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Progress in Anaerobic Digestion for Improved Biogas Generation : An Overview of Technologies and Challenges

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ABSTRACT

Anaerobic digestion (AD) is emerging as one of the most promising technologies for sustainable waste management and renewable energy production. The demand for clean energy and the increasing production of agricultural, industrial and municipal wastes have raised an interest in biogas production as an environmentally friendly alternative to fossil fuels. This review concerns the recent advances in anaerobic digestion technologies for biogas production and process efficiency. The study reviews the principles of biogas production, the stages of anaerobic digestion and key operating parameters influencing digester performance, such as temperature, pH, organic loading rate, hydraulic retention time and substrate composition. The different types of anaerobic digesters and their applications are discussed as well.

In addition, the review highlights major challenges in anaerobic digestion such as process instability, ammonia, sulfide, volatile fatty acids and other inhibitory compounds. Special emphasis is given to the use of agricultural residues as renewable and sustainable substrates for biogas generation because of their abundant and renewable availability. In addition to limitations and operational constraints, the environmental, economic and energy related benefits of biogas systems are discussed. In conclusion, the development of anaerobic digestion technologies holds great promise for the enhancement of renewable energy production, the reduction of greenhouse gas emissions, and the promotion of sustainable waste management practices. Future research should focus on process optimization, pretreatment technologies, co-digestion strategies, and integration of advanced monitoring systems to maximize biogas yield and process stability.

1. INTRODUCTION

Globalization, urbanization, industrialization, and population growth are significant contributors to the substantial rise in food waste production, especially in Asian nations[1].

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Consequently, all industrialized and semi-industrialized nations, along with the majority of developing countries, are seeking solutions to substitute these fuels and postpone the exhaustion of these resources. In contemporary civilizations, the availability of continuous, sustainable, and economical energy is essential for economic development and growth [2]. Subsequent to the Industrial Revolution, energy has progressively emerged as a principal determinant in national production and the operation of the economic mechanisms of industrialized nations, subsequently influencing developing countries. The contemporary economy and society are so reliant on energy that it is inconceivable to envision existence without it, even momentarily. Consequently, any disruption or cessation of its supply will halt the functioning of the economic system [2]. Energy is essential in residential, commercial, and industrial sectors. Consequently, it is imperative to identify novel environmentally sustainable renewable energy sources as substitutes for fossil fuels. Biogas recovery from waste materials can be seen as a sustainable source of renewable energy and a means to mitigate the substantial accumulation of solid waste [3]. For sustainable development, a fundamental prerequisite is the provision of sufficient resources, especially energy services, to meet the essential demands of individuals and society, hence enhancing social welfare and economic advancement[4]. A significant amount of fossil fuels is utilized to sustain the commercial energy supply, specifically in electricity generation. The stability of the energy network is significantly dependent on the load balance provided by fossil fuel power units. account for approximately 70% of worldwide electricity production [4]. Consequently, all nations are striving to achieve continuous and sustainable energy through whatever feasible means. Conversely, global economic growth and rising energy demand have led to an increase in oil and gas prices, resulting in a diminished reliance on these energy sources. Conventional and non-renewable fossil resources significantly affect energy security. This challenge has prompted numerous countries worldwide to focus on energy supply security and to closely monitor significant transformations in their energy economies [5]. In this context, technological advancements offer novel options for the energy production required by humanity. The identification of these novel approaches represents a significant advancement in the transformation of energy production infrastructures. The utilization of boundless renewable energy reserves has significant implications in this context [2]. Renewable resources will significantly contribute to the reduction of global CO_2 emissions. In this context, energy derived from biomass and trash is poised to become one of the most extensively employed renewable energy sources due to its assured continuous generation [6]. Furthermore, the security of energy supply is a significant concern, as the majority of natural energy resources, such as oil and gas reserves, are located in politically unstable countries [7]. Numerous companies utilize anaerobic digesters (AD) to optimize industrial waste management while benefiting from energy incentives. While contemporary biogas applications primarily emphasize energy production, an array of biogas-derived value-added compounds is enhancing their economic and environmental viability[8]. Biogas has demonstrated considerable potential as a sustainable energy source for both industrial and home applications, serving as an effective remedy for the global energy issue [9].

Although many review articles have been published on anaerobic digestion and biogas production, there has been little effort to make a comprehensive review of recent operational optimization strategies, digester configurations, process limitations and future technology developments in one integrated review. Therefore, this study critically examines current developments in anaerobic digestion technology to fill this knowledge gap and identify the most promising methods for improving biogas generation from agricultural wastes.

The primary objective of this paper is to provide a comprehensive analysis of current advancements in anaerobic digestion techniques to enhance biogas production. This study aims to examine the fundamental principles of anaerobic digestion, assess the impact of key operational factors on biogas yield, and compare various types of anaerobic digesters utilized in renewable energy generation. This paper discusses significant obstacles and inhibiting variables impacting anaerobic digestion efficacy, particularly focusing on agricultural waste as a sustainable feedstock. The paper emphasizes the environmental and economic advantages of biogas technology while outlining the existing constraints and prospective potential for enhancing process efficiency, stability, and large-scale deployment.

2. Biogas Production

Biogas generation using anaerobic digestion (AD) technologies is seen as a compelling source of renewable energy [10]. In anaerobic digestion, organic feedstocks are transformed into biogas, which contains methane (CH4) as a valuable byproduct. The energy input for biogas production is assessed to be less than that of present ethanol production, resulting in a superior energy output-to-input ratio[10].

Biogas can be produced from several biomass sources, including chicken excrement, agricultural residues, and bovine manure, through regulated anaerobic decomposition. Biogas can be further processed and condensed to yield biomethane, which may be put into natural gas pipelines[9]. Biogas can be generated through the anaerobic digestion of various waste materials, including agricultural residues, energy crops, and industrial byproducts. Anaerobic co-digestion for biogas generation employs a mixture of several feedstocks to enhance the biogenic methane concentration in the biogas[11]. Biogas is often generated in a sealed vessel where anaerobic digestion occurs effectively; this vessel is referred to as a biogas digester. It is termed so because the decomposition of organic materials occurs in the presence of microorganisms. The bacteria in the digester require daily nourishment with food waste and water.

The primary components of biogas are as outlined in table 1. Recent studies have shown the significant potential of biogas in reducing greenhouse gas emissions, enhancing waste management, and advancing circular bioeconomy methods [12].

Table1 Component Typical concentration (%)

Methane	40–80
carbon dioxide	20–55
hydrogen sulphide	0.1–5.5
Hydrogen	trace
carbon monoxide	trace
Nitrogen	trace
Oxygen	trace

Biogas can be compressed and utilized in motor vehicles similarly to how natural gas is compressed into CNG. Natural gas and biogas provide comparable hazards. Biogas typically becomes poisonous due to its inherent concentration of hydrogen sulfide [13]. The utilization of biogas is mostly associated with electricity and heat production, as well as domestic applications such as cooking and heating. Upon upgrading to biomethane, it can be fed into a gas grid or utilized as a transportation fuel, anticipated to be its primary future application. Installations for heat and electricity generating possess electrical capacities ranging from several tens of kilowatts to a few megawatts [14]. The increased production of biogas frequently resulted from the use of energy crops that directly compete with food crop agriculture (first-generation biofuels). Consequently, the investigation of lignocellulosic materials (second generation biofuels) for bio-methane production has significantly advanced in recent years, providing both ecological and economic benefits [15].

2.1. Anaerobic Digestion

Anaerobic digestion (AD) is a biochemical process wherein microorganisms degrade organic matter in an oxygen-free environment, producing energy and by-products, predominantly biogas, which consists mainly of methane and carbon dioxide [16]. Anaerobic digestion is a biological process wherein microbial communities decompose organic materials in the absence of oxygen. As seen in Fig. 1, anaerobic digestion (AD) has four stages: hydrolysis, acidogenesis (the production of acids), acetogenesis (the generation of acetic acid), and methanogenesis (the formation of methan)[17, 18]

2.1.1. Hydrolysis

Hydrolysis is theoretically the initial phase of AD, wherein complex organic materials (polymers) is broken down into smaller units (mono- and oligomers). Polymers include carbohydrates, lipids, nucleic acids, and proteins undergo hydrolysis and are transformed into glucose, glycerol, purines, and pyridines. Hydrolytic microorganisms generate hydrolytic enzymes that decompose biopolymers into simpler, more soluble molecules. [19].

Consequently, hydrolysis deconstructs organic macromolecules into their constituent components, which can subsequently be utilized by acid-producing bacteria. While hydrolysis can be an electrical process, it predominantly transpires as a biological process during anaerobic digestion. Hydrolytic bacteria can generate long-chain fatty acids (LCFAs), amino acids, and sugars from lipids, proteins, and carbohydrates by the release of extracellular enzymes during hydrolysis[18]. Specifically, for digesters processing highly lignocellulosic wastes, various waste pretreatment methods are being investigated and implemented to optimize hydrolysis [18]. No evidence suggests heightened hydrolytic activity at pH levels below 7 [20].

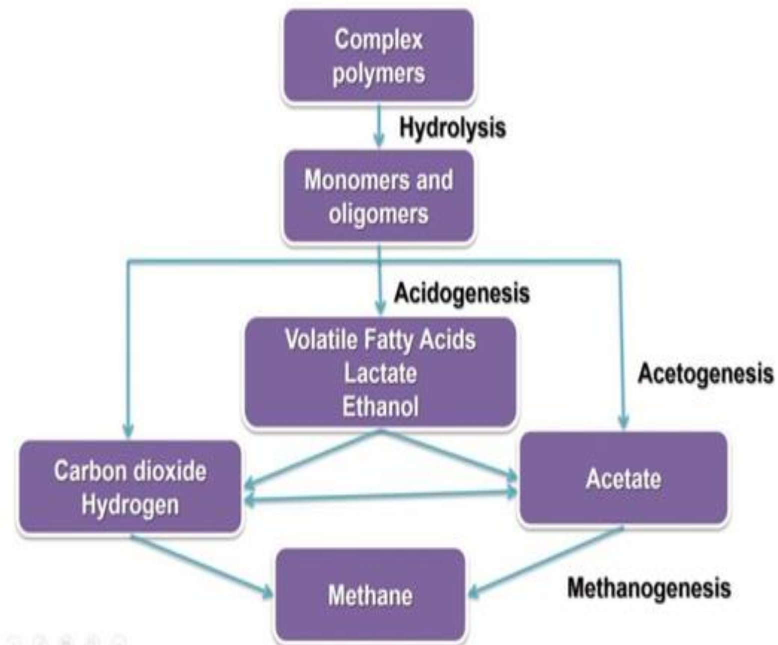

Figure 1. Anaerobic digestion stages [17, 18]

2.1.2. Acidogenic

Acidogenic bacteria transform hydrolysis products into substrates suitable for methanogenesis during the process of acidogenesis. Simple sugars, amino acids, and fatty acids are metabolized into acetate, carbon dioxide, and hydrogen (70%), along with volatile fatty acids (VFA) and alcohols (30%)[19].

In this phase, the hydrolysis products, including sugars, amino acids, and long-chain fatty acids, serve as substrates for acidogenic bacteria. These bacteria further decompose such substrates into short-chain organic acids predominantly including C1-C5 carbon molecules. During this stage, organic acids produced include butyric acid, propionic acid, acetate, and acetic acid, accompanied by the emission of other molecules such as alcohols, hydrogen, and carbon dioxide. The concentration of intermediately generated hydrogen ions typically influences the nature of fermentation products; specifically, an increase in hydrogen partial pressure results in a decrease in the formation of reduced compounds such as acetate, and vice versa [21]. It is now prudent to consider the process of synthesizing volatile fatty acids from amino acids in protein-rich waste, including wastewater. Moreover, the breakdown of individual amino acids is feasible in the presence of hydrogenotrophic bacteria. Nonetheless, this mechanism is less rapid than the Stickland reaction [18]. The Stickland reaction is generally characterized as a biochemical process in which inorganic molecules undergo simultaneous oxidation or reduction to yield specific biological products[18]. Amino acids typically decompose into pairs of volatile fatty acids through the Stickland reaction. Deamination produces ammonia, an essential consequence of amino acid catabolism.

At elevated amounts, ammonia serves as a significant inhibitor of anaerobic degradation [18].

2.1.3. Acetogenesis

Acetogenic bacteria convert the byproducts of the acidogenesis phase and certain long-chain fatty acids from the hydrolysis phase into acetate, CO2, and H_2. Reactions during the acetogenesis phase are not thermodynamically spontaneous when the partial pressure of H2 exceeds 10−4 atm. Nonetheless, methanogenic bacteria reduce this partial pressure by metabolizing the generated H_2. This syntrophic relationship, in which certain bacteria derive sustenance from the metabolic byproducts of other bacteria, renders the acetogenesis phase thermodynamically viable [8]. The transfer of hydrogen between specificities, an appealing interaction noted during anaerobic degradation, is facilitated by hydrogen produced during acetogenesis. Despite acetogenesis generating hydrogen, acetogenic microbes are adversely impacted by elevated partial pressure. Hydrogen can be swiftly utilized while sustaining a partial pressure conducive to acetone production by facilitating an exudative reaction, given the presence of atrophic hydrogen methanogens [22]

2.1.4. Methanogenesis

Methanogenesis is the final phase of anaerobic digestion, wherein methanogenic bacteria utilize available intermediates to produce methane [18]. Methanococcus voltae and Methanococcus vannellii cells were subjected to oxygen exposure for 10 hours. Subsequently, 99% of the cells had perished. Methanogenic bacteria are obligate anaerobes. Methanogenic bacteria are not only sensitive to oxygen but also limited to specific substrates. The synthesis of methanol, methylamine, and formate has also been documented [18]. Factors affecting the methanogenesis process encompass feedstock mix, feeding rate, temperature, and pH levels. Overloading the digester, fluctuations in temperature, or excessive oxygen influx can all lead to the termination of methane synthesis [19].

2.2.Anaerobic digester parameters

AD microorganisms exhibit sensitivity to various process conditions. Key process parameters include temperature, pH, organic loading rate (OLR), hydraulic retention time (HRT), and C/N ratio, as illustrated in Figure 2. The optimization of feedstock qualities and environmental conditions governs the efficiency and velocity of the digestion process [8] .

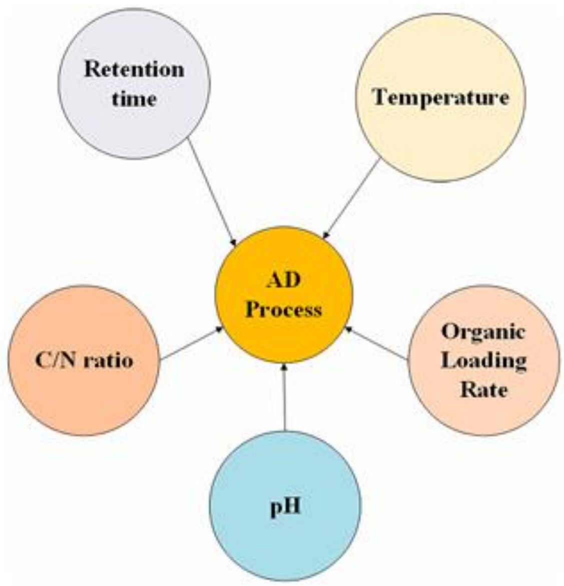

Figure 2: Important anaerobic digestion process parameters [8].

2.2.1. Temperature

Two temperature ranges are generally recognized as optimal for the peak performance of anaerobic bacteria. Thermophilic digestion is characterized by a digestion temperature of 55–60 C°. Thermophilic digestion necessitates further energy (heat) input however yields an elevated biogas generation rate [8]. Temperature stability is essential for Alzheimer's disease. The operational temperature is determined based on the feedstock, and the necessary process temperature is often provided by floor or wall heating systems within the digester[23]. The selection and regulation of temperature are vital as they influence microbial activity during anaerobic digestion (AD). AD can be conducted within three distinct temperature ranges: psychrophilic (25 C°), thermophilic (about 55 C°), and mesophilic (approximately 35 C°) [24] . Generally, it has been observed that thermophilic temperatures enhance the acceleration of endergonic metabolic reactions more effectively than mesophilic temperature conditions [24]. Temperature influences the duration of the fermentation process. The methanogenic bacteria involved in biogas production exhibit significant sensitivity to temperature variations, with their best functioning range between 33 and 38C°. Biogas production is inhibited below this temperature, while temperatures beyond it result in the destruction of the microorganisms responsible for biogas generation. Consequently, the infrastructure employed for biogas production is generally constructed subterraneously to ensure a stable temperature. Nevertheless, abrupt temperature elevations should be circumvented, since they may diminish bio-methane production by inducing detrimental alterations. To ensure a stable temperature during biomethane production studies, submerge the reactors in a water bath or position them in a temperature-controlled environment equipped with a thermostat for accurate regulation [25], Figure 3 below illustrates the impact of temperature on biogas production:

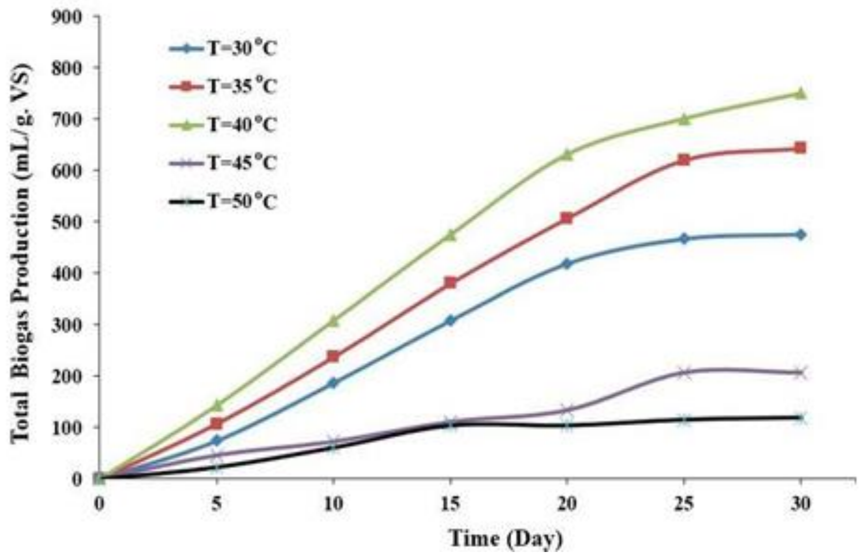

Figure (3) Effect of temperature on biogas production rate[25]

2.2.2. pH

The pH indicates the concentration of hydrogen ions in a solution. The majority of bacteria favor a neutral pH range. Methanogens are highly sensitive to pH and exhibit optimal function at approximately seven. Hydrolytic and acidogenic bacteria exhibit optimal performance within pH ranges of 5.5 to 6.5. Conversely, acidogenic bacteria have greater tolerance to an extensive pH range [26]. Ensuring an optimal pH for all microorganisms within a single digester is difficult, particularly for substrates with diverse compositions such as sewage sludge [8]. Empirical evidence indicates that methane production transpires within a limited pH range of approximately 5.5 to 8.5, with the majority of methanogens favoring a pH interval of 7.0 to 8.0. Acidogenic bacteria generally possess a reduced optimum pH value. The optimal pH range for mesophilic digestion is 6.5 to 8.0, and the process is significantly impeded if the pH drops below 6.0 or exceeds 8.3 [19]. $NaHCO_3$ is recognized as a highly effective VFA controller relative to other neutralizers, frequently attaining efficacy with a single application and sustaining a pH of 8.5 [27]. Conversely, independent research has shown positive outcomes from utilizing sodium bicarbonate to maintain pH levels within the optimal range of 6.5–7.5. This has resulted in enhanced methane production during anaerobic digestion [28]. Figure (4) below illustrates the impact of pH on biogas production:

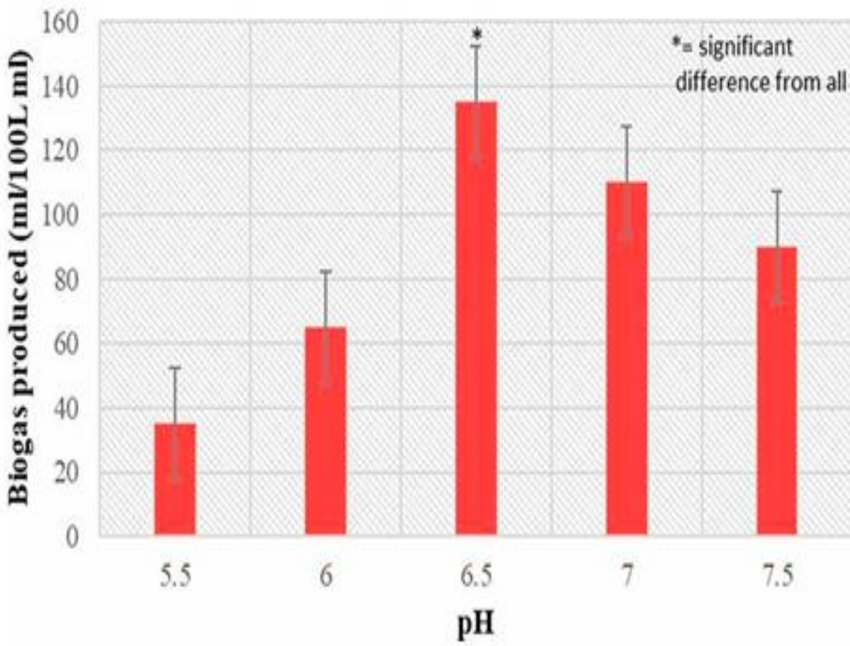

Figure (4) pH effect on biogas production [28]

2.2.3. Hydraulic Retention Time (HRT)

The hydraulic retention time (HRT) is a crucial parameter in the construction of a biogas digester [19]. This is the mean duration that organic matter persists in the digester. It is a crucial element in anaerobic digestion systems that strongly influences microbial ecology and features [29] . This metric primarily relies on the degrading capability of the microorganisms [30], This is contingent upon the type and quantity of substrate incorporated [30]. Insufficient hormone replacement therapy manifests in the following manner: In continuous anaerobic digestion, the introduction of feedstock is succeeded by the extraction of digestate; nevertheless, this procedure also results in the elimination of active microbial populations (washout) [30]. Anaerobic bacteria generally replicate every 10 days or longer. A brief HRT facilitates an increased substrate flow rate but results in a diminished gas production. Consequently, it is essential to customize the HRT to the particular breakdown rate of the employed substrates. The necessary digester volume can be determined by utilizing the desired hydraulic retention time (HRT), the daily feedstock intake, and the substrate decomposition rate [19]. as shown in the equation below:

$$HRT = V / V \quad (d) \qquad (1)$$

Where (VR) denotes the reactor volume (m^3), and (V) represents the substrate volumetric feed rate in the reactor, expressed daily ($m^3 d^{-1}$). Various hormone replacement therapies (HRT) were assessed through published studies to determine the optimal value for diverse substrates. The duration of the HRT ranges from 0.75 to 60.00 days. Some studies indicate that the optimal period of hormone replacement therapy (HRT) should range from 16 to 60 days. HRT must be maintained between 10 to 25 days to prevent the washout of microorganisms essential for the procedure. In various hormone replacement therapies, [31] utilized aquatic waste as anaerobic digestion substrate (10, 20, and 30).

2.2.4. Carbon/nitrogen (C/N) ratio

The carbon-to-nitrogen (C/N) ratio is a critical element in the design of an effective anaerobic digestion (AD) system. Substrates with an excessively low C/N ratio might generate byproducts that impede the anaerobic digestion system, whereas a high ratio may result in insufficient nitrogen for the vitality of microbial biomass [32]. A low C/N ratio indicates a higher nitrogen concentration, which will ultimately result in excess ammonia. Excess ammonia elevates digester alkalinity and impedes the digestion process, leading to less biogas production [8].

2.2.5 OLR (Organic loading rate)

OLR refers to the quantity of organic material per unit volume of the reactor undergoing anaerobic digestion within a defined time period [33]. Prior studies have demonstrated that the implemented OLR significantly affects biogas production [34]. The design and operation of a biogas plant are determined by economic and technological considerations. To attain optimal biogas production via comprehensive substrate digestion, an extended retention period of the substrate within the digester and a proportionately large digester volume are necessary. The selection of system design (digester size and type) or appropriate retention time is fundamentally a compromise between optimizing biogas production and ensuring economic viability of the plant [19]. The OLR must be determined according to the feed substrate to optimize conditions for the specific biogas facility [35], The equation of OLR is presented below:

$$OLR = m * C / VR * 100 \ (kg\ oDM\ m^{-3}\ d^{-1}) \quad (2)$$

(m) represents the substrate quantity supplied per unit time (kgd^{-1}), (c) denotes the concentration of dry organic matter (% ODM), and (VR) signifies the reactor volume (m^3).

2.2.6 Effects of Oxygen in AD

In anaerobic digesters, it is not unusual for oxygen to inadvertently infiltrate the system, primarily due to the operation of reactors in an aerobic, open atmosphere, especially during feeding and mixing procedures [36]. Consequently, the majority of anaerobic digesters undergo sporadic and fluctuating exposure to aerobic conditions. The possible effects of such aeration have not been thoroughly evaluated, yet it is widely recognized that oxygen may operate as a toxic and inhibitory agent in Alzheimer's disease [37]. Particularly for strictly anaerobic microbes such as acetogens and methanogens [38]. Moreover, aerobic respiration can result in the transformation of soluble organic molecules into CO_2. Consequently, oxygen in anaerobic digesters has been linked to reactor instabilities, protracted start-ups, diminished methane production, and potential full failure of the digestion process, as illustrated in figure (5)[39].

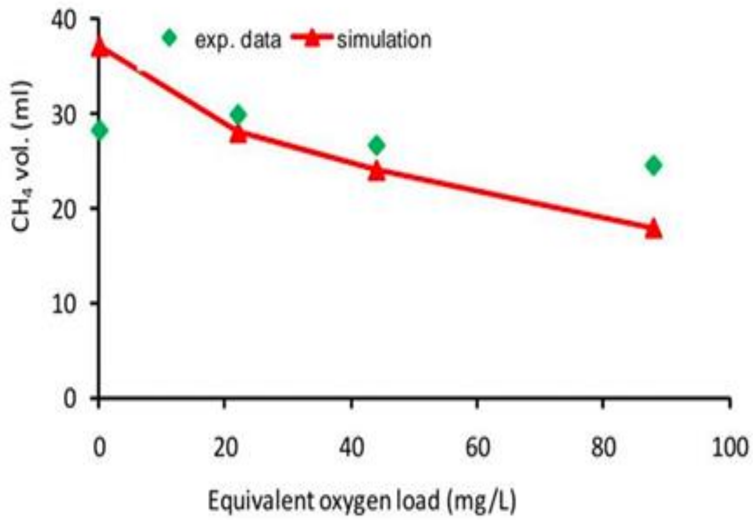

Figure (5) Effect of oxygen in the anaerobic digestion system [39]**.**

2.2.7 Mixing

The anaerobic process in the biogas facility is significantly affected by the agitation mechanism. The principal duties of the agitation system are:

a. Combining fresh and old media maintains the digester's biodegradable media, temperature, and pH levels consistently.

b. Minimize sediment accumulation at the base of the digester to optimize the volume available for anaerobic digestion and decrease the frequency of septic tank maintenance, typically conducted every 4 to 7 years [18, 40].

c. Enhance the stability of anaerobic processes and microbial metabolism. Moreover, at elevated total solids concentrations, the mixture facilitates the ascent of air bubbles from the biodegradable feedstock [18, 41].

d. Detach the foam backing from biodegradable substrates. The development of this layer may inhibit 20-50% of biogas production [18, 42]. Foam typically consists of gas dispersed within a liquid that contains a substantial proportion of gas (about 95%). Between the bubbles lies a thin film comprising the liquid phase [18, 42].

The primary mixing techniques employed in large-scale biogas generation technology are mixing methods. Biogas plants can function with or without mixing, depending on the structural concept of the digester (full mixing, nodal flow, or discontinuous concept). Plug-in flow digesters are appropriate for a range of 11% to 13%, whereas full mixed digesters are typically employed for biogas systems utilizing biodegradable substrates with total solids of 2% to 10% [18, 42].

3. Types of Anaerobic Digesters Plants

All Active Directory systems possess identical fundamental functionalities. The design may differ significantly according on location, raw material source, climate, and the intended reactor application, including the reduction of organic loads, energy generation, or bacterial concentrations [43]. The primary categories of these systems include passive, low-flow, and high-flow systems. This section examines various types of digesters and their practical applications.

3.1. Passive System

A facility that combines a biogas recovery unit with an existing manure or waste digester is referred to as a passive system. This system seldom necessitates supplementary heating or mixing. Functioning within psychrophilic and mesophilic temperature ranges, temperature parameters frequently display seasonal variations. These units are typically located in warm regions, as methane output declines below 20C°. A covered lagoon digester exemplifies a passive system.

3.1.1. Covered Lagoon Digester

Covered lagoons represent the simplest form of anaerobic digester technology, wherein feedstocks are contained within an underground lagoon and sealed with a gas-tight flexible cover, as illustrated in Figure 6. Lagoons function concurrently as reservoirs and reactors. A covered lagoon may comprise two interconnected lagoons arranged in sequence. The initial cell (cell 1) functions as the digester for biogas generation. The second cell (cell 2) contains the digester effluent for subsequent processing [8], These digesters are optimally designed for warmer places where the ambient temperature meets the necessary digestion temperature requirements. Feedstocks with a low solid content (0.5–2%) are ideal for this type of digester because they provide the efficient and cost-effective management of bigger quantities. The standard duration of HRT is 30 to 45 days. It is frequently essential to filter larger solid particles from the feedstock to avert the formation of a crust on the lagoon surface, hence enhancing biogas production efficiency.

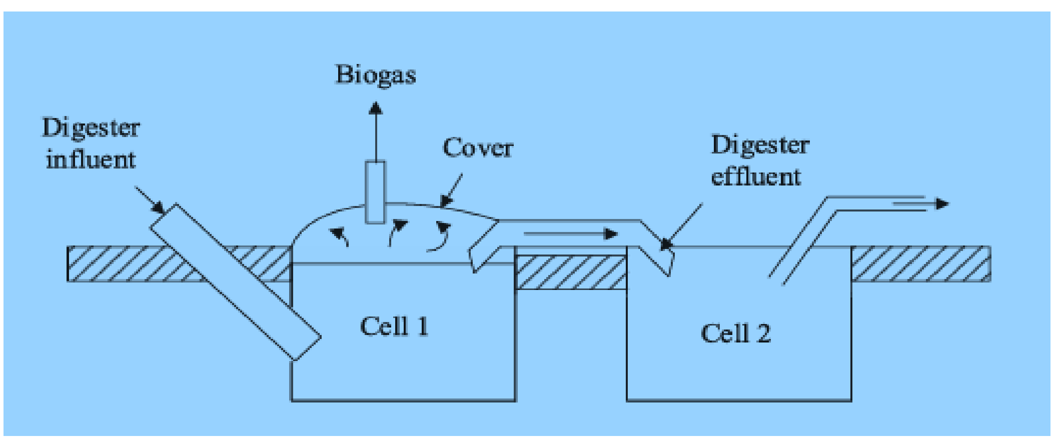

Figure 6: Schematic diagram of a covered lagoon digester [8].

3.2. Low-Rate Systems

A low-throughput system retains feedstock in the digester for extended durations (typically 10-30 days) to enhance biogas production. These devices operate within thermophilic temperature ranges of 25-40 degrees Celsius and 50-65 degrees Celsius. Nevertheless, more heating is required to sustain the appropriate temperature, often implemented using a heat exchanger [44]. The thermophilic temperature range is typically selected for farming, unless manure requires pasteurization to diminish bacterial levels [18]. In contrast to thermophilic systems, mesophilic systems frequently offer sufficient attenuation with reduced energy use [18]. This discussion encompasses three low flow systems: garage-type, plug-flow, and full-mix.

3.2.1. Garage-type digester

This procedure involves a tank containing percolation fluid. The percolation fluid contains microorganisms that multiply due to the interaction between the feedstock and microbial communities during anaerobic digestion. The digester design is akin to that of a garage, enabling the batch-wise addition or removal of feedstock [45]. The digester is designed akin to a compact garage, facilitating the incremental addition or removal of raw materials. The raw material is digested prior to each feeding cycle to optimize the condition of pathogenic bacteria, hence accelerating the warming process, as illustrated in Fig. 7 [18, 46]. Temperatures in the garage-style digesters are regulated by an integrated system that heats the walls and flooring. It enables them to function within the thermophilic range [18]. The treatment of material flow with a high total solids (TS) ratio (TS > 15%) is appropriate for these types of digesters. Garage-type digesters may accommodate materials with elevated contamination levels, as there is no requirement for material mixing. The obstruction of pumps and agitators by these impurities can adversely affect other digesters.

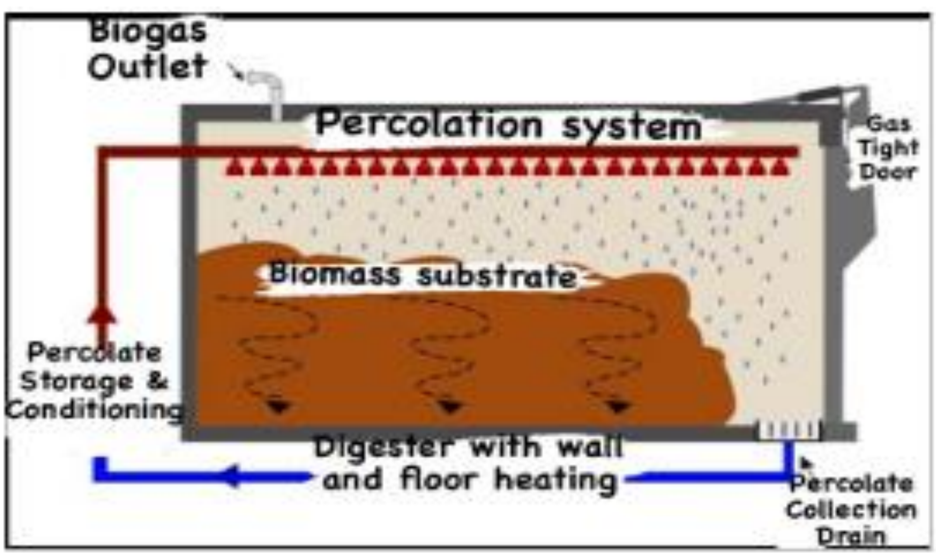

Figure 7. Schematic drawing of a garage-type digester [18, 46]

3.2.2. Plug-flow digester

Plug flow digesters operate in a manner akin to complete mix digesters, with the distinction being the feedstock lacks mechanical mixing [8]. Plug flow digesters are often subterranean and equipped with a flexible canopy. The solid content of the feedstock must be elevated (<10–15%) to facilitate fluid circulation within the reactor[8]. The demand for mixing in a flow digester, characterized by a rectangular tank where the substrate is continuously exchanged in a horizontal motion, is no longer necessary (Fig. 8). An equivalent quantity of aged material introduced into the digester is substituted by fresh material expelled from the discharge point [18, 47]. An equivalent quantity of aged material introduced into the digester is substituted by fresh material expelled from the discharge point [42]. Consequently, to guarantee that all substrates have an identical hydraulic retention time with the arrival of fresh feed material, it propels the material through the digester like to a "button," compelling the oldest material to be expelled. Biogas is gathered using an external, extendable gas collector affixed to the roof of the digester [18].

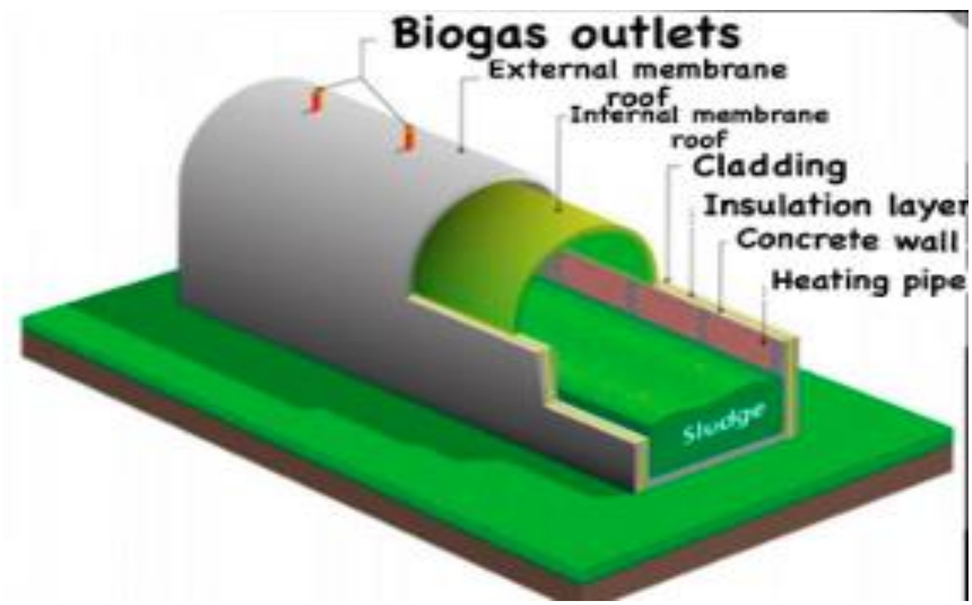

Figure 8. Diagram of plug-flow digester [18, 47].

3.2.3. Complete mix digester

A total mix digester is essentially a tank where dung is heated and combined with a dynamic population of microorganisms. The incoming liquid displaces a volume in the digester, resulting in an equivalent volume of liquid exiting. Methanogens exit the digester along with the displaced liquid [48]. Complete mix digesters operate optimally when manure comprises 3 percent to 6 percent solids. The size of the digester may pose a challenge with reduced solids concentrations.

Reduced solids result in increased volume, necessitating a larger digester to maintain microorganisms for a duration of 20 to 30 days [48]. The fundamental element of the master mix digester is the continuously stirred tank reactor (CSTR), a circular, insulated vessel constructed from reinforced concrete or heated steel. The components of the digester are subsequently blended to generate active microbiomass (Fig. 9) [18, 49]. The completely mixed digester is capable of processing a diverse array of wastes, encompassing total solids concentrations of 3–10%, dairy cow manure, processing byproducts, and pig manure. To keep the solids suspended, their agents in the reaction tank may be agitated either intermittently or continuously. Examples of mixing systems include mechanical rotors, liquid circulation, and gas circulation [18]. Employing a two-phase configuration rather than a single-phase system can enhance the efficacy of a fully mixed digester [18]. In this configuration, bacterial fermentation decomposes raw materials in the initial stage, while methanogens convert organic acids into biogas in the subsequent stage [18].

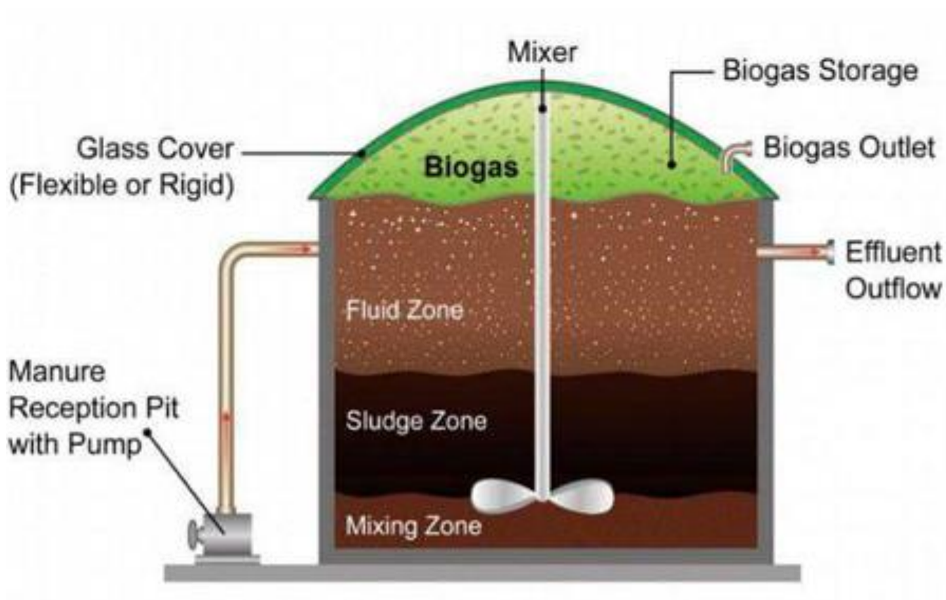

Figure 9. Schematic drawing of a fully mixed digester [18, 49]

3.3. High-Rate Systems

Systems with elevated rates exhibit distinct characteristics by efficiently segregating the low-energy-density fraction of the entering liquid, which remains in the digester for a brief duration, while the solids are kept for an extended period [50]. A greater density of microorganisms can be accommodated in the reactor per unit volume, hence decreasing the retention time to 10 days. The retention of methanogenic bacteria yields enhanced biogas production and diminished reactor area requirements [18]. Two conventional high-throughput systems are integrated film reactors and fixed membrane disruptors.

3.3.1. Fixed film digester

This digester design facilitates microbial proliferation as a thin film on the surface, commonly referred to as a biofilm [8].

In this digester, methanogenic bacteria proliferate on substrates such as wood chips or small plastic rings within a digestion column. These digesters are also referred to as Attached Growth Digesters or Anaerobic Filters [48]. This approach decreases the hydraulic retention time (HRT) while producing an adequate quantity of biogas. Once the requisite AD microbiota was immobilized as a biofilm, the slower-growing cells were safeguarded against washout, resulting in a biomass retention time independent of hydraulic retention. The reactor's augmented microbial biomass per unit volume facilitates reduced hydraulic retention times, typically ranging from 2 to 6 days. The primary drawback of stationary membrane digesters is the potential for medium clogging resulting from the elevated solids concentration in the input material [18]. The solid separator influences the digester's efficiency; therefore, the inflow concentration should be adjusted to optimize the separator's performance, typically at 15% total solids (TS). A portion of potential biogas production is squandered due to the necessity of removing carbon-rich particles to meet size specifications. The compact dimensions of fixed membrane digesters provide a notable benefit over conventional digesters when space is limited, as illustrated in Fig 10 [18, 51].

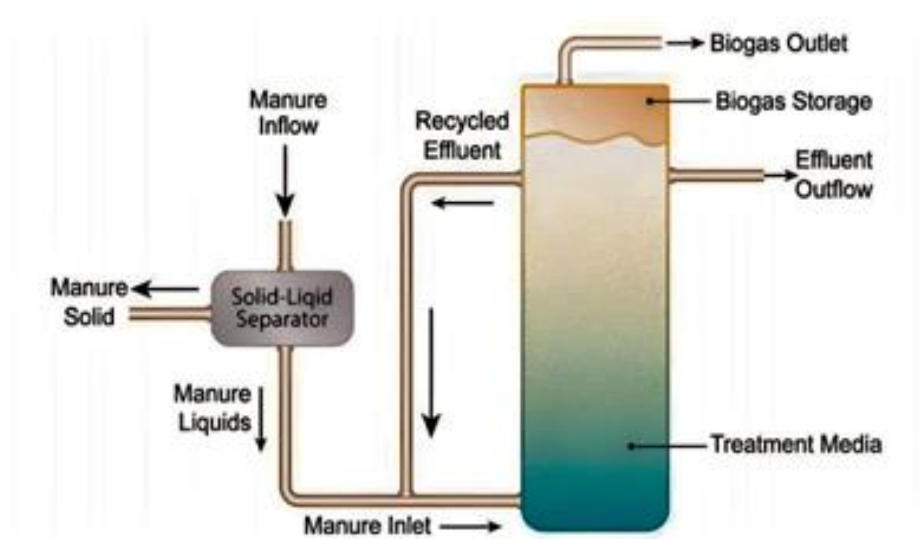

Figure 10. Schematic drawing of fixed film digester [18, 51]

3.3.2. Suspended media digesters

In these digesters, microorganisms are maintained in a continuous upward flow of liquid. The flow is modified to permit the expulsion of smaller particles while retaining larger ones within the digester. Microorganisms establish biofilms around bigger particles, while methanogens remain within the digester. Effluent is occasionally repurposed to ensure a consistent upward flow [48]. Smaller particles are removed by the constant upward liquid flow of the suspended media digester, but bigger particles are retained within the digester (shown in Fig. 11) [18, 47]. Microorganisms form biofilms around bigger particles, so augmenting the concentration of methanogens in the reactor [18, 49]. Upflow anaerobic sludge beds (UASB) and inductive media digesters are the predominant types of sludge media digesters, with the primary distinction being the dry matter content of the raw materials utilized. Medium-induction reactors are optimal for highly concentrated waste streams (6-12% TS), whereas UASB systems are better appropriate for dilute effluents (3% TS).

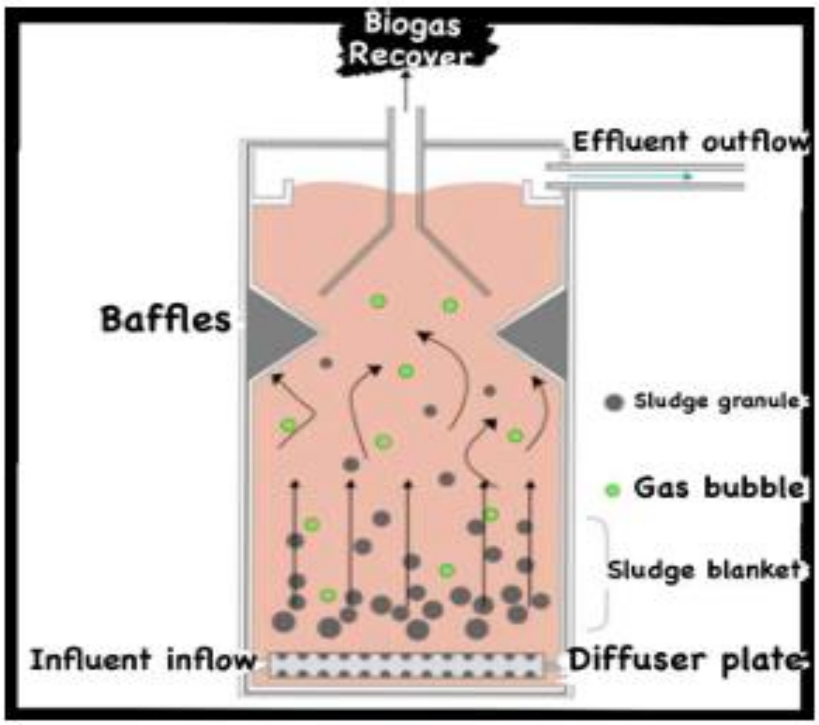

Figure 11. Schematic drawing of the suspended media digester [18, 47]

4. Challenges Affecting Anaerobic Digestion

The low carbon-nitrogen (C/N) ratio in FDE has been recognized as a significant obstacle to the anaerobic digestion (AD) process. Farm dairy effluent possesses an average carbon-to-nitrogen (C/N) ratio of 9:1, well below the optimal range of 15:1 to 45:1[52, 53]. The compounds ultimately enter the wastewater and may adversely affect the anaerobic digestion system [52, 53]. The component restricts hydrolysis, leading to insufficient degradation and minimal methane generation. An novel approach to addressing this issue is the incorporation of additives [53, 54]. Additives have garnered significant study interest recently [53-55]. They have demonstrated encouraging potential for full-scale implementation. Common additives comprise direct interspecies electron transfer (DIET) materials, including activated carbon, biochar, hydrochar, carbon fiber, and neutral red [53, 54]. These materials facilitate electron transfer through direct interspecies interactions and enhance biodegradability via adsorption capacity. Additives are said to enhance both the quality and quantity of gas [53, 56], Utilized neutral red (phenazine) and charcoal in the anaerobic digestion of landfill trash, resulting in enhanced methane production potential by 34% and 18%, respectively. Temperature is Mesophilic anaerobic digestion (MAD) and thermophilic anaerobic digestion (TAD) are the predominant methods for biogas production, attributed to their accelerated metabolic rates and enhanced organic loading capacities [53]. The co-digestion of food waste with manure, sewage sludge, and lignocellulosic biomass may be advantageous due to the dilution of harmful substances, improved nutrient balance, and synergistic interactions among microorganisms [57]. The augmented biogas yields indicate enhanced financial viability. Co-digestion of garbage is a prevalent practice in Europe [58], and may be implemented in dairy farms seeking to embrace anaerobic digestion technology. Biogas generated in the digester. During foaming, the biogas generated is not emitted into the gas phase but rather disseminated within the liquid [18, 58]. Essential trace elements encompass nickel (Ni), cobalt (Co), molybdenum (Mo), iron (Fe), and selenium (Se) for methanogens, as well as zinc (Zn), copper (Cu), and manganese (Mn) for hydrolytic bacteria [18, 59] .Enhancing digester designs and operational procedures is a crucial factor in improving the organic loading rate, methane yield, and stability of anaerobic digestion systems utilizing food waste [18, 59].

5.Inhibition of Anaerobic Digestion

1. Toxic substances: Sulfates and other sulfur oxides are readily converted to sulfides during anaerobic digestion. When soluble sulfide attains a specific concentration, the aerobic digestion process is mostly driven by methane generation [18].
2. The inclusion of more ions, such as Mg^{2+}, Na^{+}, and Ca^{2+}, leads to a reduction in the toxicity of these ions [18, 60].

   Furthermore, additional inhibitors of AD, including temperature and pH, are referenced in sections (4.3) and (5.2) above.

6. Agricultural waste

Agricultural wastes include the byproducts generated throughout several agricultural operations and processes [61]. Although these waste compounds derive from natural sources and typically exhibit low environmental toxicity, their substantial accumulation can adversely affect the health of humans, plants, and animals [62]. Agricultural waste refers to refuse generated at farming locations as a result of agricultural activities. An agricultural facility generates a diverse array of waste during standard operations. These are the liquid or solid leftovers of agricultural activities, including animal waste, crop residues (such as maize stalks), insecticides, and fertilizers [18, 63]. The categorization of agricultural waste essentially encompasses four principal types: agro-industrial waste, livestock waste, crop residue, and aquacultural waste (as depicted in Fig. 14)[64, 65]. Agro-waste predominantly consists of cellulose, lignocellulosic substances, hemicelluloses, pectin, and lignin. The cellulose concentration in agro-waste varies between 30% and 40%, hemicellulose between 30% and 50%, and lignin between 8% and 21%. The nutrient composition of crop residue (CR) exhibits fluctuations in nitrogen concentration ranging from 0.30% to 3.0%, phosphorus content from 0.60% to 0.70%, and potassium content from 0.70% to 3.5%, contingent upon the types and species of plants [61]. Agricultural waste has garnered increased attention due to its potential significant impact on the ecology. Nonetheless, it can also be employed for other beneficial applications, such as fuel for energy generation [18]. This phenomenon is especially evident in certain nations, such as India, which possesses a substantial cattle sector and an annual growth rate of 6%. The efficient use of byproducts directly influences the economic and environmental harm to the nation. Inadequate utilization or neglect of byproducts leads to lost income opportunities and elevated expenses for their disposal. In prosperous nations, the majority of animal agriculture waste comprises pig excrement, however in several underdeveloped countries, especially in Southeast Asia, cow manure predominates [18].

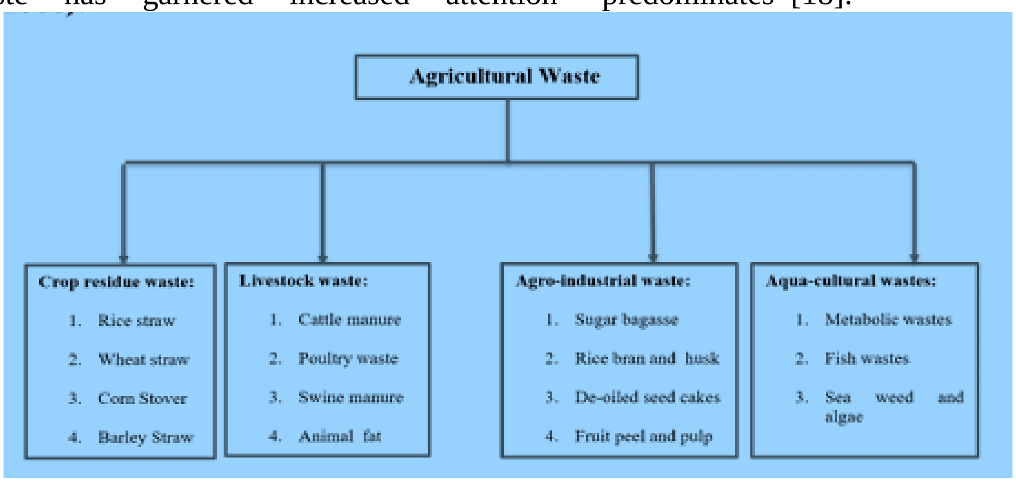

Figure (14) Agricultural waste categories [64, 65]**.**

6.1. Crops Waste Digestion

Anaerobic biodegradation is most pronounced for inedible crop residues from food crops (including leaves and plant waste) and residues from energy-specific crops (such as maize, tubers, cabbage, and wheat). Cell walls and their primary constituents, such as lignocellulosic materials, cellulose, hemicellulose, and lignin, constitute the majority of plant biomass. Cellulose is a linear polysaccharide polymer composed of glucose units linked by 1,4-glycosidic bonds [18]. Corn stalks are the most prevalent agricultural residue, producing about 750 million tons annually, followed by rice and wheat with annual outputs of 600 million and 360 million tons, respectively [66]. Chemically, crop leftovers often contain about 0.6 to 1% nitrogen, 14 to 23% potassium, and 40 to 45% carbon, in addition to vital components such as phosphate and micronutrients required for plant growth [67].

6.2. Fruits and Vegetables Waste Digestion

Fruit and vegetable waste is very conducive to energy recovery by anaerobic digestion due to its elevated moisture content (>80%), substantial organic composition (volatile solids exceeding 95% of total solids), and quick biodegradability [18, 63]. Organic waste from fruits and vegetables decomposes rapidly and is often co-digested with other feedstocks.

6.3. Livestock Waste Digestion

Livestock waste consists of several components, including liquid manure, wastewater, and solid manure from multiple farm animals. The agricultural industry in Europe produces around 1,500 million tons of animal manure each year, creating an extra possibility for activated carbon generation [68]. This type of waste originates from cellulosic feed and the undigested byproducts excreted by animals, making it a sustainable and renewable resource. Animal manure, owing to its organic composition and high carbon content, can be subjected to thermal conversion or further processing, leading to the production of diverse carbon compounds. This attribute indicates the possibility of animal dung to serve as an energy source [69].

7. Advantages of Biogas

The benefits of biogas can be summed up like this: [70, 71]:

1. **Non-polluting:** Biogas is regarded as non-polluting in nature. Biogas generation is anaerobic, hence conserving resources by eliminating the need for supplementary fuel. Moreover, it mitigates indoor air pollution of all types and curtails deforestation.
2. **Biogas is a renewable energy source:** The only way to run out of biogas is to stop all actions that make waste. It gives off free energy as well.
3. **Because it also uses trash from dumps:** It cuts down on pollution from oil and water.
4. **A lot of jobs are found:** The process of building biogas plants creates a lot of jobs. These jobs are great for people who live in remote places.
5. **Use cheaper technology:** Biogas is being used in more places because biogas-using technology is getting better. In addition to making power, biogas can also be used to heat homes. Biogas, which is compressed natural gas (CNG), is also used in cars.
6. **It lowers the greenhouse effect:** Biogas made from waste gases lowers the greenhouse effect. It's a source of power. Making biogas is easy and most of the garbage that goes into it breaks down naturally, so it is becoming a more valuable resource.
7. **Not much money is needed:** A small-scale biogas plant can be set up quickly and cheaply. Farmers can take care of themselves if they use the trash that their animals make to make biogas for the farm.

8. Disadvantages of Biogas

The following is a summary of biogas' drawbacks :[72, 73]

1. **Composed of impurities:** Despite undergoing numerous refining operations, biogas retains various pollutants. Utilizing this impurity-laden

biogas as fuel post-compression may result in the corrosion of engine metals.

2. **Limited technological advancements:** Due to the scarcity of technical innovations implemented to optimize and decrease process costs, the existing systems are inefficient. Consequently, neither large-scale industrial biogas generation nor its depiction on the energy map is exhibited. Investing in biogas generation may alleviate certain current challenges.
3. **Biogas is intrinsically volatile:** It becomes combustible when methane interacts with oxygen. This occurs due to the instability of biogas, rendering it explosive and contributing to waste management challenges.
4. **Large-scale biogas production is economically unviable:** Enhancing the efficiency of biogas systems is likewise a formidable challenge.

9. Future Perspectives

Future trends in anaerobic digestion will concentrate on increasing methane yield, process stability and economic feasibility through technology innovation and process optimization. The advanced pretreatment technologies, such as mechanical, thermal, chemical and biological methods are likely to play a key role in improving the biodegradability of the lignocellulosic agricultural residues and enhancing the efficiency of biogas production.

The use of co-digestion techniques with various types of organic substrates is expected to enhance the nutrient balance, alleviate process inhibition and boost methane production. Furthermore, the application of artificial intelligence, machine learning and real-time monitoring systems may allow for more precise control of the process and predictive management of anaerobic digesters. Future studies should be directed to design high-efficient microbial consortia, bioaugmentation techniques, and new reactor designs that can work under different environmental conditions. Moreover, the upgrading of biogas to biomethane quality and the integration of anaerobic digestion systems into circular bioeconomy schemes will improve their role in sustainable energy production and greenhouse gas reduction . The successful use of these advances will strengthen the position of anaerobic digestion as a leading technology for renewable energy generation, sustainable waste management and global climate change mitigation.

Further studies are necessary to assess the technological and economic viability and life-cycle environmental effects of emerging anaerobic digestion technologies under real-scale functioning conditions.

10. Conclusion

Anaerobic digestion is a mature and effective technology for the conversion of organic wastes to renewable energy along with solving the problems of environmental pollution and waste management. The results reported in this review reveal that the efficiency of biogas production is greatly affected by operational parameters, substrate properties, digester design and microbial activity. Process performance has been substantially improved by recent technological developments, including improved reactor configurations, optimized operating conditions and advanced monitoring methods.

However, challenges such as process inhibition, feedstock variability, high initial investment costs, and operational complexities still hinder the widespread implementation of anaerobic digestion systems . Agricultural wastes are still among the most promising feedstocks due to their wide availability and considerable biogas potential. Utilization of suitable pretreatment techniques and co-digestion strategies can further improve methane yield and the overall system efficiency.

In conclusion, anaerobic digestion is a key component in the transition toward sustainable energy systems and circular bioeconomy models. Continued research and technological innovation are needed to overcome the existing limitations, improve the stability of the process and the economic feasibility of biogas production. The combination of advanced digestion technologies with sustainable waste management strategies will make a significant contribution to global energy security, environmental protection and greenhouse gas mitigation initiatives.

Author Contribution Statement

Ahmed Hameed Mohammed is a master's student, while Sroor Atallah Khalifa and Salam Salman Chiad Alharishawi act as thesis supervisors.

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