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Biogas and its Possibilities: An Overview

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ABSTRACT: Biogas production is a well-established technique that may be used to generate sustainable energy as well as valorize organic waste. Biogas is the end result of a biologically mediated process known as anaerobic digestion, in which different microbes degrade organic materials through various metabolic pathways. Since ancient times, the technique has been extensively used in private homes to provide heat and electricity for hundreds of years. The biogas industry is booming these days, and new breakthroughs are laying the groundwork for biogas facilities to become sophisticated bioenergy manufacturers. In this context, biogas plants serve as the foundation for a circular economy model that focuses on nutrient recycling, greenhouse gas reduction, and biorefinery applications. This study covers the current state-of-the-art in anaerobic digestion for biogas generation and discusses future prospects. Furthermore, a historical overview of the biogas industry from its inception to current advances provides insight into the process optimization possibilities that are emerging.

KEYWORDS: Anaerobic digestion, Biogas, Biowastes, Industrial waste, Solid waste.

1. INTRODUCTION

Anaerobic degradation or digestion (AD) is a microbial-mediated process in which organic carbon is transformed to its most oxidized state (CO2) and its most reduced form (CO3) via a series of oxidations and reductions (CH4) [1], [2]. In the absence of oxygen, a broad variety of microorganisms work synergistically to catalyze this biological pathway. AD is widely recognized for its role in carbon recycling in wetlands, rice fields, animals' intestines, aquatic sediments, and manures, among other places. This technique is also widely used in the industrial sector to valorize organic waste. In many nations, waste and wastewater management has become a political concern. Biowastes, such as sludge, manures, agricultural or industrial organic wastes, contaminated soils, and so on, have historically been used as biofertilizers in untreated soils, deposited in landfills, or even thrown into the environment. Environmental awareness, on the other hand, has resulted in stringent laws prohibiting such activities. The European Union, for example, has particular licensing regulations for the disposal of biodegradable organic waste in landfills. In many instances, treating biowaste using AD procedures is the best method to turn organic waste into usable goods like electricity (in the form of biogas) and soil conditioner (fertilizer) [3]. This effectively implies that after stabilizing biowastes via energy extraction, the residual residues may be returned to agricultural soils, delivering all of the required beneficial nutrients while also preserving humus and soil structure. In contrast to the aerobic process of bacterial biomass, the primary benefits of the industrial AD process are the creation of a flexible energy carrier and a high degree of organic matter reduction with a modest increase.

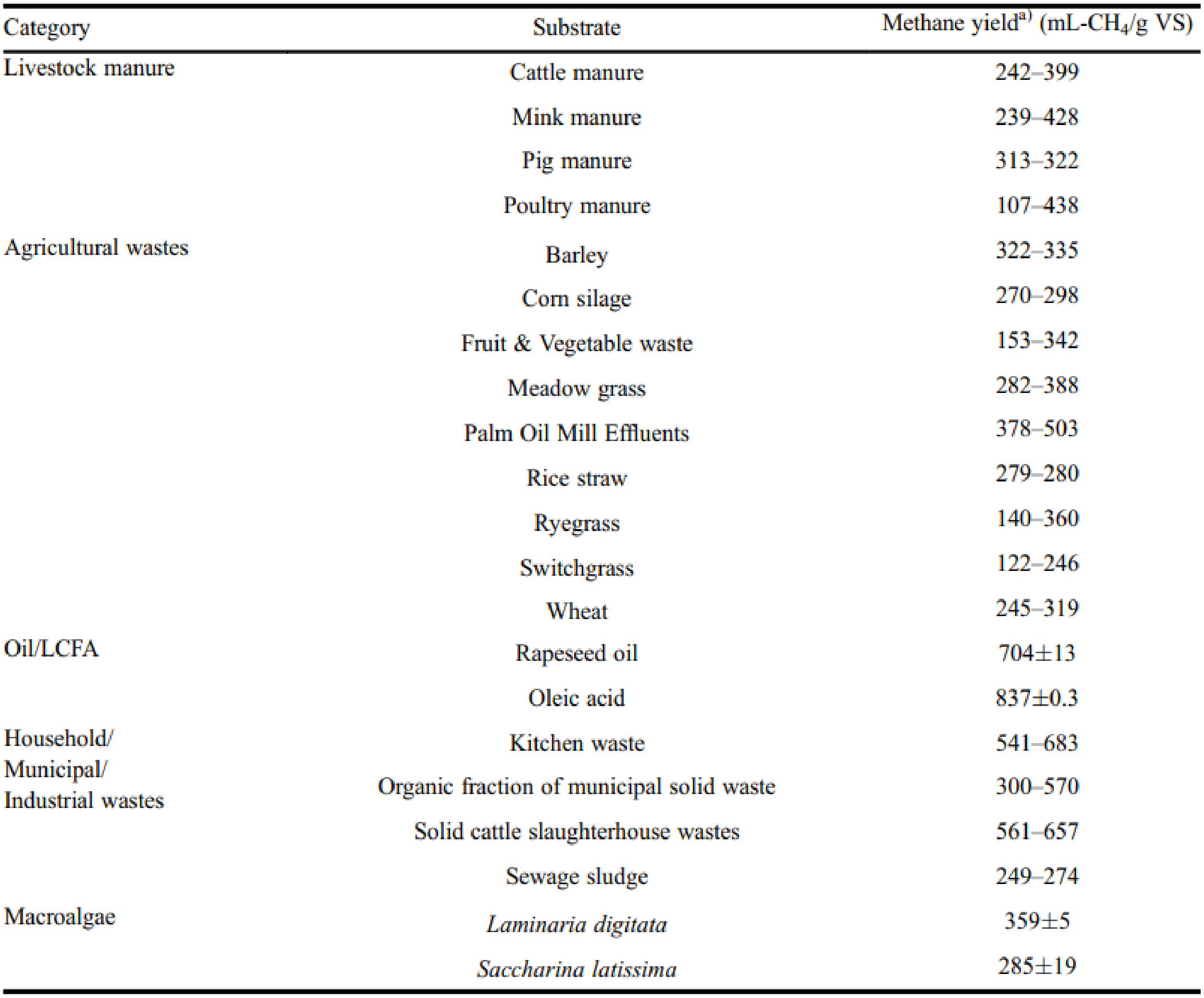
This study will outline existing biogas production expertise and discuss new developments that are expected to play a key role in the near future.

1.1. Biogas and Its Utilization for Energy Production:

1.1.1. Feedstock Strategies:

Depending on the influent feedstock, the applied temperature, and reactor design, there are many methods to categorize the operating mode of biogas plants. The consistency and dry matter concentration of the influent to be treated define the reactor type for anaerobic digestion. Total Suspended Solids (TSS) reactors with flocculent sludge may be utilized for influent substrates ≤ 500 mg/L. Immobilized granular sludge type reactors, such as UASB or EGSB, may be utilized for increased TSS concentration in influent substrates (0.5 to 2–3 g TSS/L). Finally, Continuous Stirred Tank Reactors (CSTR) are most frequently used for slurries with TSS in the range of 30 to 70–80 g/L, such as manure. Special kinds of rector designs have been designed for greater dry matter content substrates (>100 g/L), taking into consideration mixing and conveyance of the solid influents. Between dry and wet fermentation, there is an initial difference. The term "dry fermentation" refers to a degradation process characterized by a high solids content ranging from 15% to 35% (or even higher for batch garage type reactors using solid waste), whereas "wet fermentation" refers to a degradation process characterized by a solids content of up to 10%, and thus a higher liquid content [4]. The choice between these two fermentation methods determines the initial design of the plant's structure. It's worth noting that, depending on the chemical makeup of the substrate, the methane output varies considerably (Table 1).

Table 1: Methane yield of various organic residues [5]**.**



Category	Substrate	Methane yield$^{a)}$ (mL-CH_4/g VS)
Livestock manure	Cattle manure	242–399
	Mink manure	239–428
	Pig manure	313–322
	Poultry manure	107–438
Agricultural wastes	Barley	322–335
	Corn silage	270–298
	Fruit & Vegetable waste	153–342
	Meadow grass	282–388
	Palm Oil Mill Effluents	378–503
	Rice straw	279–280
	Ryegrass	140–360
	Switchgrass	122–246
	Wheat	245–319
Oil/LCFA	Rapeseed oil	704±13
	Oleic acid	837±0.3
Household/ Municipal/ Industrial wastes	Kitchen waste	541–683
	Organic fraction of municipal solid waste	300–570
	Solid cattle slaughterhouse wastes	561–657
	Sewage sludge	249–274
Macroalgae	*Laminaria digitata*	359±5
	Saccharina latissima	285±19

Table 2 shows the potential methane output of common compounds suited for anaerobic digestion. Only a few biogas facilities use a mono-digestion method (i.e. the digester processes only a single feedstock). Due to limited methane potential, high concentrations of inhibitors (e.g. phenols, ammonia, etc.), or seasonal availability of particular substrates, the majority of biogas plants use co-digestion feeding methods. Various organic wastes, which typically have different properties, are processed in the same anaerobic digester during the co-digestion concept.

Table 2: Theoretical methane yield of typical compounds[6]

Compounds	COD/VS (g/g)	CH_4 yield[a) (mL-CH_4/g VS)	CH_4 yield[a) (mL-CH_4/gCOD)	CH_4 content[a) (%)
Carbohydrate $(C_6H_{10}O_5)_n$	1.19	417	350	50
Protein[b) $C_5H_7NO_2$	1.42	497	350	50
Lipids $C_{57}H_{104}O_6$	2.90	1015	350	70
Ethanol	2.09	732	350	75
Acetate	1.07	375	350	50
Propionate	1.51	529	350	58
Iso-butyrate/Butyrate	1.82	637	350	63
Iso-valerate/Valerate	2.04	714	350	65

1.2. Main Operational Parameters Influencing the Biogas Process:

1.2.1. pH and Volatile Fatty Acid:

The biogas generation process takes place within a certain pH range of about 6 to 8.5. If the pH of the reactor reaches certain levels, the process will degrade, leading in a significant reduction in methane output. Changes in pH may be linked to other operational factors; for example, a rise in organic acids (acidification) would usually lower the pH, while an increase in ammonia concentrations or CO2 removal will often raise it. It should be noted that the pH decrease caused by VFA buildup is also depending on the substrate utilized. Some organic wastes, such as cow dung, have a high buffer capacity and may therefore keep the pH of the system in check. A pH decrease will only occur if the concentration of VFA is very high, surpassing a specific threshold, and the process is often already significantly affected. As a consequence, VFA buildup may be seen as a side effect of an already impeded process rather than the real cause.

1.2.2. Temperature:

The entire digestion process takes place in anaerobic reactors that run at mesophilic (30°C–40°C, mostly 35°C–37°C) or thermophilic (50°C–60°C, primarily 52°C–55°C) temperatures. The choice of operating temperature and its maintenance at stable levels is critical, since these variables have a significant impact on the growth of the digesters' microbial structure. Temperature variations lead to process imbalances, which result in the buildup of Volatile Fatty Acids (VFA) and a reduction in biogas production [7]. Thermophilic environments provide a variety of benefits over mesophilic ones, as is well documented.

1.3. End-Use of Biogas in the Energy Sector:

Biogas has traditionally been used to generate heat or combined heat and electricity (CHP). Biogas is widely used to fuel cooking stoves and provide lighting, particularly in poor nations where electrical power is scarce and people depend on biomass to meet their energy requirements. The biogas reactors in these regions are small, with a typical capacity of just 2–10 m3, making CHP and purification procedures unable to accommodate [8]. On the other hand, in farm-scale or centralised biogas facilities, the produced gas is burnt in a CHP unit, where it is converted to roughly 35–40% electrical energy, 45–50% heat, and 15% energy losses, depending on the efficiency of the engine. It's worth noting that the pollutants in biogas, particularly hydrogen sulphide, must be eliminated to prevent combustion engines from being damaged or corroded. Furthermore, organic bound minerals and salts are produced and contained in the reactor's effluent stream as a consequence of carbon transformation, which may be used as soil conditioners (i.e. biofertilisers). As will be addressed later, biogas usage as a transportation fuel or as a natural gas replacement is receiving increasing attention these days. To do so, the biogas must be purified of contaminants and, in particular, CO2. This resulted in an increase in cleaning and purifying procedures, which increased the biogas sector's market potential.

2. DISCUSSION

2.1. Anaerobic Digestion: Current Status:

Hydrolysis, acidogenesis, acetogenesis, and methanogenesis are the four stages in the typical model for anaerobic decomposition of organic matter. Extracellular enzymes hydrolyze organic polymers to soluble oligomers and monomers in fermentative bacteria at first. Bacterial species then use the dissolved products to make short-chain fatty acids (those with less than six carbons), acetate, alcohols, hydrogen, and carbon dioxide. Acetogenic bacteria oxidize short-chain fatty acids with more carbons than acetate and alcohols, producing acetate, formate, hydrogen, and carbon dioxide. Finally, archaea (or syntrophic interactions between syntrophic acetate oxidizing bacteria and hydrogenotrophic archaea) use the latter components to create methane. This flow shows a simplified version of the procedure, which still needs much study to properly understand.

Nonetheless, in recent years, our understanding of the biogas process has grown considerably. New substrates, innovative applications, AD solutions, buildup of Long Chain Faty Acids, new process monitoring tools, and various reactor designs are only a few of the latest technical and methodological breakthroughs. The fast progress in comprehending the complicated AD microbial process was aided by the substantial decrease in the cost and needed time of high throughput sequencing methods. Not only has information about the diverse microbial makeup been revealed, but also about the expression of different genes under varied environmental circumstances, opening up vast opportunities for future research. To decode the AD black box, sophisticated –omic technologies are now used. To link particular metabolic processes with microbial species, genome-centric metagenomics is combined with metatranscriptomics, metaproteomics, metabolomics, or stable isotope probing. Apart from syntrophic interactions between AD microbiome members, it was recently demonstrated that the AD food chain resembles a funnel concept (Fig. 2), with novel microbes with broad functional roles at the beginning of the process; subsequently, the community becomes increasingly specialized as it approaches the final step of methanogenesis [9].

The biogas process has been known and used for many years, but it gained fresh attention following the increase in energy costs in the 1970s, as a result of a desire to discover alternative energy sources to decrease reliance on fossil fuels. Despite the fact that the price of fossil fuels has dropped since 1985, interest in the biogas process has remained owing to the environmental advantages of anaerobic waste decomposition. The treatment of primary and secondary sludge from residential wastewaters, household solid wastes, manures, industrial wastes, and agricultural leftovers are the major uses of biogas. However, manures, industrial wastes, and agricultural residues are the main contributors to energy output, while municipal biomasses (sludges and household wastes) play only a minor role, and the biogas process can be seen as waste treatment methods for these waste streams rather than bioenergy production factories.

2.2. Anaerobic Digestion: Past:

The biogas process has been known since the dawn of civilization. Plinius made the first mention of biogas, and he was referring to strange fires that sprang from marshes or other subterranean places. This phenomenon was thought to be produced by dragons or other mythological creatures during the time. Furthermore, anecdotal evidence indicates that biogas was utilized to heat bath water in Assyria around the 10th century before Christ (BC). Alessandro Volta, an Italian scientist and chemist who discovered methane in the marshes of Maggiore Lake in 1777, was the first to try to explain biogas. After that, Cruikshank demonstrated the lack of oxygen molecules in methane in 1801 and Dalton in 1804 gave the accurate methane formula [10]. The microbiological foundation for the AD process was discovered through systematic studies that began in the second half of the nineteenth century. Béchamp was the first to show that methane was produced by a microbiological process in 1868 [11]. Shortly later, it was discovered that enzymatic activity hydrolyzed the polymers, resulting in the production of organic acids as intermediates. A Dutch scientist demonstrated in the early twentieth century that methane-reducing bacteria may directly use the results of cellulose fermentation. There was also an effort to learn more about the microbes involved for the various stages of the AD food chain. The principles underlying current advances in anaerobic digestion linked to biogas upgrading were originally defined more than a century ago; Söhngen's studies with enriched cultures in 1910 resulted in the derivation of the stoichiometric equation of hydrogenotrophic methanogenesis [11]:

$$CO_2 + 4H_2 \rightarrow CH_2 + 2H_2O$$

2.3. Anaerobic Digestion: Future Perspectives:

Despite the fact that Alzheimer's disease has been recognized and used for hundreds of years, the technology and applications are still very basic. So long, the process has been mainly regarded as a "black box," with the microbiology underlying it considered as fixed and unchangeable. The biogas microbiome has begun to be decoded, thanks to recent advances in microbial ecology, which have taken advantage of rapid advances in sequencing technology and analytics. Some research are now underway to discover new uncultivated microorganisms as well as to clarify several of their metabolic relationships. It is undeniable that fresh knowledge is acquired at an incredible rate. This new information will be utilized to guide the AD in a more customized manner in the future, suited to the process's particular requirements. The biogas industry is expected to enter an era in which sophisticated microbial resource management, microbial composition interventions, and, in some instances, completely tailored microbial consortia will be used. This will result in a more efficient AD process with better biomass use. Furthermore, it is certain that microbiology will play a significant part in the diagnosis and monitoring of the Alzheimer's disease progression via the use of specific biomarkers.

3. CONCLUSION

Biogas generation is a well-established technology that may be utilized to produce sustainable energy as well as valorize organic debris. Biogas production method is an established technology for energy generation. However, current developments offer new possibilities for utilization of biogas, increasing its potential applications. Since the biogas industry is experiencing significant growth, it is envisioned that more sophisticated monitoring and management of the process is going to offer greater usage of the treated biomasses. A better knowledge of microbial insights is likely to play a more significant role for customizing the biogas process and for decoding the anaerobic digestion "black box". Finally, it is anticipated that in the future the biogas plants are going to form sophisticated bioenergy factories with more safe and steady operation.

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