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Review on Comparison of Single Stage and Multistage and Dry-Wet Anaerobic Digestion for Biomethane Production and Evaluation the Waste Management Strategy

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Abstract

The circular bioeconomy depends on anaerobic digestion technology to obtain energy from waste materials while minimizing ecological contamination. The research looks at how well single-stage and multi-stage anaerobic digestion systems work, comparing their advantages and disadvantages by examining design elements, stability conditions, and the amount of biogas produced from different types of feedstocks. A comparison study evaluated the benefits together with restrictive factors and real-world uses of single-stage and multi-stage anaerobic digestion systems. The examination used microbial stability as well as biogas production rates, cost-effectiveness, and compatibility with various feedstocks to determine the various factors. Single-stage anaerobic digestion systems produced cost-effective operation along with simple management, which benefits small-scale facilities operating on uniform organic waste. Their microbial stability was restricted, which eventually led to diminished biogas production output. Multi-stage anaerobic digestion systems are more expensive to set up and keep running, but they allow for better control of the process and produce more biogas when dealing with a mix of agricultural waste and regular trash. System design stands as a fundamental element that determines the results of anaerobic digestion processes. The selection between single-stage or multi-stage systems depends on whether waste streams are simple and uniform or complex. Future development of anaerobic digestion technology requires concentration on lowering operating expenses along with the implementation of time-sensitive monitoring equipment and integration with clean energy facilities. The development of these steps represents fundamental requirements for establishing scalability of anaerobic digestion system as the primary waste management technology.

Keywords: Anaerobic digestion, single and multi-stage, dry and wet, hydrolysis, acidogenesis.

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Introduction

Anaerobic digestion (AD) functions as an essential waste management technology which produces renewable biomethane specifically from organic matter. The biogas production process requires microorganism consortiums to break down organic materials without oxygen while producing a gas combination primarily containing CH4 and CO2. AD fits global sustainability goals which aim for renewable energy development and greenhouse gas reduction so it represents an appealing solution for transforming organic waste into energy. The need to optimize AD system efficiency grows stronger because of escalating worldwide energy requirements and worsening environmental conditions. Various industrial sectors together with agriculture and municipal waste management utilize this process in their operations. Organic waste from agricultural, municipal and industrial sources can successfully pass through AD systems for biogas creation followed by biomethane development as renewable fuel. Biofertilizer properties of residual digestate from AD operations create value in the circular economy through nutrient delivery to soil systems (Al-Wahaibi et al., 2020).

The operational efficiency together with scalability of AD systems depends significantly on how designers configure the systems. Different configurations of AD systems fall under two main categories as single-stage and multi-stage systems that additionally include classifications of dry or wet digestion options. Various operational characteristics including processing methods and scalability occur in each configuration which determines their performance for different organic feedstocks. Single-stage AD systems process all biological functions in one reactor because they cost less to maintain while being easy to operate but this setup does not guarantee optimal biochemical conditions. Multi-stage systems build multiple reactors to divide hydrolysis from acidogenesis alongside methanogenesis which results in enhanced process control though it adds operational complexity together with high initial costs. Similarly, dry and wet anaerobic digestion configurations impact system performance and resource utilization. The dry AD system performs best with solid organic waste materials because it needs minimal water while producing optimal methane outputs. The implementation of dry and wet anaerobic digestion schemes requires specialized equipment alongside management obstacles which make continuous operation less straightforward. The wet AD process handles materials which have lower total solids such as wastewater sludge and manure but it enables better microbial function and mixability. Wet digestion process uses larger amounts of water and produces higher leachate quantities while needing extra energy for agitation mechanisms and pumping systems (Chua et al., 2013).

Single-stage AD systems experience widespread adoption because of their basic design yet they maintain limited stability when processing various organic waste streams. Methane production suffers from negative consequences when hydrolysis and acidogenesis and acetogenesis and methanogenesis run together within one reactor because of pH imbalances and volatile fatty acid accumulation. The simultaneous use of different microbial communities occurs through multi-stage AD systems since each stage operates separately which stabilizes the process conditions across digestion Better operational control through this method enhances the effectiveness of running the system but its increased set-up and maintenance costs become economic hurdles. The analysis between dry and wet digestion reveals how operational needs meet resource utilization requirements. The method proves beneficial by minimizing water requirements and allowing organizations to accept larger organic material inputs without limitations as it suits dry regions lacking sufficient water access. Dry ad works with enhanced concentrations to produce greater methane yields from each processed volume, increasing system- wide energy efficiency.

High-solid feedstocks need proper mixing equipment combined with specialized systems to stop clogging while keeping microbial activity uniform throughout the process. Wet AD operation provides better handling and mixing effectiveness because of its low solids content yet requires increased energy for heating as well as pumping systems and leachate control.AD configurations need to ensure both environmental sustainability alongside economic sustainability alongside operational efficiencies. Process stability along with superior methane production comes at the expense of elevated initial expenses and elevated operational expenses from multi-stage systems. The application of dry digestion repairs water requirements but requires sophisticated mechanical equipment for its implementation. Every AD installation requires a distinct configuration selection which must align with local feedstock availability together with predominant infrastructure and governing regulations. New improvements in AD technology implement pre-treatment methods along with co-digestion methods together with real-time monitoring systems to enhance process efficiency and financial viability while solving existing operational issues. The complete understanding of these system configurations becomes essential for both biomethane optimization and economical and sustainable AD operations. The research investigates how single-stage and multi-stage anaerobic digestion systems perform together with dry and wet digestion processes through an assessment of their energy efficiency and operational expenses and scalability and environmental effects. This paper examines both novel technologies and innovative methods which boost AD operational performance. Exploring this review will produce crucial knowledge needed to pick the suitable AD solution for waste management and energy sustainability.

This research examines the long-run sustainability of various AD systems by evaluating their greenhouse gas emissions reduction abilities and nutritional substance recovery outcomes together with their connexon to existing waste management structures. This study will advance optimized AD technology through system-specific deployment recommendations by analyzing both strengths and weaknesses of each method. The resulting data will enable policymakers together with engineers and industry stakeholders to develop anaerobic digestion as an essential element in their sustainable energy plans and environmental management systems (Cuetos et al., 2010).

2. Literature

2.1 Dry and Wet Anaerobic Digestion.

2.1.1 Dry Anaerobic Digestion

The two foremost strategies for biologically treating natural waste are dry and wet anaerobic digestion, each with unique houses and makes use of. The total solids content of dry anaerobic digestion is usually better than 20%. For strong natural waste, together with agricultural residues or the organic part of municipal stable waste, this approach is often employed. Compared to wet anaerobic digestion structures, dry anaerobic digestion. (DAD) structures have the advantage of requiring less water, generating less leachate, and handling better prices of organic loading. Research has proven that as compared to moist anaerobic digestion sludge's, dry anaerobic digestion sludge's show off higher specific methanogen interest (SMA) and higher methane production performance. This is primarily due to the fact hydrogen trophic methanogens are more sensitive to hydrogen partial stress and constrained hydrogen mass switch in DAD structures (IRENA et al., 2018).

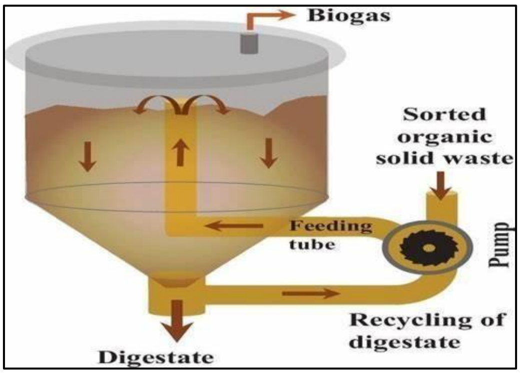

Figure 1. Solid State Anerobic Digestion : https://www.researchgate.net/figure/Schematics-of-DRANCO-solid-state-anaerobic-digestion-SSAD_fig4_361431588

- **Advantages**

1. The dry count number/general solids ratio is 20–40% as opposed to the maximum of 20% for wet digestion.
2. Less want for warmth and energy.
3. Extremely resilient to impurities. (Including sand, fibers, big particles and many others)
4. The capability of transportable biogas bin.
5. Overseeing more than one digester right away (Mohan & Jagadeesan, 2022).

- **Disadvantages**

1. Specialized technology is required for the digesters loading and unloading.
2. The want to manipulate how biogas and warmth production vary.
3. Not totally blended
4. In discontinuous structures, every batch calls for the microbial system to begin.
5. Lower methane yields oftentimes while compared to wet AD structures (Ojo, 2021).

2.1.2 Wet System

The overall solids content material (TSC) of wet anaerobic digestion (WAD) is less than 15%. Usually, its miles used to deal with liquid natural waste, like manure or wastewater sludge. Because the substrate is much less viscous, there may be progressed mixing and accelerated microbial activity on this technique. Wet systems require greater water and generate extra leachate, which calls for extra remedy, but they may be usually easier to hold and much less vulnerable to clogging. Continuous stirred-tank reactors (CSTRs) normally rent moist anaerobic digestion systems to make sure regular blending and powerful biogas production (Petersson et al., 2006).

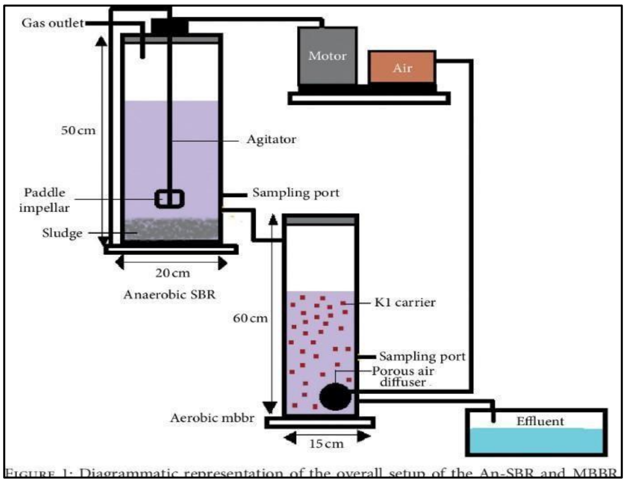

Figure 2. Wet State Anerobic Digestion: https://www.bing.com/images/search?view=detailV2&ccid=5S7AGvdJ&id=643B815C5C97CF77F64974FA3D75466D1C609F70&thid=OIP.5S7AGvdJnNq0iYakl8knBgHaGp&mediaurl

- **Advantages**

1. Greater adaptability within the substances that need to be processed.
2. Minimal operating and investment charges.
3. Biological desulfurization incorporated (Priadi et al., 2014).

- **Disadvantages**

1. To lessen the dry dependency content of the combination, liquid wishes to be delivered.
2. Desires a luxurious but dependable mixing gadget.
3. The facility wishes loads of electricity for its strolling agitators and pumps.
4. Decreased amount of dry remember inside the digestate.
5. Production of wet digestate, with the intention to need more investment and be capable of replace present day land application techniques (Riadi et al., 2020).

- **Comparison**

Table 2. 1. Comparison of dry wet AD

Comparison criteria	Wet digestion	Dry digestion
Input material	Max 20% dry matter	20%-40% dry matter
Water consumption	Dilution may be necessary	Percolate renewal
Process stability	Easier to intervene in the case of biological malfunction	Need to manage several digesters simultaneously
Heat need	20-30% heat produced	Lower need for thermal insulated installations
Power need	Pumps and mixers	low
Fuel need	None, except if dual fuel engines	None, expect of dual fuel engines
Digestate	Pumpable	Removed with loader
Man Power need	Possible automation	Important for loading unloading
Biogas production	Linear production	Not a linear production
security	Plant commissioning –high risk period	Loading/unloading –high risk period

2.2 Single and Multi-Stage AD

Although there are various varieties of anaerobic digestion structures in use, they all use the same biochemical procedures. Certain structures are easy to construct, run, and keep at a low cost; others, like multi-stage structures, are extra complicated and can require the use of sensors to assist alter the method as it actions alongside.

2.2.1 Single Stage

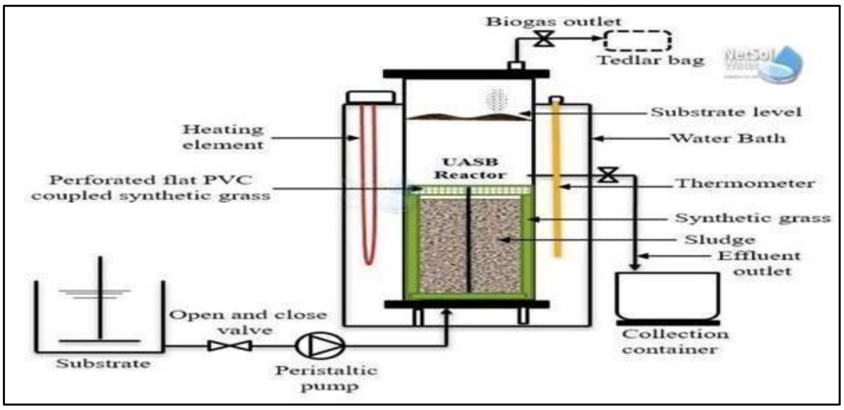

Figure 3. Single stage UASB reactor: https://www.netsolwater.com/design-procedure-for-uasb-reactor.php?blog=2361

All phases of anaerobic digestion in those sorts of digestion systems occur in a single reactor below identical running situation. They are simpler to create, gather, and run. A component of these digesters are batch systems, meaning that feedstock is installed and allowed to digest for a predetermined amount of time, known as the retention time. Following this period, the effluents are emptied and sparkling feedstock is delivered. Biogas production ceases all through the offloading and reloading segment until the new substrates start to produce biogas. Such structures are run in parallel whilst the production of biogas is required continuously, taking into consideration the exchange offloading and reloading of the biogas without experiencing any shortages. Some structures are non-stop unconnected structures that produce biogas, continuously evacuate effluent, and continuously feed rectors. It is important to use warning while the usage of the ones digesters to make sure that the state-of-the-art substrates are loaded on the proper charge. If not, the digestion environment will flip acidic, that could have an unfavorable effect at the degree of methanogenesis (Sankina et al., 2017). In addition, control over the offloading charge is essential to avoid disposing of any remaining substrate or living microorganisms. Unconnected-degree structures produce much less biogas than systems wherein the levels of anaerobic digestion are separated because it's miles not possible to regulate and gather the perfect running conditions for the various levels.

2.2.2. Multi Stage

Two or more rectors are ordinarily utilized in multi-degree digestion structures to separate the hydrolysis and methanogenesis in an effort to optimize the biogas yield under particular running situations by using high-quality-tuning each level independently. In a -degree device, the growth of methanogens limits the reaction fee inside the 2D degree, that's optimized for methanogenesis. In the first degree, the hydrolysis of carbohydrates is the rate-limiting step, and inside the second degree, hydrolysis and fermentative acidification reactions are optimized. The capacity of multi-level structures to mitigate instability added on via variations within the substrate loading rate or its heterogeneity is considered one of its primary blessings. This is because inhibitors are diminished all through the hydrolysis and acidification phases, and substrates from the primary level arrive on the methanogenesis stage already homogenized.

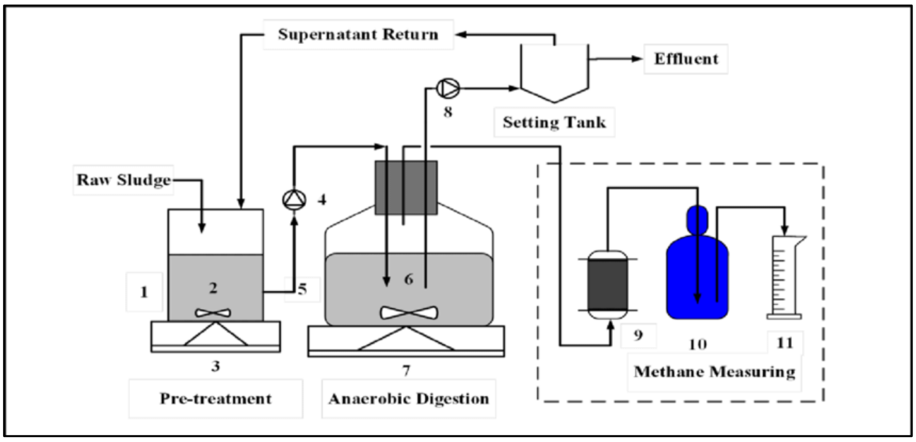

Figure 4. Two phase system : https://www.google.com/url?sa=i&url=https%3A%2F%2Fwww.researchgate.net%2Ffigure%2FTwo-stage-anaerobic-digester-experimental-set-

However, compared to unconnected-level systems, the operational prices of those digester systems are Better. As formerly mentioned, each step of the digestion process occurs in a single reactor under uniform situations. In assessment, multi-stage anaerobic digestion systems characteristic reactors designed in a manner that allows the diverse stages of the digestion to occur in separate reactors. As an end result, multi-stage anaerobic digestion structures have some clean benefits over single-stage structures. By regulating and satisfactory-tuning operating parameters for each stage, the division of tiers consequences in the optimization of the digestion process (Charithangi, 2023). However, multi-stage systems are extra pricey than unconnected- stage structures because of their higher operating and protection necessities. Additional benefits of multi-degree structures over unconnected-stage ones consist of better Odor manage, shorter retention times, quicker loading quotes, much less extent wanted within the digester, fewer foaming problems, and higher overall performance.

Table 2. Comparison of single and multi-stage AD

Parameter	**Single-Stage AD**	**Multi-Stage AD**
Number of Reactors	1	2 or more

Process Complexity	Simple	Complex
Biogas Yield (m^3/kg VS)	0.30 - 0.45	0.45 - 0.65
Methane Content (%)	50 - 55	55 - 65
Retention Time (Days)	20 - 40	20-25
Hydrolysis Efficiency (%)	Moderate (Lower hydrolysis rate)	High (Optimized hydrolysis stage)
Methanogenesis Efficiency	Lower (Due to mixed conditions)	Higher (Optimized conditions)
Volatile Solids Reduction	40 - 60%	60 - 80%
Operational Cost	Lower	Higher (Due to multiple reactors & control systems)
Foaming Issues	Higher risk	Lower risk
Odor Control	Moderate	Better Odor control
System Stability	Less stable (Sensitive to load changes)	More stable (Better handling of fluctuations)
Loading Rate (kg VS/m^3/day)	1.0 - 3.5	3.5 - 6.0

2.3 Evaluation of Single and Multistage AD for Biochemical Reaction.

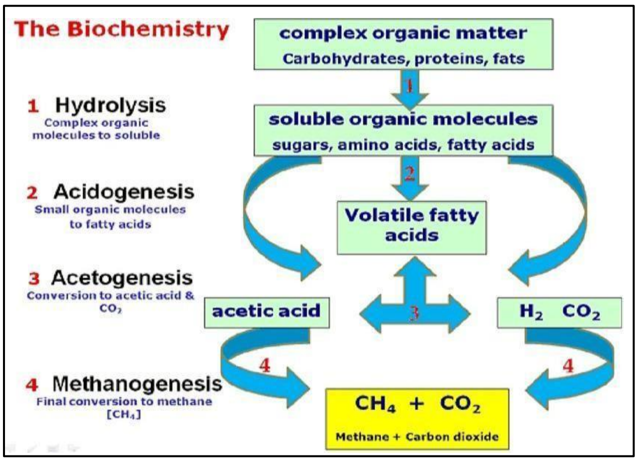

Figure 5. Bio Chemical Reaction of AD: https://www.researchgate.net/figure/Biochemical-process-flow-diagram-of-Anaerobic-digestion-process-Adapted-from-Waste-to_fig1_357743285

AD is an advance biochemical reaction that turn carbonic materials into Biogas via engaging with various microbial communities. There are 4 types of steps needed to be happened in the process called Hydrolysis, acetogenesis, acidogenesis and methanogenesis which are requiring specific environmental and controlled conditions. The arrangement of the anaerobic reactor directly impacts for the reaction process. Single stage and Multi stage systems are two type of arrangements that can be involved to anaerobic digestion with various advantages and limitations. In single stage reactor systems, all stages of the biochemical reaction happen within a single vessel under a controlling operating situation. This simple arrangement is a reason to create this system cost effective, easier to build up and more convenience to conduct. These systems are frequently operated in batch processes, where substrate is included into the vessel at specific time and allowed to digestate for proper retention timeline. Once one batch is completed, then digestate is removed from the reactor and it is time to introduce new substrate for the process. However, there are plenty of limitations in the single stage reactors (Otero et al., 2010). During the offloading and reloading phases, biogas yield ceases until the new substrates begin to degrade. To hold successive biogas production, aggregated reactors must have operated in parallel,' which adds complexness and requires limited synchronization. Continuous single stage systems, which feed substrates and evacuated effluents continuously, destination this issue but introduced other challenges,' such as maintaining optimum loading rates. Excessive substratum loading could disturb the digestion environment as well as leading to acidification and reduced methanogenesis efficiency. Another drawback is the unfitness to optimize conditions for each digestion phase inside a super reactor. For example,' hydrolysis and acidogenesis prosper in acid conditions, whereas methanogenesis requires an electroneutral pH and clear-cut microbe consortia. This restriction often results in suboptimal biogas yields compared to multi stage systems (Kizito & Mwakaje, 2015).

Multi stage systems destination the challenges of single stage systems by separating the digestion phases into two or more reactors, allowing each phase to go under optimized conditions. Typically, hydrolysis and acidogenesis occur in the first reactor, while methanogenesis was conducted in the second. This family improves the efficiency of each phase and maximizes boilersuit biogas production. One meaningful reward of multi stage systems is their power to deal variations in substratum composing and loading rates. By isolating hydrolysis and acidogenesis from methanogenesis, inhibitors generated in the early stages as well as such as changeful fatty acids,' was reduced before entering the methanogenic reactor. This reduces the risk of transcription unbalance and enhances biogas yield efficiency. Additionally, multi stage systems offer alive benefits, including shorter bid times, high loading rates, meliorate Odor control, reduced foaming issues,"' and small digester volumes. These systems also provided greater traceableness in managing feedstock heterogeneity, which was authorized for substrates with varying compositions," such as domesticated sound deplete or rural residues. However, as well as multi-level systems come with high live and tending costs due to the need for additive reactors," pumps, and check systems. These systems also required skilled cut for monitoring and fine-tuning operating parameters for each stage. Despite these challenges,' the benefits of increased biogas yields and fermented constancy oft justified the high investment as well as " peculiarly for large or commercialized operations (Latare & Jadhav, 2020).

For substrates with high lignocellulosic content, such as rural residues," multi stage systems may have been more efficient due to their power to optimize hydrolysis. Multi stage systems offer ameliorate Odor control, faster digestion rates, and reduced iota impact, making them backlog for projects with bluish iota standards. Both single stage and multi stage anaerobiotic digestion systems have their roles in property bioenergy production. Single stage systems are a first-class option for small-scale, low-priced applications, while multi stage systems allow super efficiency and scalability for large or highly developed operations. The conclusion should be guided by the stockpile requirements of the learn as well as balancing factors like feedstock type, alive scale as well as ' and budget constraints. Overall,' multi stage systems offer the best prospects for maximizing biogas yield and ensuring long term turn stability, peculiarly in scenarios required high executing and iota compliance. Their power to optimize conditions for each phase of digestion makes them a decimal tool in advancing attribute bioenergy solutions.

2.4 Discussion of Microbial Behaviour with each of Critical Setups

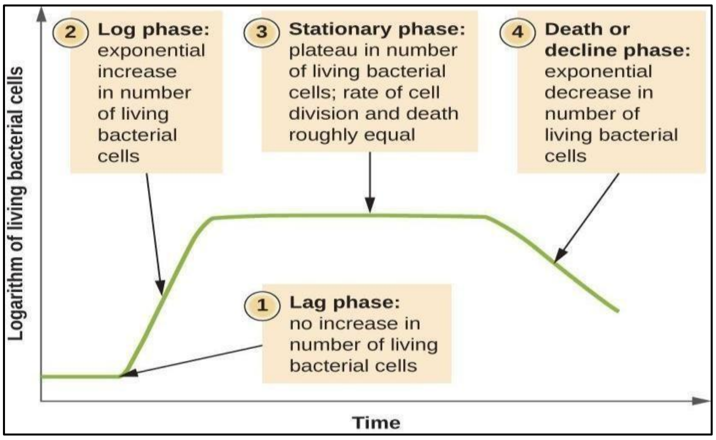

Figure 6: Microbial Growth Phases: https://microbiologynotes.org/bacterial-growth-curve-definition-phases-and-measurement/

In single stage anaerobiotic digestion, all phases of the ferment hydrolysis, acidogenesis, acetogenesis, and methanogenesis occur inside a super reactor under homogeneous operating conditions. This simpleness makes single stage systems easier to construct,' manage, and operate, and they are more cost efficient than multi stage systems. However, this conformation has constitutive, challenges regarding bug dynamics. Microorganisms involved in anaerobic digestion had well defined biota and nutritional requirements. For instance, hydrolysis and acidogenic bacteria flourish at slightly acid pH and relatively high constitutive, loading rates as well as whereas methanogenic arcana needs non-objective pH and are live to toxic intermediates like exchangeable fatty acids VFW (Taher & Mohammadi, 2019).

In a multi stage system,' maintaining optimal conditions for all bug groups simultaneously is challenging. The allow was often suboptimal performance as well as ' with imbalances in bug activity leading to issues such as acidification and reduced methane yield. Moreover, as well as the clutch appendage style ordinarily used in single stage systems, where feedstock is loaded and allowed to concentrate for a set storage time, hike impacts microbe behavior. Biogas production ceases during offloading and reloading because the microbe environment needs new substrates for stability (Khan & Zubair, 2019). The continuous single stage systems solved this problem through endless substrate addition and waste removal however these systems require specific loading rate controls to avoid substrate overload which may affect methanogenesis. Despite these challenges as well as single stage systems are appropriate for applications where simplicity as well as low cost, and temperate biogas yields are acceptable. However, they often produced less biogas than multi stage systems due to the unfitness to severally optimize the conditions for clear cut microbe communities. In contrast as well as ' multi stage anaerobiotic digestion systems separated the digestion ferment into two or more reactors, each tailored for appropriate stages of microbe activity. For example, hydrolysis and acidogenesis occur in the first reactor, while acetogenesis and methanogenesis was confined to consequent stages. This interval enables correct check over biology conditions, optimizing microbe executing at each stage (Sharma & Tripathi, 2017). Biogas production ceases during offloading and reloading because the microbe environment needs new substrates for stability. The continuous single stage systems solved this problem through endless substrate addition and waste removal however these systems require specific loading rate controls to avoid substrate overload which may affect methanogenesis. Ulti stage systems allow for maintaining these conditions in the first reactor without compromising the requirements of methanogens in the unconventional reactor. The methanogenic phase, dominated by methanogenic arcana,' was peculiarly live to pH fluctuations as well as ' VFW,' and toxic compounds. By delivering homogenized and stabilized substrates from the first stage,' multi stage systems make environs that fosters pair methanogenic activity, enhancing methane yield and ferment stability. Furthermore, the family of stages reduces the risk of microbe ban caused by substratum heterogeneousness or toxic intermediates. The operation of multi-stage systems remains complex but their high price tag results in multiple advantages that include enhanced biogas production while minimizing maintenance costs and improving Odor control effectiveness along with system stability in different nutrient conditions. The combined advantages of multi-stage systems suit them perfectly to industrial biogas production or complex microbial environments because they provide optimized conditions for different microbial strains. The operation of single-stage systems requires inter-stage media elements which produce system imbalances that diminish overall operational performance. Multi-stage systems achieve equilibrium between microbial communities through environmental condition adaptations which separate their populations into distinct areas. Methanogens benefit from the sequential process of multi stage systems because these systems protect them from the negative effects of VFW produced during acidogenesis (Yang & Zhang, 2018).

By controlling parameters like pH, temperature, and liquid storage time HRT in each stage, multi stage systems maximized microbe efficiency and biogas production. The option betwixt single stage and multi stage systems depend on single factors as well as including substratum characteristics, scale of operation, cost considerations, and desired biogas output. The single stage system would meet basic requirements because it combines simple design with affordable initial capital costs. These configurations proved most suitable when used on substrates with uniform types and minimal repression characteristics. High-efficiency biogas production requires multi stage systems which excel particularly when using compound or changeful substrates. Their power to severally optimize each stage of digestion enhances biogas yield and ferment resilience. Although they connote high alive and tending costs,' these are often branch by the improved performance as well as shorter storage times,' and reduced digester book requirements (Ma & Zhai, 2016).

2.5 Techno Economical Evaluation of both Single and Multistage Anaerobic Digestion Systems

Single stage anaerobic digestion system has integrated all the phases in biochemical reaction of AD called hydrolysis, acidogenesis, acetogenesis and methanogenesis under a single anaerobic reaction with controlled operational optimum conditions. This uniqueness makes simplicity and cost effectiveness of the system to design, construct, operate and control. They are especially suitable for small scale conductions and low complexity substrates due to their minimal infrastructure requirements. Nevertheless, these systems face plenty of limitations Biogas production decreases during the phases of offloading and reloading in batch operations happening down time and inefficiency unless operated in parallel systems. Continuous flow systems address this problem by providing continuous substrate inserting and effluent removal. But adverse substrate insertion rates can lead to imbalance the process, such as acid emergencies, which inhibits methanogenesis pathway. Further single stage systems have not to optimize conditions for the certain biochemical reaction chain, resulting in lower bigas quantity compared to multistage systems. Multistage systems have two or more reactors to implement the phases of digestion, providing optimum controlled conditions like PH, Temperature, OLR and retention time at any of stages. For example, hydrolysis and acidogenesis are conducted in the first stage while methanogenesis is implemented in the second stage. This advance system enhances the biological methane yield, reduce substrate heterogeneity and decrease the effect of inhibitors, making multi stage systems more suitable against substrate variability (Garcia & Rodrigo, 2017). The main obstacle of the multistage system is their higher capital and operational costs due to additional equipment, reactors, advance maintenance needs and more sophisticated monitoring and controlling systems. Nevertheless, these costs can be neglected by improved performance characteristics and predictive applications, including shorter retention time, higher biogas yield. Better Odor control and fewer foaming issues. Stand with the economical perceptive, the choice between single stage and multistage system has been determined by the applying scale, substrate characteristics, and intended application. For small scale industries with consistent and steady feedstock, single stage systems offer a cost-effective advantage despite their lower effectiveness. On the other hand, for larger industries with diverse and challenging substrates, multi stage systems give excellent performance and stability, despite their higher investment. Finally, multistage systems are recommended for long term productions, seeking advance maximum efficiency and stability. Their skill to optimize each biochemical phases of AD and handle variable substrates makes them the best choice for emerging sustainable bio-based energy development.

2.6 Importance as a Waste Management strategy

As a waste treatment technology, the process of AD performs two functions: it minimizes environmental pollution while recovering resources to support the principles of circular economy. The choice between a single-stage or multi-stage AD system establishes how efficiently the system runs while determining financial stability and cost-effectiveness of biological digestion processes. AD executes efficient waste management of different organic materials including municipal solid waste together with agricultural residues and industrial effluents. Through the degradation system the process efficiently processes organic waste to eliminate landfill use and decrease emissions produced by waste decomposition. The AD system stands apart from traditional disposal practices because it blocks dangerous pollutant releases while generating usable methane. Multi-stage AD systems optimize waste breakdown processes by combining hydrolysis and methanogenesis activities which results in more efficient conversion of waste materials (Silva & Carvalho, 2019)

AD is an essential technology for renewable energy production because it produces biogas which mainly contains methane (CH4) and carbon dioxide (CO2). After upgrading biogas obtains methane-rich richness which makes it suitable for power generation and heating applications and vehicle fuel use. Systems that use multi-stage AD procedures produce higher quantities of methane between 55-65% whereas traditional single-stage systems yield 50-55% methane. The replacement of fossil fuels by biogas production through AD systems enables communities and industries to reduce their carbon emissions according to worldwide sustainability initiatives. The process of AD creates valuable side products from biogas production that includes digestate which functions as biofertilizer. A distinctive benefit of using AD is that the digestate contains beneficial nutrients which support sustainable agricultural practices. The byproduct enables farmers to substitute artificial fertilizer usage while concurrently preventing water contaminant runoff and creating better soil conditions. The combination of different stages in AD enhances waste breakdown efficiency which produces better quality digestate through stabilized nutrient concentrations (Abdalla & Hegazy, 2016).

Waste treatment efficiency lies in different ways between single-stage and multi-stage AD systems. Single-stage AD technologies provide basic but economical operation which makes them appropriate for modest volume waste processing requirements. The inability of single-stage AD systems to separate different biochemical reactions leads to poor digestion performance and decreased biogas production together with erratic system operation caused by pH imbalance and toxic byproduct formation. Improved process control occurs through multi-stage AD systems because these systems maintain hydrolysis, acidogenesis and methanogenesis in independent reactor environments. Through reactor segmentation operational stability improves while higher organic feed capacities increase and the system becomes more robust to changes in feed materials. Systems with multiple stages for AD perform much better yet demand elevated financial resources with extra operational skills. Several reactors together with complex monitoring technologies and specialized staff increase the project expenses beyond single-stage systems. Municipal and industrial applications that choose multi-stage AD gain long-term advantages in biogas output and waste reduction together with system stability even if the upfront cost is initially high. The revenue generated by selling biofertilizers and biogas can reduce costs of operation because anaerobic digestion operates as a sustainable financial waste management system (Zivkovic & Bogdanovic, 2014).

AD waste management adoption will increase because of reactor innovation and microbial improvement and automated processes. High-rate anaerobic digesters together with co-digestion practices plus pretreatment methods for lignocellulosic materials can boost the operational performance of single-stage along with multi-stage AD systems. The general adoption of AD technology needs significant attention from policymakers who should provide incentives towards widespread implementation especially in urban waste management and agricultural sectors (Mahajan & Kumar, 2021).

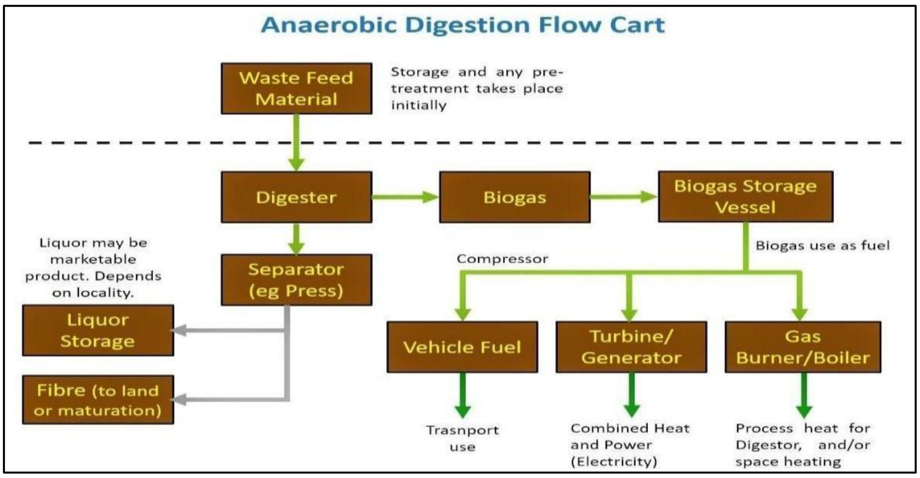

Figure 7. Anaerobic digestion flow as a waste management strategy: https://sswm.info/content/anaerobic-digestion-organic-waste

Conclusion

AD functions as a key technology for sustainable waste management through renewable energy production as a part of circular economy development. The research has reviewed the technological along with biological operations and economic characteristics of one-stage and multiple-stage AD facilities while detailing their strengths and weaknesses. Single-stage AD systems provide affordable operations for small-scale operations with stable feeding materials yet multi-stage systems excel at efficiency and flexibility which supports their use in large-scale applications. Different microbial processes in multi-stage AD systems operate separately throughout distinct reactors to maximize environmental conditions for hydrolysis, acidogenesis, acetogenesis and methanogenesis. Better substrate breakdown occurs together with improved biogas production volumes because of enhanced inhibitory compound control. The flexibility of multi-stage systems enables efficient management of numerous types of feedstock materials thus providing outstanding capabilities for industrial-scale operations that include co-digestion procedures. The implementation of these systems faces challenges because of their elevated expenses and increased technical complexity as well as higher initial and running costs. The successful implementation depends on automated systems along with optimal sensors and pre- treatment equipment that improve operational outcomes at decreased expenses. The use of AD systems encounters multiple obstacles due to their variable feedstocks and unstable processes which affects their economic viability requirements. The research field should aim at optimizing microbial consortia stability and developing real-time monitoring systems for adaptive control as well as pre-treatment method investigation to boost hydrolysis rates and accelerate biogas production. The mix of AD technology with solar and wind energy systems would create more efficient and sustainable power generation. The expansion of AD technology needs proper government policies and beneficial economic stimulus programmers. The implementation of favorable policies which include biogas subsidies and carbon credits and feed-in tariffs needs to be established by governments to stimulate investments in AD infrastructure development. Public- private partnerships enable knowledge exchange for developing cost-effective solutions which help the mass deployment of these technologies. Researchers must join forces with industry representatives and government authorities to make technological progress and improve the availability of AD systems. Government policies together with advantageous economic stimulus programmers must exist for AD technology to expand properly. The expansion of AD infrastructure development demands governments to create supportive policies containing biogas subsidies and carbon credits and feed- in tariffs. Knowledge exchange through public-private partnerships leads to the creation of economical solutions for mass implementation of such technologies. Researchers and government authorities and industrial representatives need to cooperate to advance AD technology and increase its availability.

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