the environment.

The digestate produced from the AD has some impacts on the environmental system. Though it can be as nutrient-rich fertilize, improper utilization of digestate results it severe impacts on environment (Albahnasawi et al., 2024). If applied to land in excess, the nutrients in the digestate go into water bodies thereby triggering eutrophication and formation of poisonous algal blooms that deny water its oxygen and kills aquatic life. Untreated digestate contains paths that can negatively affect human and animal health as well as soil and water quality. Composting of digestate, further treatment and safe disposal including use on land requires adequate methods and controls to prevent pollutions and foul up water sources. The utilization of organic waste in methane production through AD also includes the evaluation of the life cycle aspects of removing organic waste from the landfill and transferring it into energy recovery (Dari et al., 2024). Although AD decreases the quantity of landfill waste and that leads to the reduction of leachate and the methane gas produced by the open decomposition of wastes, the process of AD requires the utilization of energy and water. The profitability of AD depends on the technology application, the energy conversation and the factors of environment including availability of wastes and energy demand. Life cycle assessments that assess the potential environmental effects throughout every stage of a product from the consumption of input resources to the disposal of output goods are very important in determining and optimizing a suitable sustainability status of AD systems (Khan et al., 2024).

## CASE STUDIES AND COMPARATIVE ANALYSIS

**Introduction to Waste Management in China**

In China, the environmental aspect of waste management of organic waste forms part of the environmental policy, mainly because the country produces a massive amount of urban and rural waste. Rodrigues et al. (2024) explain that besides rampantly depending on technology – more so the progressive one, China integrates conventional disposal techniques as a unique approach compared to the world where the technological use and policy implementation deviations are profound. This also makes clear how China has endeavored to align its local requirements with global sustainable objectives and proactively embraces key innovations to advance environmental improvement.

It is with regard to the scale of organic waste management that Kothari et al. (n.d.) provide a clear understanding of the differences between urban and rural areas. Population density leads to higher production of solid wastes; hence, sophisticated technologies are practiced mainly in urban areas. On the other hand, rural places may use the basic and cheap technology applicable to situations with less waste disposal and infrastructure. This indicates that there is a need to ensure that management strategies can be adjusted with regard to prevailing circumstances in order to serve the necessary purpose effectively.

Adding more weight to these, Baruah et al. (2018) have explained the technological advancement occurring in the Chinese waste management industry. These are not just accretions in operational efficiencies but are well in line with the commitments made by the country to cut down its emission intensity and improve the overall availability of renewable sources of energy. They are important at this time as China aims to turn issues of waste management into a force for sustainable development, which would assist in attaining Chinese and global environmental goals. Thus, China promotes itself not only as a country that is ready to implement the most progressive technologies in waste management but also as a country engaged in the search for ways to ensure increased ecological stability.

Detailed Case Studies of AD Projects in China

In China, the case of the application of AD technology demonstrates a positive trend towards the use of sustainable technology in waste management and the generation of methane. Various projects throughout the country demonstrate site specific variations in adapting the technology to the waste and socio-economic environments.

Beijing Biogas Plant: The Beijing Biogas Plant in the capital city is ample proof of the operation of the thermophilic AD technology. There as explain by González et al. (2022) this one employs thermophilic digestion, which is carried out at higher temperatures to promote faster decomposition of solids and better methane generation. This process is very important in controlling a high turnover of the organic wastes produced in urban centers since the density and variety of wastes produced in urban centers must be treated through efficient mechanisms. The thermophilic approach is, therefore, not only more efficient and faster in terms of energy recovery by the production of gas, but also eradicates more pathogens than the mesophilic approach through the high temperatures at which the process operates.

Shanghai Green Energy Project: This work illustrates the difficulties and possibilities connected to the application of high-fat organic waste typical of business and catering sectors. From Alvarez-Vasco & Zhang (2013), fats can reduce microbial activity in the AD processes hence low biogas production. The Shanghai green energy project implements a doubly fed AD system that provides mesophilic digestion followed by thermophilic digesting and enhanced fats and oils break down. This developed digestion process assists in counteracting or reducing the capability of fats in reducing microbial action, hence enhancing the production of methane from high energy wastes normally thrown away by the food service industries.

Guangdong Rural AD Facility: is much unlike the complex system the high-tech facilities of developed countries and large cities suggest; a streamlined system necessary for establishing in rural areas where money may be scarce. Laré et al. (2024) explain how this facility employs a simple and inexpensive digester that can be constructed and managed due to its simplicity and can be employed by farmers with few resources, and little technical experience. At the same time, this approach helps local communities manage their organic waste, bolster the local energy economy, and increase rural energy security while decreasing dependence on foreign sources.

Case Study – A Regional Approach: Reflecting on the work by Salakkam et al. (2019) on another region's use of AD technology, it also makes sense that such systems need to be adjusted to local climatic and economic conditions. In this case, the AD facility is expected to balance the highly fluctuating nature of agricultural waste, especially in areas where farming is intensive. This is possible because the system implements different strategies where it can easily switch operations to functioning at a higher output during periods where feedstock is abundant and, at a minimum, during periods where feedstock is scarce. This flexibility is essential to ensure that biogas plants in the arable lands operate smoothly when waste output is high throughout the harvesting periods. Described examples from the Chinese districts show a wide range of uses and advancements of AD technology, serving to underline how the local context, from mega-urban to rural environments, defines technological and operational paradigms. These distinct scenarios illustrate that China accords with the utilization of green power generation and renewable energy in the sanitation industry as both national and global environmental efficiency. Similar variety also provides useful information for other countries that intend to achieve maximum results from AD technology, taking into account regional and material-specific conditions.

**Comparative Analysis of AD Technologies Across Case Studies**

Comparing AD technologies applied to different cases in China, we conclude that there are a wide variety of interdependences and relationships between cost optimization, work performance, advancement, and mass applicability of AD. All of these factors are essential to determining the general sustainability and possibility of expanding the usage of these technologies throughout the country.

Cost-Effectiveness: As pointed out by Hayyat et al. (2024), the efficiency and effectiveness of financial recovery and investment return of AD technologies in different projects differ substantially. For example, in urban infrastructural programs such as the Shanghai Green Energy Project, the return on investment is high owing to the concentration of the energy content in the processed waste as well as the amount charged for space utilization in urban centers. On the other hand, rural projects like the Guangdong Rural AD Facility include low-cost technology that is more basic to match the economic capacity of those rural areas. Such disparity in financial flows highlights the need for developing the financial approach which will take into account the conditions of economic environment of the country and the type of organic waste to be processed.

Operational Efficiency: Methane yields and operational efficiency of AD systems are argued by Møller et al. (2022) as the critical factors to assess environmental effects. Such efficient systems include the Beijing Biogas Plant, which currently incorporates thermophilic processes that produce a higher amount of methane than other discretional systems and, therefore, lower greenhouse gas emissions per unit of energy. This efficiency is important in reducing the impact of waste management practices on the environment given that most countries' environmental laws are conservative, and the public is becoming increasingly conscious about the environmental footprint of their activities.

Technological Innovation: It is well explained by Kataki et al. (2023) that incorporation of such advanced technologies like Anaerobic Membrane Bioreactors or (AnMBRs) remained central to the improvement of the efficacy and flexibility of AD systems. These technologies enable higher, digestate and biogas separation thus enhancing the methane quality with uses in applications such as vehicle fuel. The usage of such innovations is even more significant in technologically driven urban complex developments since high capital outlay may be made on advanced technological applications required to enhance the throughput resulting from the utilization if complex technologies.

Scalability and Adaptation: Another important criterion is flexible scalability of AD technologies, which may be significant in view of the further introduction of such technologies across China. Fatima & Zeeshan (2024) described that the scalability issues are relative to the basic design and actual running environment of project. For instance, while urban systems are designed to be scaled up to accommodate the expanding waste management needs of towns and cities, the rural systems emphasize flexibility on systems that can be easily adapted on namely low cost but denably easily restorable systems that will not require the Higher complex inputs to maintain.

The comparative analysis makes it possible to conclude that there is a need to develop the strategic deployment of AD technologies in China by considering local waste characteristics and the economic situation, as well as the environmental objectives. In this way, the selected strategy guarantees both the technological and operational efficiency of each of the projects as well as their compliance with the criteria of sustainability of the country's economy and global trends towards the formation of a circular economy.

**Implications and Future Directions**

The aims to highlight these benefits and future prospects of the AD technologies in China's solid waste management practices and related policy, technological, and academic opportunities. As Díaz-Herrera et al. 2023, there is a great demand for support interventions for further technological within AD processes modernization and enhancement of efficiency. Higher subsidies and political encouragement might speed up implementation of high-profile technologies like, for instance, the anaerobic membrane bioreactors as well as thermophilic digestion systems. The guidelines and financial incentives also expanding financial solved for AD projects add to the scalability and economic viability of these solutions, and make these technologies available for widespread application in both the urban and countryside environment.

According to Wang & Qiao (2024) reveal that optimized AD processes can bring efficient environmental profits. Such improvements consist of a considerable minimization of the share of organic waste buried in landfills and a decrease in the emission of greenhouse gasses. AD technology can effectively capture and convert methane emissions from decomposing waste while offering another source of energy to China to support its carbon reduction goals. It is thus important that we establish the limitations of current methodologies when it comes to the development of AD technology. From the published literature as compiled by Rodrigues et al. (2024) and Anyaoha et al. (n.d.). Future research should strive to increase the output of methane from various waste sources. This implies the assessment of various methodologies of pre-treatment of different types of organics and improved strategies for handling variations in waste characteristics. Additionally, exploring the integration of AD with other renewable energy technologies could provide holistic solutions to energy production and waste management, furthering the impact of AD on sustainable development.

## RECOMMENDATIONS AND FUTURE DIRECTIONS

The Methane production from organic waste in china has the possibility to be developed economically and sustainably hence it should be encouraging. Utilizing this potential needs appropriate and specific changes in efficiency, costs, and resource utilization and operations scalability. Several strategic approaches and major topics in the overall bioenergy research are worthy of significant emphasis for the optimization of AD technologies (Dhanker et al., 2022). The other key driver to enhance the performance and profitability of methane production is the adoption of new and improved AD solutions. The AnMBRs and thermophilic digestion have been seen to improve the rate of organic degradation and the production of biogas. Such systems, despite the higher first cost, yield lower operational costs by stabilizing the digestion process and increasing the quality of the biogas generated (Banu et al., 2021). This was further proved by the enhancement of the biodegradability of organic waste especially in the case of hydrolysis pre-treatment process leading to increase in methane output. Energy efficient technologies used in the mixing as well as heating processes also play a major role in decreasing the energy intensity of AD processes thus increasing their cost efficiency.

Co-digestion techniques that involve the use of organic waste with other waste types can counterweight the nutrient concentrations, prevent negative impacts on microbes, and take advantage of mutualistic synergies (Abou et al. 2023). This approach not only stabilizes the digesting process but also makes it economically more viable as the basic feed stock base is widened and the volume of biogas produced is increased. There is a need for subsequent research to address limitations first seen in diverse compositions of organic waste that may hamper stability of and efficiency of AD. Creating synergistic, resistant microbial consortia and also enhancing their functionality as a results of variations in feedstock characteristics is a compelling direction in the field. The genetic and metabolic manipulation to activate methanogenic bacteria for better function may open new promising opportunities for finding additional capacities of biogas production (Bhatia et al., 2024). Another important research area that needs to be explored is the search for new pretreatment and post-treatment technologies for efficient elimination of high percentage of contaminants typically plastics and the other non-degradable solid wastes from the organic wastes. These technologies would increase the resistibility of the AD process so that it will not be affected by the impurities of the feedstock and operational challenges frequently encountered.

There is great potential in China to expand methane generation through organic waste since the generation roman organic waste is high across the country. For such a system to be scalable, there must be a concerted effort to develop larger, more centralized AD plants capable of processing large quantities of waste (Wang et al., 2024). Implementation of government policies and provision of incentives is required in this respect to undertake infrastructure development. Strong policies that protect organic waste from being mixed with other waste as well as providing mechanisms to transport organic waste to centralized AD centers would improve the scalability of methane production immensely. Based on the results, the partnerships between the public and private sectors might become critical in boosting the development of AD technologies. These partnerships that blend public supervision and financial support with the core private motivations could promote the use of AD systems in different municipalities, (Náthia et al., 2018). Combining AD systems with the existing ecosystems for waste disposal and energy production seems to be optimally important. This could involve connecting AD facilities to municipal heat networks, or using biogas as a renewable feedstock for power stations so as to combine waste and energy chains.

## CONCLUSIONS

An analysis of methane production from organic waste in various projects in China has revealed that they contain a great potential for its sustainable use in development of energy sources. Exploratory work shows that the improved AD processes such as the inclusion of thermophilic processes and anaerobic Membrane bioreactors increases methane production and process efficiency. Only these technologies help to address not only the high variability and difficult nature of organic waste but also address the concern of low conversion efficiency of organic material to methane. Regarding the versatility of AD projects, precise examples have been revealed featuring the urban environment and the rural climate as well, indicating that this technology has rather flexible performable conditions. Paper and case studies, including Beijing and Shanghai, show the economic feasibility as well as the environmental advantages of incorporating AD in multifaceted municipal waste management systems: a notorious waste stream can be transformed into a source of renewable energy. The thing to appreciate about organic waste is the fact that it is a hugely neglected resource that holds massive potential in offering a solution to energy crisis. This potential could be seized when there is further development of AD technology, favorable policies and investment into the infrastructure; in light of China's environmental and energy security agenda.

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## AUTHOR CONTRIBUTIONS

Ruqia Syed Writing the original draft of the manuscript and conceptualization. Dr .Baolei Pei writing-review & editing, conceptualization, supervision, validation, and Funding acquisition. Yunpeng zhang writing-review & editing, validation and software. Jian Cao writing-review & editing, conceptualization, Resources, and visualization. Usman: writing, review, formating. Alexander joe: writing-review & editing, conceptualization, and validation.

## COMPETING OF INTEREST

No conflicts of interest have been disclosed by the authors.

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