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Enhanced Biogas Production Using Anaerobic Co-digestion of Animal Waste and Food Waste: A Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

The current review is based on various reports that utilize a variety of kitchen waste & cafeteria leftovers like banana peels, orange peels, onion residues, and kiwi peels and their procedure of methane production under varied conditions. This review also covers the anaerobic digestion [AD] process which is reported to enhance biogas production under enhanced nitrogen supply such as ammonium chloride. We also covered an analysis of biogas production utilizing a mixture of cow dung slurry and kitchen refuse at various environmental conditions. Combining food waste and cow manure through anaerobic co-digestion can generate renewable biogas, reduce environmental impact and improve methane quality, making it a viable method for enhancing biogas production efficiency. Biogas derived from fruit waste and cow manure through anaerobic co-digestion shows increased production compared to processing fruit waste alone. Some factors affecting biogas

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production include temperature, pH levels and microbial activity. The study explores the dual functionality of fruit waste as an energy source and organic fertilizer. Combining fruit waste and cow manure under mesophilic conditions enhances biogas production. The study suggests that biogas production can improve agricultural practices, reduce environmental impact and serve as an alternative to traditional fuels like firewood.

Keywords: Biogas production; anaerobic co-digestion; animal waste.

1. INTRODUCTION

The diminishing reserves of fossil fuels are insufficient to satisfy the growing energy demand. They are recognized for their role in the release of greenhouse gases [GHGs], which contribute to the phenomenon known as global warming. Conversely, the improper management of organic waste like animal and food waste poses a significant environmental pollution risk [1]. The versatility of biogas as an energy source for electricity generation, heating, and fuel production is evident in the global surge in biogas-based electricity generation capacity, which has risen from 65 Gigawatt in 2010 to 120 Gigawatts in 2019, over the last six years [2017-2022], the biogas sector experienced a growth rate of 19%, reaching 445 Terawatt-Hour in 2022 as shown in Fig. 1.

Unfortunately, in many cities and areas, food waste like kitchen waste is improperly disposed of in landfills or simply discarded. This not only affects the health of the populace by causing diseases like malaria, cholera and typhoid but is also disastrous to the environment. Uncontrolled dumping of wastes results in the pollution of surface and or groundwater by leachate and the spread of diseases causing organisms such as flies, mosquitoes, and rats. Further, kitchen waste leads to stink and produces methane, which is a greenhouse gas that supports global warming as illustrated below in Fig. 2.

In nations like India, biogas technology is pivotal in providing a sustainable energy source, reducing reliance on fossil fuels and tackling sustainability issues, thus contributing to societal and economic stability [2]. Fossil fuels, such as oil, coal, and gas, contribute substantially to the global primary energy consumption, resulting in the emission of carbon dioxide [CO_2] and other greenhouse gases into the atmosphere [3,4]. On the other hand, biogas production plays a significant role in the advancement of sustainable energy production by transforming organic waste into valuable resources such as biogas, biosolids and liquid fertilizer, thereby promoting waste reduction and energy retrieval [5]. Also, biogas assumes a crucial role in the area of sustainable energy generation owing to its integral renewable characteristics, wide-ranging applications and positive environmental implications. The process of biogas production along with its subsequent conversion into renewable methane offers plenty of opportunities for various industries to align with their sustainability objectives by harnessing waste streams as raw materials, thereby leading to a notable decrease in their overall environmental footprint [6]. On a global scale, there has been a rapid surge in the capacity of biogas-driven power generation, emphasizing its remarkable competitiveness and feasibility as an energy source for electricity production, heating systems, fuel provision and even the manufacturing of sustainable chemicals and biofuels [7]. Particularly in nations such as India, initiatives focused on biogas not only serve to enhance livelihoods and boost agricultural sustainability but also make substantial contributions to the integration of green energy sources and the mitigation of pollution, thereby emphasizing its vital role in the ongoing transition towards sustainable energy outlets [8,9].

It may be crucial to underline the need for more research investigations into evaluating the techno-economic viability of computational fluid dynamics[CFD] analysis methods used in large-scale industries when these techniques are applied in practice [10]. However, these research efforts must also be directed toward the improvement of the existing state, which has to come with corresponding solutions to barriers such, as the imperative need for more investments and the increase in operating costs that may accrue from these innovations. Therefore, this review focuses on recent work on Biogas production using anaerobic co-digestion [AD] methods [11,12]. This method aims to yield a sustainable energy resource that is predominantly composed of methane [CH_4], along with significant concentrations of carbon dioxide [CO_2] and various other gases, thereby contributing to the ongoing efforts towards the diversification and optimization of sustainable energy sources [13,14].

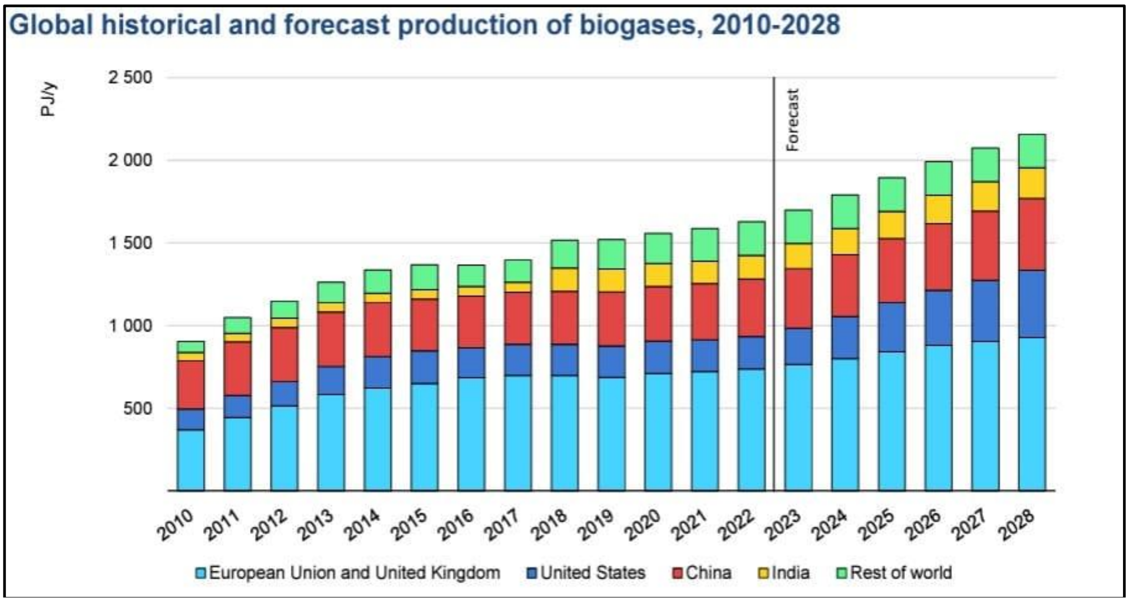

Fig. 1. IEA's forecast for Biogases

Source: Special section: Biogas and biomethane, IEA's renewables 2023

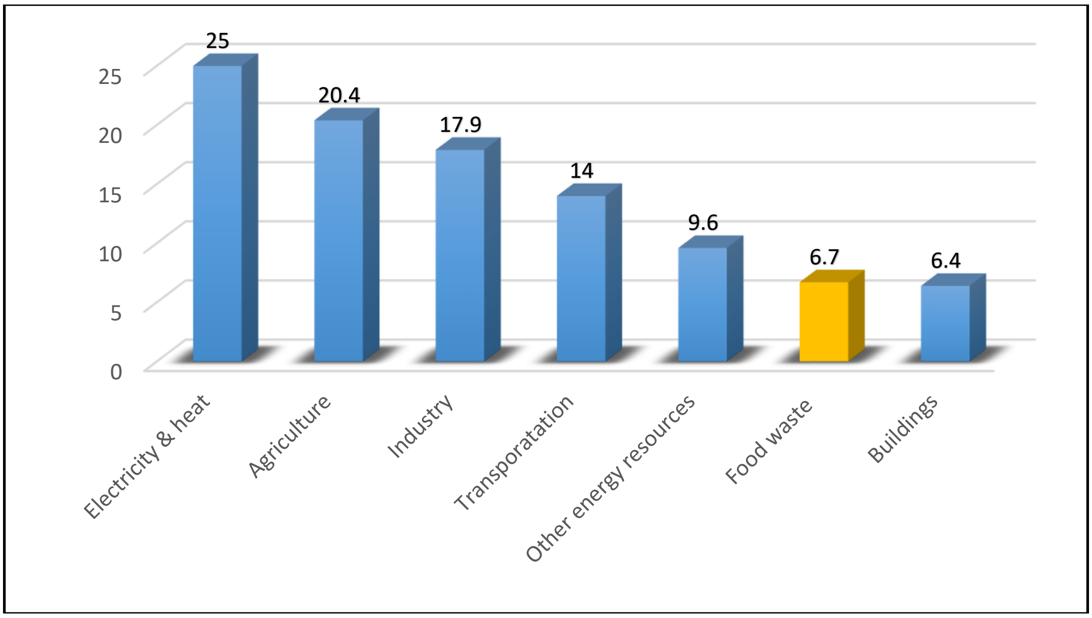

Fig. 2. Causes of Greenhouse gases

2. CHALLENGES IN BIOGAS PRODUCTION

Common challenges encountered in the production of biogas encompass various operational flaws, low productivity levels, inefficiencies in biodegradability, inadequate stability, as well as the presence of impurities such as CO_2, H_2S and other pollutants. These impurities not only diminish the quality of biogas but also lead to reduced efficiency in machine operations within the production process [15,16]. Moreover, the diffusion of biogas technology faces several obstacles including economic constraints, financial limitations, market dynamics, regulatory hurdles, administrative complexities, local opposition, challenges related to site selection, and ecological concerns as presented in the Fig. 3. These multifaceted challenges often result in the abandonment of biogas projects [17].

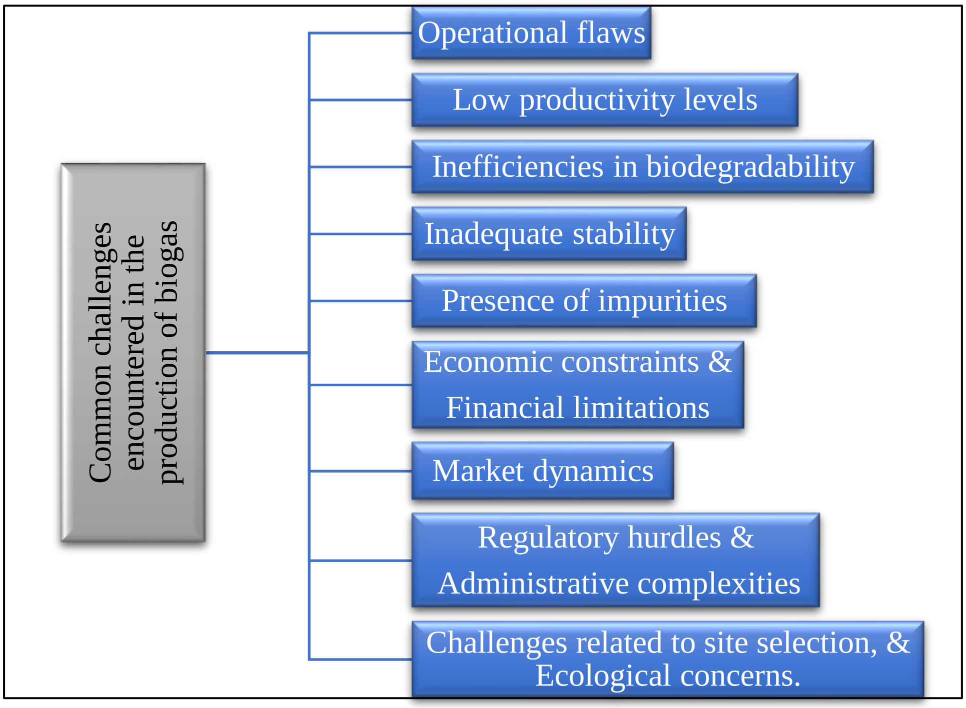

Fig. 3. Common challenges encountered in the production of biogas

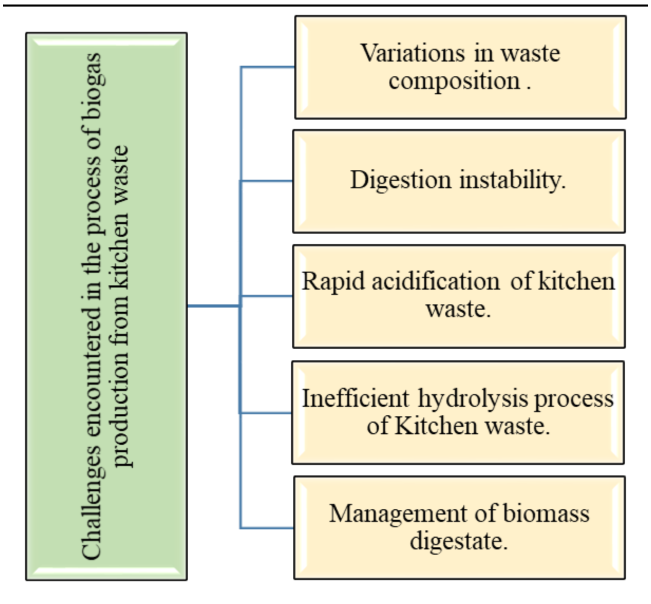

Fig. 4. Challenges encountered in the process of biogas production from kitchen waste.

Moreover, apart from the organic matter like food scraps and packaging materials, other items that contribute to the accumulation of kitchen refuse within college dining halls and cafeterias encompass disposable utensils, napkins and beverage containers, which are typically utilized once and then disposed of, consequently augmenting the overall amount of waste generated. Particularly during peak meal periods, such as breakfast, lunch, and dinner, the volume of kitchen refuse tends to escalate significantly due to the preparation and serving of substantial quantities of food to cater for the significant number of students and staff members dining during these periods. The surplus food that remains unconsumed, alongside the packaging materials utilized for food delivery, collectively contributes to the escalating waste production. The packaging materials employed in college dining establishments, including plastic containers and Styrofoam trays, exhibit a protracted breakdown period of hundreds of years in landfills, thus exacerbating the issue of landfill pollution.

3. BIOGAS FEEDSTOCK

3.1 Kitchen waste and Animal Waste

Kitchen waste, which includes various organic materials such as food scraps and leftovers, has been recognized as a valuable and promising resource for biogas production. Kitchen waste, a common byproduct of households, is known to be abundant in a variety of organic compounds such as volatile solids [VS], which play a vital role in the process of AD. Numerous research studies have demonstrated that kitchen waste typically consists of 85-96% volatile solids, highlighting its significant potential as a highly conducive substrate for the generation of methane via AD [18] as illustrated in However, the high moisture content in kitchen waste makes it unsuitable for incineration or landfilling [Table 1]. Moreover, the organic constituents present in kitchen waste, which encompass a diverse range of materials like banana peels, orange peels, kiwi peels, and, onion residues, have been specifically recognized for their efficacy as raw materials in the context of biogas production [19].

3.2 Classification of Kitchen Waste

Numerous categories of kitchen waste have been distinguished through rigorous analysis and classification processes. These categories encompass a wide range of sources, such as hop pot [HP], fast food [FF], Hebei cuisine [HC], university canteen [UC], Households, packaging materials and other forms of mixed kitchen waste [Other], each presenting unique characteristics and implications for waste management practices [20] as illustrated in Fig. 5.

Kitchen waste, which includes various organic materials such as food scraps and leftovers, has been recognized as a valuable and promising resource for biogas production as shown in Fig. 6. This is attributed to its inherent capacity to undergo AD processes, ultimately leading to the generation of biogas. Numerous scientific investigations have demonstrated that through the optimization of key factors such as temperature, pH levels, organic loading rates and the ratio of inoculants, the yield of biogas obtained from kitchen waste can be substantially augmented and improved [21].

Table 1. Kitchen waste's chemical composition

S.N.	Waste Composition [%] [g/100g dry peel]				
	Composition	**Banana peel [19].**	**Orange peel [19].**	**Kiwi peel [22]**	**Kitchen waste [23]**
1.	Protein	10.44	9.73	12.62	6.7
2.	Fat	8.40	8.70	3.70	8.7
3.	Carbohydrate	43.40	53.27	76.92	24.8
4.	C/N ratio	26.0-28.0	30	28	38.2

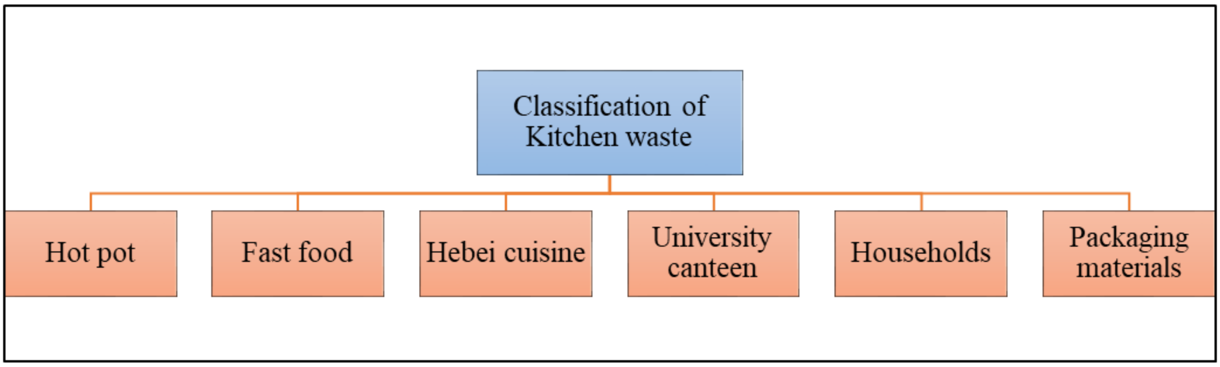

Fig. 5. Classification of Kitchen waste

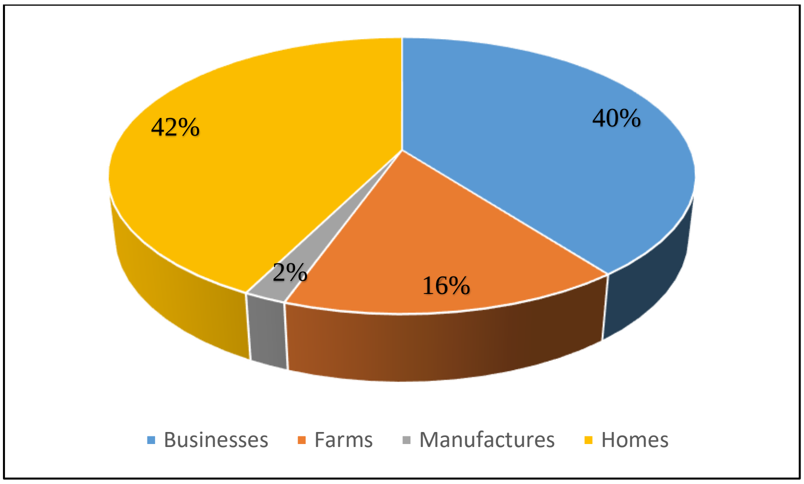

Fig. 6. Sources of food waste

The utilization of kitchen waste for biogas production not only presents notable advantages in terms of economics but also offers significant environmental benefits when compared to the use of traditional fossil fuels. The production of biogas from kitchen waste represents an environmentally sustainable approach that adheres to the principles of the circular bio-economy. Valorizing biomass waste for energy generation practices aids in reducing environmental pollution and curbing the emission of greenhouse gases, thereby contributing positively to overall environmental sustainability [24].

Upon subjecting kitchen waste to AD processes, the outcome is the generation of biogas. This biogas mainly consists of methane and carbon dioxide, constituents that hold considerable value as an energy resource. The use of this biogas as an energy source offers a viable and sustainable solution for meeting energy demands in various sectors.

Empirical research suggests that a wide array of kitchen waste materials, ranging from banana peels to onion residues and other organic components, can be efficiently converted into biogas [25]. This conversion process provides a renewable energy alternative that can be utilized for purposes such as heat generation and electricity production, or even as a substitute for conventional vehicle fuels.

Moreover, research studies have shown that generating biogas from kitchen waste is proficient economically and ecologically as well. This practice has the potential to boost energy generation capabilities while simultaneously reducing the dependency on finite fossil fuel resources, thereby promoting a more sustainable and eco-friendly energy landscape.

Kitchen waste, a common byproduct of households, is known to be abundant in a variety of organic compounds such as volatile solids [VS], which play a vital role in the process of AD. Numerous research studies have demonstrated that kitchen waste typically consists of 85-96% volatile solids, highlighting its significant potential as a highly conducive substrate for the generation of methane via AD [18]. However, the high moisture content in kitchen waste makes it unsuitable for incineration or landfilling.

Moreover, the organic constituents present in kitchen waste, which encompass a diverse range of materials like onion residues, banana peels, kiwi peels, and orange peels, have been specifically recognized for their efficacy as raw materials in the context of biogas production. These organic components have been found to yield substantial amounts of methane, with recorded values ranging between 0.325 to 0.523 L·gDOM, further underscoring their suitability for this particular application [26].

The presence of these organic compounds within kitchen waste serves to supply the essential carbon sources required by methanogenic archaea and various bacterial species to thrive within the AD environment. This symbiotic relationship ultimately fosters enhanced biogas production rates and facilitates the efficient recovery of energy from kitchen waste, thereby presenting a sustainable solution for organic waste management [27,28]. Malakahmad *et al.,* [2011] stated that, within the framework of biogas generation, it is recommended that the solid content of the feeding material should fall within the range of approximately 10-15 percent. Furthermore, it is known that bacteria tend to utilize carbon at a rate 25-35 times faster than nitrogen. As a result, maintaining a favorable C/N ratio [25-35/1] is essential for the effective functioning of the digester in terms of gas generation. The substrate composition comprises intricate organic polymers, which are decomposed through extracellular enzymes synthesized by hydrolytic bacteria, leading to their dissolution in the aqueous medium.

4. BIOGAS PRODUCTION TECHNOLOGY

Biogas production technology involves two basic steps which is further broken down into four processes, namely: 1.] Hydrolysis, 2.] Acidogenesis,3.] Acetogenesis and 4.] Methanogenesis

Biogas production encompasses a set of crucial steps that are essential for the overall process. Initially, the procedure may involve the pre-treatment of the organic substrate to create a slurry that possesses a specific dry matter content, a careful task that sets the foundation for subsequent stages. Subsequently, AD commences within a specialized digestive tank, where the organic waste is subjected to decomposition facilitated by methanogenic microorganisms. This complex biological process concludes in the generation of biogas, a valuable outcome with significant environmental and energy implications. The process of breaking down organic waste material is a gradual process, which takes place step by step in four stages and each stage is crucial for the overall efficiency of the process as illustrated in the Fig. 7.

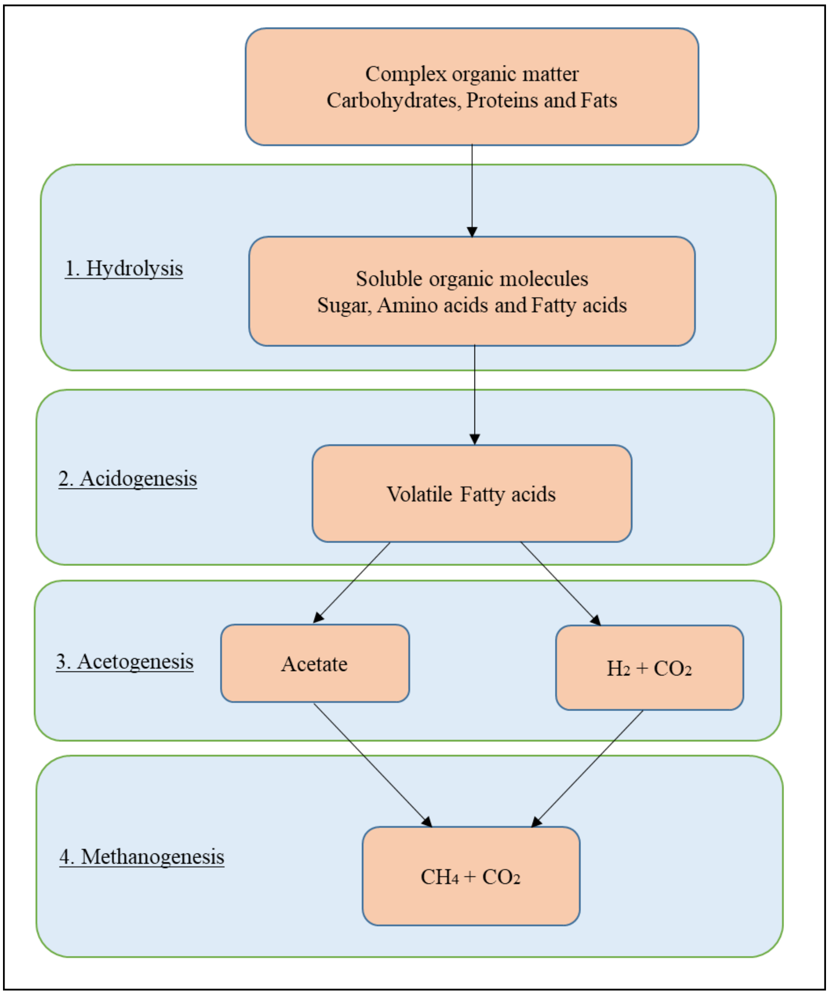

Fig. 7. Biogas production technology

4.1 Hydrolysis

Hydrolysis as the first phase in AD intends to break down organic substances like carbohydrates, proteins, and fats into soluble organic compounds composed of basic units of sugars, amino acids, and fatty-acid respectively [Fig. 3].

Equation [1] shows the hydrolysis reaction,

$$[C_6H10O_5]n + nH_2O \rightarrow n\ C_6H_{12}O_6 + nH_2 \quad [1]$$

4.2 Acidogenesis

Following Hydrolysis, the process transitions to the stage of acidogenesis, a critical phase involving the fermentation of the previously generated soluble organic molecules. In this step, acidogenic bacteria consume soluble organic compounds converting them to alcohols, aldehydes, VFAs, acetate, and also produce H_2 and CO_2 gases. Equations [2]-[4] demonstrate the chemical reactions that occur in the acidogenesis phase.

$$C6H12O6 \leftrightarrow 2CH3CH2OH+2CO2 \quad [2]$$

$$C6H12O6 \rightarrow 3CH3COOH \quad [3]$$

$$C6H12O6 + 2H2 \leftrightarrow 2CH3CH2COOH+2H2O \quad [4]$$

4.3 Acetogenesis

Acetogenesis emerges as the subsequent step in the AD process, where the products derived from fermentation namely alcohols, aldehydes, and VFAs are transformed into hydrogen [H_2], carbon dioxide [CO2], and acetic acid [CH3COOH]. Notably, the production of acetic acid necessitates the involvement of acetogenic bacteria, which rely on oxygen and carbon for this conversion process. Equations [5]-[7] illustrate the chemical reactions occurring in the acetogenesis phase.

$$CH3CH2COO + 3H2O \leftrightarrow CH3COO + H + HCO3 + 3H2 \quad [5]$$

$$CH3CH2OH + 2H2O \leftrightarrow CH3COO + 3H2 + H \quad [6]$$

$$C6H12O6 + 2H2O \leftrightarrow 2CH3COOH + 2CO2 + 4H2 \quad [7]$$

4.4 Methanogenesis

Lastly in the methanogenesis stage which is the final stage of degradation, two groups of methanogenic bacteria willfully involved in the production of methane from acetate or from hydrogen and carbon dioxide. These specialized bacteria show strict anaerobic features, requiring a lower redox potential for growth than most other anaerobic bacteria emphasizing complex and selective mechanisms in the biological processes in the field of biogas production [29]. Equations [8]-[10] depict the responses at this point.

$$CO2 + 4H2 \rightarrow CH4 + 2H2O \quad [8]$$

$$CH3COOH \rightarrow CH4 + CO2 \quad [9]$$

$$2CH3CH2OH + CO2 \rightarrow CH4 + 2CH3COOH \quad [10]$$

5. CO-DIGESTION FOR METHANOGENESIS

The implementation of co-digestion techniques for managing agricultural waste within communities enhances sustainable energy practices by optimizing biogas production from diverse feedstocks like food waste, showcasing both economic viability and environmental advantages [30]. Moreover, the investigation into co-digestion practices alongside the utilization of immobilized bio-film techniques has been conducted to effectively address the limitations encountered in AD processes [31], ultimately leading to the enhancement of biogas production.

Additionally, there has been a notable focus on the importance of pretreatment methods and the co-digestion of substrates as a means to boost the efficacy of biogas production and to reinforce the incentives for the development of sustainable energy sources [32,33]. Furthermore, the integration of modular design concepts and the principles of circular economy within biogas production facilities have been identified as further mechanisms to contribute to initiatives promoting green energy and effectively tackling environmental challenges [34]. The collective approaches encompassed within these strategies are geared towards the optimization of biogas production, the sustainable fulfillment of energy requirements, and the mitigation of adverse environmental impacts.

However, in response to the increasing need for novel approaches in the production of biogas to tackle environmental concerns and the growing energy requirements, several research studies have shed light on a variety of strategies. These encompass the utilization of waste biomass employing sophisticated pretreatment methodologies aimed at enhancing the generation of biogas [35], the incorporation of bio-electrochemical systems [BES] with the objective of enhancing the performance of AD through the acceleration of the degradation of organic material and the subsequent amplification of biogas production [36].

Kitchen waste is considered to be a valuable and significant source of organic material that possesses a high level of calorific and nutritive value, especially beneficial for the growth of microbes within a given environment. This particular characteristic plays a crucial role in significantly boosting the overall efficiency and effectiveness of methane production processes, consequently leading to a notable and substantial rise in the final output quantities. According to, [Aljumah & Alyahya, 2023], the utilization of kitchen waste as a key resource within the realm of biogas production presents potential environmental advantages and benefits that are worthy of exploration and analysis. Primarily, the incorporation of kitchen waste in such processes aids in the reduction and minimization of food waste on a global scale, addressing a pressing and prevalent issue that has far-reaching implications and consequences. Concurrently, this utilization strategy also serves to elevate the levels of renewable energy generated through these operations, highlighting a dual benefit that emphasizes the interconnectedness of environmental sustainability and resource optimization. Secondly, the process of AD, which involves breaking down kitchen waste to produce biogas, emerges as an eco-friendly and cost-effective approach to energy generation, thus playing a vital role in the realm of sustainability endeavors [37]. Therefore, this method has the potential to offer improvement in the physical size of the biogas production reactors as well as reduction of their cost of manufacturing and hence, an improvement of the efficiency of the entire production process. Furthermore, it should be noted that the transformation of kitchen waste into biogas plays a crucial role in minimizing the emission of harmful pollutants into the surrounding ecosystem [24]. This practice is in line with waste-to-wealth approaches that are centered around the concept of converting waste materials into valuable resources such as biogas. Additionally, it should be emphasized that the AD process leads to the creation of biogas predominantly comprised of methane and carbon dioxide [38]. These gases have the potential to be utilized as a renewable energy source, thus further boosting efforts towards environmental conservation. In summary, the conversion of kitchen waste into biogas for energy generation serves not only to tackle issues related to waste management but also to foster the generation of renewable energy and the safeguarding of the environment.

Therefore, the anaerobic co-digestion of animal waste and food waste represents a viable method for generating renewable and eco-friendly biogas, thereby reducing environmental impact [39,40,41]. Furthermore, the slurry created during the process acts as beneficial organic fertilizer for agriculture and helps maintain soil fertility [42,43].

The use of cow dung slurry and kitchen garbage as feedstock for biogas production has also been explored [44,45]. Additionally, the addition of ammonium chloride as an external nitrogen source has been found to significantly increase biogas production from canteen waste [46,47]. Furthermore, research has shown that various kitchen waste, such as banana peel, orange peel, onion residues, onion peel and kiwi peel can be effectively fermented to produce methane, making them valuable raw materials for biogas production. These findings highlight the potential of kitchen waste as a resource for innovative biogas production.

6. INNOVATIONS IN BIOGAS PRODUCTION

The application of bioprocess technology has a profound influence on both the effectiveness and cost-efficiency of biogas generation. Bioprocess technology, particularly AD, plays a crucial role in converting organic waste into biogas, thereby presenting a sustainable approach for generating renewable energy and managing waste [48]. This complex procedure encompasses the decomposition of organic substances such as food leftovers or animal excretions into biogas, which boasts a high content of methane and can be harnessed for the production of thermal energy and electrical power [49].

Moreover, the progression of bioprocess technologies has paved the way for the emergence of novel pathways like the Heat, Power & Chemicals [HPC] technology. This innovative approach facilitates the transformation of biogas into important chemical substances like bio-methanol. Noteworthy benefits of this conversion process include reduced carbon emissions and a promising level of economic viability, thereby expanding the horizons of sustainable energy production and resource utilization [50]. Through the utilization of bioprocess technology like AD, organic waste can be efficiently converted into a valuable reservoir of energy, concurrently addressing the environmental repercussions linked to waste disposal and the release of greenhouse gases.

Recent advances in the field of biogas production techniques have been primarily concentrated on the improvement of both efficacy and sustainability aspects. The sector has witnessed a significant shift with the introduction of membrane-based separation technology, a groundbreaking innovation that is reshaping the biogas upgrading market by providing a more economically viable and efficient alternative compared to conventional methodologies [51].

The emergence of various pre-treatment techniques, encompassing physical, chemical, thermal, and innovative processes have been crucial in enhancing the production of methane from organic waste materials. These technologies emphasize the critical importance of employing such methods to enhance the efficiency of AD processes, thereby highlighting their indispensable role in the biogas production landscape [52]. Furthermore, the application of biological pre-treatment techniques has exhibited significant potential in increasing lignocellulose hydrolysis and improving the generation of biogas from lignocellulosic waste materials [53]. This highlights the urgent necessity for the adoption of efficient and cost-effective strategies to streamline the AD process and enhance biogas output [54].

The development of anaerobic digesters and pre-treatment procedures stands as a key element in the endeavor to expand biogas production from a wide array of organic residues. The primary objective is to elevate the yield and purity of bio-methane to cater to a broader spectrum of commercial applications, necessitating continuous advancements in these technological domains [55]. Moreover, it has been recognized that the utilization of bio-electrochemical systems [BES] presents itself as a viable and feasible approach to enhance the performance of AD processes. This in turn facilitates the acceleration of organic matter breakdown, enhances the quality of biogas produced, and puts forth potential future trajectories for the expansion and implementation of BES technology within the realm of AD systems [35].

Recent trends with biogas production strategies include the integration of artificial intelligence [AI] and the Internet of Things [IoT] as the key determinants towards improved yield as well as production rate. This integration has been exemplified by the successful application of an artificial neural network [ANN] genetic algorithm [GA] model, achieving an impressive efficiency rate of 78.2% [56]. The integration of artificial intelligence [AI] and machine learning [ML] has significantly influenced the efficiency of biogas production processes through the facilitation of predictive modeling, optimization, and real-time monitoring. Various research studies have indicated that the application of AI and ML methodologies, such as artificial neural networks [ANN] and genetic algorithms [GA], can provide precise predictions of biogas yields, fine-tune production parameters, and improve overall efficiency, consequently resulting in heightened biogas production rates and enhanced operational performance [57,58,56]. Through the utilization of sensors and Internet of Things [IoT] technologies to oversee critical variables influencing biogas production, these sophisticated technological approaches have showcased the capability to elevate biogas yields, achieve heightened levels of operational efficiency, and lay the groundwork for further progressions within the domain of AD.

According to [59], the use of Fish waste for the production of biogas can result in significant reductions in greenhouse gas emissions, with estimations reaching as high as 1,619 tons of carbon dioxide equivalent. This process also has the added benefit of generating electricity in a sustainable manner. Recent advancements in enzyme-based biogas production techniques have exhibited promising outcomes in augmenting the yields of biogas, as highlighted in recent research endeavors**.** Enzymes have been identified to wield a pivotal role in the process by aiding in the breakdown of intricate nutrients into more simplistic forms, thereby enhancing the overall efficiency of biogas production [60]. Various scientific investigations have delved into the utilization of specific enzymes such as amylase and cellulase for the purpose of pretreating substrates like rice husk waste, culminating in notable escalations in the production of biogas, a phenomenon well-documented in the realm of biogas research [61]. Nevertheless, it has been noted that the practical utility of enzymatic pretreatment in specific crop combinations may be constrained, even though considerable advancements have been discerned in the digestion of agricultural biomasses possessing intricate lignocellulosic configurations, resulting in substantial surges of over 30% in biogas production, as corroborated by empirical evidence [62]. Furthermore, the implementation of a multi-enzymatic biopreparation has illustrated a remarkable 30% augmentation in the efficacy of biogas production when conditioning organic waste before the fermentation process, thus underscoring the immense potential of enzyme-centric methodologies in fine-tuning methane fermentation processes for optimal outcomes in biogas production [63].

Advances in biotechnology and genetic engineering have led to a substantial improvement in the efficiency and cost-effectiveness of biogas production, marking a significant milestone in the field. The emergence of biogas biorefineries that possess the capability to convert methane into valuable products by employing metabolic engineering techniques on methanotrophs has not only broadened the spectrum of bioproducts but has also played a pivotal role in boosting the financial viability of the entire process [51]. Moreover, the utilization of microbial community analysis methodologies, genetic alterations in both plants and microbial organisms, as well as the integration of mixed culture biotechnology strategies, have been crucial in fine-tuning AD processes, resulting in higher biogas yields and enhanced process robustness [64]. In addition, recent breakthroughs in culture-independent "omics" technologies, including but not limited to metagenomics and meta-transcriptomics, have transformed our comprehension of microbial communities and their intricate metabolic pathways throughout AD. These advancements have opened up new avenues to optimize biogas production efficiency from a wide array of organic sources characterized by complex structures, thereby showcasing the potential for significant improvements in sustainability and environmental impact [36]. These remarkable advancements emphasize the promising outlook for a sustainable future in biogas production, emphasizing the pivotal role of biotechnological and genetic engineering methodologies in driving innovation and progress in this critical domain.

The incorporation of bioprocess technology into the production of biogas provides a multitude of noteworthy environmental advantages. Primarily, it enables the effective utilization of biodegradable materials present in waste, thereby addressing critical environmental issues associated with waste disposal. This approach plays a pivotal role in tackling the pressing concerns linked to the management of waste materials [65]. Secondly, the conversion of organic waste, including livestock waste, into biogas serves to substantially diminish the environmental footprint by reducing water pollution and offering valuable bio-fertilizers of superior quality for agricultural purposes. This not only helps in curbing environmental degradation but also contributes to enhancing agricultural practices through the provision of nutrient-rich bio-fertilizers. Moreover, the utilization of algae as a primary source material for biogas production presents a sustainable substitute for traditional fossil fuels. This practice helps reduce the negative impacts of climate change and presents a viable solution that does not compete significantly with food crops for resources [66]. The integration of algae into the biogas production process represents a promising avenue for reducing carbon emissions and transitioning towards more sustainable energy sources [67].

7. FACTORS AFFECTING BIOGAS PRODUCTION

Current developments in the field of producing biogas from kitchen waste revolve around the optimization of factors such as temperature, pH levels, and the rate at which organic materials are loaded into the system. These optimizations are aimed at boosting the production of methane gas, a key component of biogas. Research studies have indicated that a combination of kitchen waste and cattle dung can lead to a substantial increase in the overall biogas output. Specifically, findings have shown that a kitchen waste ratio of 75% in the mixture results in a 17.3% enhancement in biogas generation compared to a ratio of 25%. Moreover, there is increasing interest in the utilization of bio electrochemical systems [BES] within AD processes. This innovative approach has demonstrated the potential to expedite the breakdown of organic matter, thereby improving biogas production outcomes. Furthermore, the implementation of BES has been linked to enhancements in the composition of microbial communities engaged in the biogas generation process. This suggests a novel pathway towards deriving biogas from kitchen waste. Looking ahead, future advancements in this field may concentrate on refining the efficiency of the hydrolysis stage to increase biogas production. This could involve enhancing the breakdown of organic compounds through strategies such as biofilm pretreatment. Such methods have the potential to not only increase biogas production levels but also to accelerate overall rates of degradation. Additionally, the integration of organic substrates with higher carbon content presents an opportunity to further amplify methane production during the fermentation stages. This dual-purpose approach not only benefits the productivity of fermenters but also contributes to the improved management of organic waste materials.

These organic components have been found to yield substantial amounts of methane, with recorded values ranging between 0.325 to 0.523 L·gDOM, further underscoring their suitability for this particular application [26]. The presence of these organic compounds within kitchen waste serves to supply the essential carbon sources required by methanogenic archaea and various bacterial species to thrive within the AD environment. This symbiotic relationship ultimately fosters enhanced biogas production rates and facilitates the efficient recovery of energy from kitchen waste, thereby presenting a sustainable solution for organic waste management [27,28].

The impact of the composition of kitchen waste on its potential for biogas production is a topic of significant interest and importance within the realm of research. It has been demonstrated through various studies that the ratio at which kitchen wastes are mixed with other substrates such as cattle dung or food waste can have a profound impact on the overall biogas yields obtained from the process. For example, an empirical investigation revealed that a specific mixing proportion of 75% kitchen waste in the total slurry volume resulted in a notable increase of 17.3% in the production of biogas when compared to a scenario where only 25% of the slurry consisted of kitchen wastes [21]. Furthermore, it is crucial to acknowledge the essential role played by the hydrolysis process of food waste, a prevalent component found in kitchen waste, in the facilitation of biogas generation. This process is particularly vital as higher ratios of inoculum to feed have been observed to correspond with elevated biogas yields [38]. In conclusion, the optimization of the composition of kitchen waste can be achieved through the implementation of appropriate mixing ratios and pretreatment techniques. This optimization process is fundamental in significantly augmenting the potential of kitchen waste for biogas production.

8. UTILIZATION OF KITCHEN WASTE

However, through the utilization of kitchen waste, a multitude of environmental problems can be solved from the reduction of waste in landfills to mitigating greenhouse gas emissions and produce renewable energy. Through the process of converting kitchen waste into valuable resources such as biofertilizers, bioenergy, and biofuels utilizing advanced techniques like AD and solid-state fermentation, a substantial decrease in the environmental repercussions stemming from waste accumulation is achieved [37,68].

Research findings indicate that kitchen waste has the potential to function as a superior fertilizer in comparison to mineral-based fertilizers, thereby enhancing crop yields and soil characteristics, thereby making significant contributions to sustainable agricultural practices and the global food supply chain [69].

Cutting-edge advancements in technology, such as the utilization of high-efficiency food waste recycling mechanisms that operate on solar power, facilitate the conversion of kitchen waste into botanical organic fertilizers. This contributes to promoting energy conservation, reducing harmful emissions, and controlling environmental pollution in densely populated regions. [70].

In light of the challenges presented by the escalating levels of municipal solid waste, particularly in bustling metropolitan areas like India, the adoption of cost-effective and user-friendly approaches to managing kitchen waste can pave the way for sustainable waste-to-energy solutions and the emergence of new avenues for business development. Simultaneously, this practice contributes to the alleviation of environmental pollution issues and the creation of employment opportunities [71].

9. MICROBES INVOLVED IN BIOGAS PRODUCTION

The study of the microbial populations inhabiting anaerobic digesters holds significant importance as they organize the intricate process of decomposing organic compounds into simpler molecular structures, subsequently transforming them into vital biogas components like methane and carbon dioxide. It is crucial to note that various categories of microorganisms have distinct roles in different stages of the AD mechanism, thereby contributing to the overall effectiveness and productivity of biogas generation. A comprehensive analysis of the diversity, population size, and interrelations among these microorganisms is imperative for the improvement of biogas generation methodologies and the promotion of sustainable approaches to managing organic waste. The pivotal involvement of microorganisms, encompassing both bacteria and archaea, is evident in the facilitation of biogas formation via the intricate processes of AD. These microorganisms showcase a wide array of functionalities including but not limited to hydrolysis, acidogenesis, acetogenesis, and methanogenesis, together facilitating the effective transformation of organic waste into valuable biogas resources [72,73,74,75].

Numerous research studies have shown that a wide variety of microorganisms play a complex role in facilitating the biogas production process, including but not limited to taxonomic classes such as *Clostridia, Bacteroidia, Betaproteobacteria, Gammaproteobacteria, and Alphaproteobacteria* [75]. These microbial entities exhibit a synergistic relationship, working collectively to efficiently convert organic waste into biogas. Within this intricate network of microorganisms, specific bacterial strains like *Proteiniphilum, Proteiniborus,* and *Pseudomonas*, as well as archaeal counterparts such as *Methanocorpusculum, Methanobacterium, Methanomassiliicoccus, Methanoculleus, and Methanosarcina*, play a pivotal role within anaerobic digesters and significantly contribute to the overall biogas production process [72]. The metabolic functions, active genes, protein expressions, and intricate interactions exhibited within this microbial consortium serve to augment the productivity levels of AD, consequently resulting in heightened biogas yields and the creation of valuable by-products [76].

Moreover, the utilization of advanced molecular methodologies such as metagenomics enables researchers to delve deeply into the intricate diversity and metabolic pathways of these microorganisms, thereby furnishing invaluable insights that can be harnessed for the improvement and maximization of biogas production processes [76]. Proteolytic microorganisms, for example, have been identified in research studies as having the capacity to notably enhance the production of biogas by as much as 80%, concurrently leading to a reduction in the levels of Chemical Oxygen Demand [COD] by approximately 58% as evidenced by scientific investigations [77].

The influence of bacterial metabolism in AD is of significant importance as it greatly impacts the overall efficiency of the process by aiding in the conversion of organic matter waste into biogas. The microbial communities residing within digesters play a crucial role in driving this intricate process, where various factors such as temperature fluctuations, pH levels, loading rates of the substrate, and the existence of inhibitory compounds exert notable effects on their composition and functionality. These diverse factors collectively contribute to the intricate balance within the AD system, thereby influencing the productivity and efficiency of the biogas generation process [73]. Throughout the different stages of AD, ranging from hydrolysis to methanogenesis, distinct populations of bacteria are involved, each playing crucial roles in the overall process. It is noteworthy that variations in microbial diversity have been observed across different digestion chambers, highlighting the complex nature of these microbial communities and their dynamic responses to varying environmental conditions. Understanding these intricate relationships and the dynamics of bacterial populations within anaerobic digesters is essential for unraveling the complexities of the process of producing biogas and maximizing its efficiency [74]. The metabolic activities of bacteria, including the crucial role of syntrophic acetate-oxidizing bacteria [SAOB], are indispensable for the degradation of acetate within AD systems. Whether through acetoclastic methanogenesis or symbiotic interactions with methanogens, these bacterial populations significantly influence the efficiency of biogas production [78]. Therefore, a thorough comprehension of the metabolic pathways and interactions within these diverse bacterial communities is paramount for enhancing the overall performance, sustainability, and resilience of AD systems.

The manipulation of the bacterial community composition within AD systems is a key aspect that can be strategically altered to maximize their impact on the overall process efficiency, as elucidated in a multitude of scholarly articles. A comprehensive understanding of the microbial composition, functional gene configurations, and metabolic pathways present in anaerobic digesters is paramount to enhance their operational performance and effectiveness [73] [79]. Numerous research studies have indicated that the makeup of bacterial communities in distinct compartments of anaerobic digesters exhibit variability, showcasing simpler community structures during the initial stages such as the breakdown of chicken manure, while more intricate communities are observed in the primary digestion chambers, ultimately influencing the overall efficacy of the AD process [80]. Moreover, the utilization of high-throughput sequencing techniques and bioinformatics tools serves as a critical component in the evaluation of microbial diversity and interactions within anaerobic digesters, thereby offering valuable insights into the optimization of biogas production processes [79]. Through the manipulation of the bacterial community via diverse operational and environmental parameters including but not limited to temperature, pH levels, and substrate loading rates, there exists a significant potential to improve the efficiency and performance of AD systems to a substantial degree.

Genetically modified microorganisms have been identified as playing a crucial and essential role in the enhancement of the effectiveness and longevity of processes involved in the production of biogas. It has been indicated through scholarly investigation that progressions achieved in the realms of genetic manipulation and metabolic engineering have played a paramount role in the substantial amplification of the output of biofuels, which encompasses biogas, through the employment of specially designed microbial varieties tailored for large-scale production at a reduced expense. The combination of genetically modified organisms within the context of biogas production serves as a catalyst for the augmentation of efficiency and sustainability within the overall process [81,82]. Moreover, empirical research has demonstrated that the incorporation of highly effective ligninolytic strains, such as Enterobacter hormaechei KA3, into AD environments can result in the enhancement of lignin breakdown, amplified production of biogas and methane, accelerated rates of organic matter removal, and consequently an elevation in the overall efficacy of the biogas generation process [35]. The strategic application of genetically engineered microorganisms offers the potential to optimize biogas production, enhance process stability, and mitigate substrate inhibition, thus playing a critical role in advancing a sustainable and efficient biogas generation system.

10. CONCLUSION

Utilizing kitchen waste as a valuable resource within the framework of biogas generation presents a variety of potential advantages that necessitate exploration and analysis. Extensive research findings have unequivocally demonstrated that the process of AD applied to kitchen waste can result in the substantial generation of biogas, a gas predominantly comprised of methane and carbon dioxide, thereby representing a notable and consequential energy source with multifaceted utility. Moreover, the employment of kitchen refuse for the specific purpose of biogas production plays a pivotal role in the commendable endeavor of waste reduction, particularly in the domain of food waste mitigation, thereby engendering positive implications for environmental sustainability by mitigating the deleterious consequences associated with emissions during the natural decomposition of organic matter in landfills. Noteworthy scientific investigations have elucidated that the incorporation of kitchen discards into the intricate framework of biogas production processes can exert a positive influence on the overall biogas output, as evidenced by empirical data showcasing that distinct ratios of mixing various components can yield substantial improvements in the volume of biogas generated, thus underscoring the importance of strategic formulation in optimizing biogas yields. Furthermore, the strategic utilization of kitchen waste as a fundamental constituent in the production of biogas holds promise in facilitating the global transition from conventional fossil fuel dependency towards a more sustainable trajectory rooted in renewable energy sources, thereby aligning with the overarching objective of advancing the proliferation of green energy technologies and ameliorating the adverse impacts of anthropogenic activities on the global climate landscape.

Biogas, which is generated through the process of AD using organic matter like agricultural residue and animal waste, presents notable economic and environmental benefits when compared to the utilization of traditional fossil fuels. The generation of biogas serves not just as a sustainable and renewable energy source but also contributes to efficient waste management practices, aids in the reduction of greenhouse gas emissions, and yields valuable organic fertilizers. The incorporation of biogas into energy systems proves to be instrumental in meeting the ever-growing global energy demands in a sustainable manner, fostering a healthier and cleaner environment, and enhancing soil fertility through the application of organic byproducts [83]. Moreover, the adoption of biogas technology stands as a viable and environmentally conscious substitute for conventional fuel sources, providing a pathway toward diminishing dependence on finite reserves of fossil fuels. Through the transformation of organic waste into a usable form of energy, biogas emerges as a pivotal player in advancing the agenda of sustainable development, tackling the challenges presented by global climate change, as well as bolstering overall energy security and economic feasibility [84].

Overall, biogas production aligns with sustainable development objectives by promoting renewable energy sources, curbing greenhouse gas emissions, improving waste management, and fostering economic opportunities, positioning it as a crucial contributor to sustainable energy production [85]. Biogas has the advantage that it can be utilized in a variety of engines without any modification such as diesel engines, petrol engines, turbines, micro turbines, and stirling engines for the purpose of generating electricity [86]. Also, the integration of bioprocess technology within the realm of biogas production not only addresses the prevalent issues associated with waste management but also plays a pivotal role in diminishing environmental pollution and fostering the adoption of sustainable practices in the energy sector [87].

11. FUTURE SCOPE

However, current challenges in biogas production encompass a variety of operational flaws that hinder the effectiveness of the process, alongside the existence of impurities such as CO_2 and H_2S which have the detrimental effect of reducing the calorific value of the produced biogas, thereby diminishing its overall quality. Furthermore, there exist limitations in the AD processes which further compound the challenges faced in biogas production. To overcome these challenges, the research and development emphasis is now being placed on different approaches of methods for enhanced processes, biogas cleaning technologies, membrane-modified biogas upgrading, and the use of co-digestion and pre-treatment processes and a biological hydrogen methanation technique. These coordinated approaches are intended to optimize the biomethane output and quality of the biogas, improving methane production efficiency, and reducing the operational problems which are a consequence of the presence of contaminants in the biogas. Furthermore, there is a rising concern for researching other resources like distillery wastewater used for the generation of biogas and press mud obtained from sugarcane industries. Apart from this, there is a rising focus on the best design suitable for large-scale biogas production, based on the circular economy. These courses of action have the potential to eliminate the existing problems experienced in biogas production.

DISCLAIMER [ARTIFICIAL INTELLIGENCE]

Author[s] hereby declare that NO generative AI technologies such as Large Language Models [ChatGPT, COPILOT, etc] and text-to-image generators have been used during writing or editing of manuscripts.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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