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Review

An Overview of Biogas Production from Anaerobic Digestion and the Possibility of Using Sugarcane Wastewater and Municipal Solid Waste in a South African Context

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Abstract: Bioenergy production from waste is one of the emerging and viable routes from renewable resources (in addition to wind and solar energy). Many developing countries can benefit from this as they are trying to solve the large amounts of unattended garbage in landfills. This waste comes in either liquid (wastewater and oil) or solid (food and agricultural residues) form. Waste has negative impacts on the environment and, consequently, any form of life that exists therein. One way of solving this waste issue is through its usage as a resource for producing valuable products, such as biofuels, thus, creating a circular economy, which is in line with the United Nations (UN) Sustainable Development Goals (SDGs) 5, 7, 8, 9, and 13. Biofuel in the form of biogas can be produced from feedstocks, such as industrial wastewater and municipal effluent, as well as organic solid waste in a process called anaerobic digestion. The feedstock can be used as an individual substrate for anaerobic digestion or co-digested with two other substrates. Research advancements have shown that the anaerobic digestion of two or more substrates produces higher biogas yields as compared to their single substrates' counterparts. The objective of this review was to look at the anaerobic digestion process and to provide information on the potential of biogas production through the co-digestion of sugarcane processing wastewater and municipal solid waste. The study deduced that sugar wastewater and municipal solid waste can be considered good substrates for biogas production in SA due to their enormous availability and the potential to turn their negative impacts into value addition. Biogas production is a feasible alternative, among others, to boost the country from the current energy issues.

Keywords: energy; biogas; anaerobic co-digestion; substrate type; sugarcane processing wastewater; municipal solid waste

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1. Introduction

Energy accessibility and waste management are some of the most significant challenges developing countries face, including South Africa [1]. Energy demands exceed the existing energy supply due to the continual increase in population globally. Regularly used energy resources, such as oil, coal, and natural gas, are diminishing and they emit greenhouse gases that contribute to climate change [2]. Accordingly, the research focus in many countries has shifted to finding and implementing efficient and green alternatives, such as renewable resources, as solutions to these conventional energy sources, which are detrimental and waning [3]. Examples of renewable energy resources are those that can be replenished naturally, such as solar photovoltaic and wind power. However, the energy demands of a constantly growing population using coal-powered stations cannot be supplemented with only solar and wind energy as these are predominantly weather-dependent [4].

Waste generation and management have been dealt with in many ways, one of which is using it as a resource for producing valuable products, such as biogas, which contributes to the circular economy [5]. Further, this is in line with the UN's Sustainable Development Goals 5, 7, 8, 9, and 13. Biogas can be produced from many substrates, including organic solid waste, wastewater/effluent, etc., as substrates/feedstock in biodigestion. Feedstock is any substrate that can be converted to biogas/methane through anaerobic bacteria. These range from solid wastes to readily degradable wastewater and sludge. This waste must contain a substantial amount of organic matter, which is then converted into biogas [6]. Conventionally, anaerobic digestion is a practical way to treat animal and agricultural waste, macroalgae, and sewage sludge from aerobic wastewater treatment plants [7–9]. However, a change happened after 1970, as soon as environmental consciousness grew in connection with the demand for renewable energy reforms and new waste-management strategies [10]. Industrial and municipal waste has also been identified as eligible for anaerobic digestion, as shown in Figure 1. This resource is one of the sustainable and viable routes to help many developing countries manage massive amounts of the waste left unattended in landfills and discharged into water streams and oceans [11]. This waste negatively impacts the environment and, consequently, life in such an environment, i.e., human and animal lives [12,13].

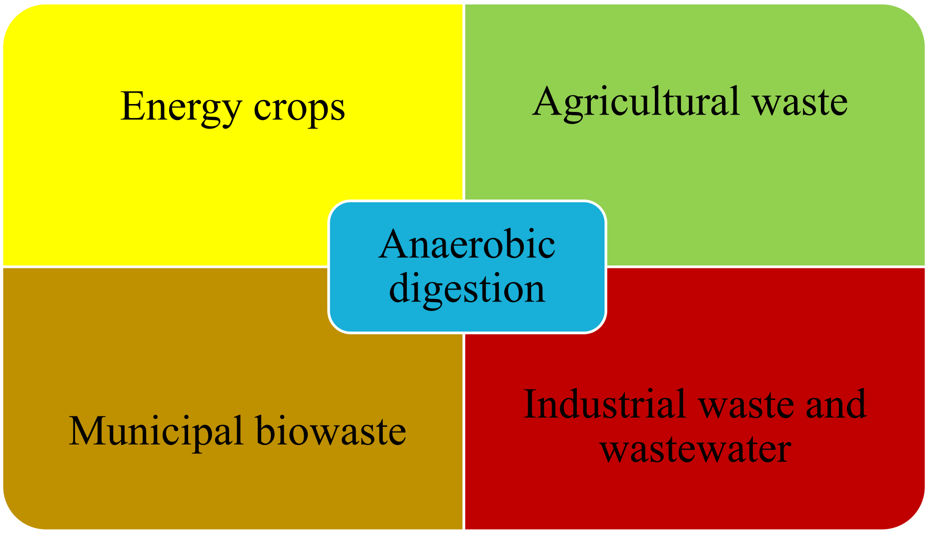

Figure 1. Sources of suitable substrates for anaerobic digestion [14].

Clean, renewable energy in the form of biogas can be achieved through anaerobic digestion (AD) of waste matter [15]. AD comprises a series of biochemical reactions that result in the production of biogas, a mixture of methane, carbon dioxide, and negligible traces of other elements. Different waste matter, including the organic part of municipal solid waste, industrial waste, wastewater from manufacturing processing, and agricultural waste produced from livestock and crop production, is used in the AD process. Notably, the biogas formation process produces some by-products, such as slurry (digestate), which provides an added benefit, since the spent waste (slurry) can be used as organic compost by farmers due to its nutrient composition [16]. However, it is crucial to check the safety of this digestate for its use as a fertilizer since there can be potential incidences of heavy metals and pathogenic bacteria [17]. In addition to the environmental benefits of waste management, there are also socio-economic rewards. It is envisaged that countries would raise their annual turnover for different sectors, generate thousands of jobs, and save billions of dollars a year after fully implementing waste-management solutions [18].

Since research has shown that the digestion of a single substrate produces less biogas than a co-digestion of two or more substrates, municipal solid waste and sugarcane processing wastewater are deemed to be good co-substrates for biogas production. Further, sugarcane wastewater has low carbon-to-nitrogen ratio, which enables the use of a complementary substrate [19]. Both these substrates contain significant amounts of organic content, digested by the anaerobic bacteria [20,21]. This review looks at the anaerobic digestion process and seeks to provide information on the potential of biogas production through the co-digestion of sugarcane processing wastewater and municipal solid waste. South Africa is experiencing "load shedding" because energy demand is higher than the currently generated energy; therefore, urgent solutions are required to solve this issue. Biogas production is a viable alternative among others to boost the country from the current energy issues.

2. Possibility of Generating Renewable Energy from Biogas Using Sugarcane Processing Wastewater

Sugarcane is used for sugar production at the business scale and contributes about 80% of the world's sugar revenue [22,23]. In South Africa, the provinces of KwaZulu-Natal and Mpumalanga are the major sugarcane producers contributing to the prosperity of the sugar industry's economy [24]. The same sugarcane that contributes to countries' economies is characterized by the generation of large quantities of organic wastewater, with excessive chemical oxygen demand that pollutes the environment [25,26]. Therefore, the sustainable advancement of the sugarcane industry requires reducing and treating sugarcane processing wastewater. One way of treating this sugarcane processing wastewater is by discharging it into wastewater-treatment systems where there would be physical or chemical nutrient removal. Nevertheless, such methods present disadvantages of secondary pollution, high operation costs, and limitation of nutrient reusability [27,28]. Sugarcane processing wastewater is an attractive substrate for bacterial cultivation to produce beneficial products, such as biogas, biomass, enzymes, and organic acids, due to its high carbohydrates, minerals, and sugars [26,29]. Many researchers [30–32] have studied the conversion of biogas to electricity. Wang, et al. [33] analyzed the efficiency and sustainability of biogas to electricity production from a large-scale biogas project in China using pig manure. Even though they obtained lower yield results compared to traditional coal and natural gas power plants, electricity generated from biogas still brings more advantages and reduced antithetical environmental effects, as opposed to fossil fuels [33].

3. Municipal Solid Waste

A continual increase in the worldwide populace has led to rapid urbanization in many countries. It is estimated that about two-thirds of the world's population will live in cities by 2025 because more than 150,000 people move to urban areas each day [34]. This rise in urbanization has resulted in cities that generate thousands of tons of municipal solid waste daily and this is projected to increase significantly in the near future [35]. Municipal solid waste is an amalgamation of waste from households, markets, backyards, street cleaning, institutional establishments, such as hospitals, and industrial and commercial wastes. Management of this type of waste in urban areas pertains to its disposal, collection, resource recovery, recycling, and treatment to promote the quality of both the environment and health while supporting the economy's efficiency and productivity through generating employment and income [36]. The most preferred waste-management method is the one tuned to take the circular economy direction since it leads to sustainable development. The circular economy focuses on the upper ranks of the waste hierarchy, as shown in Figure 2, including prevention, reuse, and recycling, because these promote cleaner production and minimal waste [37]. Particularly, a circular economy has been adopted globally since it offsets issues of resource depletion and the detrimental environmental effects that lead to climate change. Traditionally, the production and consumer approach, which translates to the linear economy, has been used through a typical "take, use, and dispose of" model [38]. Some of the drawbacks of a linear economy are apparent when the consumer generates waste and disposes of it, causing pollution to the environment and depleting resources [39]. On the other hand, a circular economy follows waste generation minimization and pollution reduction, hence, protecting the environment through a "resource-product-waste-resource" model [40].

South Africa has also embarked on an integrated waste-management structure that considers waste prevention, recycling, recovery, and controlled and supervised disposal. This idea will help to efficiently manage and safeguard human health and the environment, with a significant focus on sustainable development economically, socially, and environmentally. It was suggested that this integrated waste management should incorporate hierarchical waste techniques, which focus more on the avoidance of and reductions in waste than on collection, storage, and disposal [41]. On a local scale, a study of the optimization and financial viability of landfill gas to electricity was conducted in Durban. The study demonstrated that the conversion of landfill gas to electricity provides viable projects with options for optimizing and improving the financial feasibility of the developments [42]. The study also suggests that researchers should look at the possibility of sugarcane waste to produce renewable energy. Favourable results from this research may add more value to sugarcane, as a plant boosts the economy and creates jobs. Consequently, this review looks at the process of biogas production, with a particular focus on two different substrates, i.e., sugar wastewater and the organic part of municipal solid waste. These substrates are simple biodegradable materials that can be broken down by microorganisms in an AD process, which includes a series of biochemical reactions, as explained in the following section.

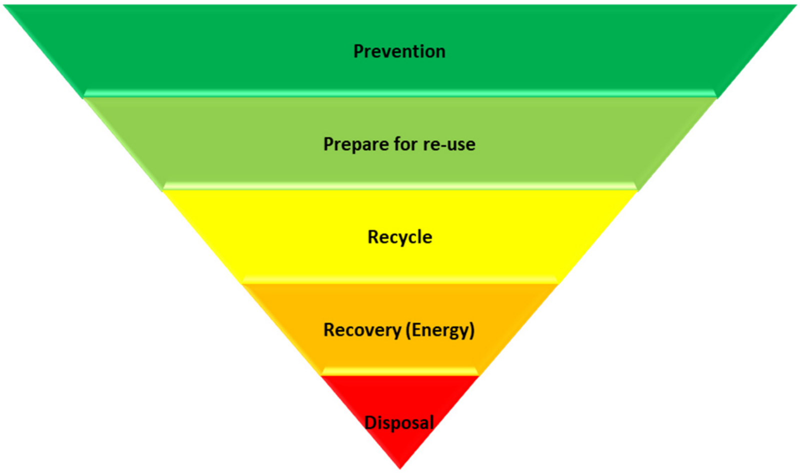

Figure 2. Waste hierarchy adapted from [43].

Anaerobic digestion and composting are biological treatments used to treat biodegradable waste. Studies show that waste management leads to lower environmental impacts, lower economic costs, and lower energy consumption. It is suggested that energy-rich waste should be prevented because of the low recovery of resources and harmful environmental effects of landfilling [44]. The advantages attached to waste management include reducing solid waste (about 70–80% mass and 80–90% volume), leading to a preserved landfill space [45], removal of organic contaminants (halogenated hydrocarbons) [46], reduction in greenhouse gases [47], and naturally compatible exploitation of renewable energy from waste, predominantly when the plant used is designed to generate heat and power [48].

4. Anaerobic Digestion Process

This is a four-step anaerobic biological decomposition of organic substrates, namely, hydrolysis, acidogenesis, acetogenesis, and methanogenesis. The brilliance of this process is that all the phases are connected since a by-product of one step becomes the substrate of the next step, all in one system [49]. These biochemical decomposition phases have a series of chemical reactions, as illustrated in Figure 3 and detailed in the subsequent subsections.

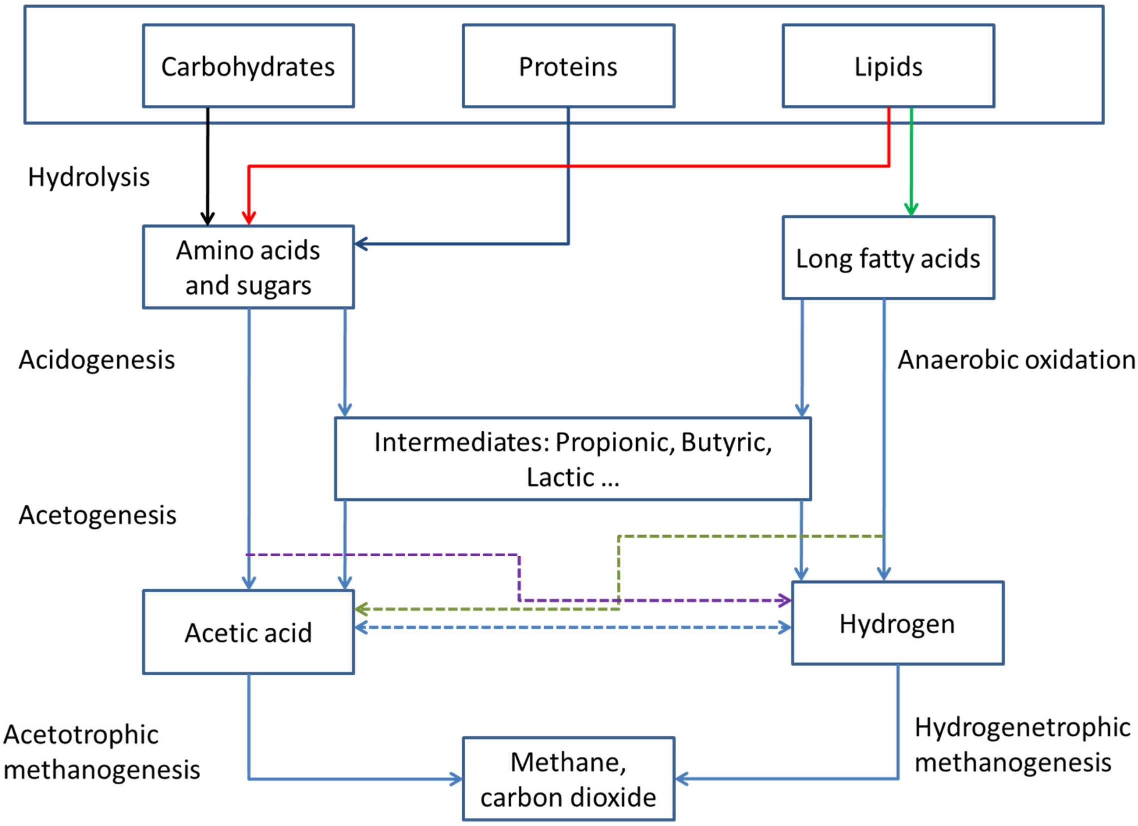

Figure 3. Anaerobic digestion was adapted from Bajpai [50] and Khanal [51].

4.1. Hydrolysis

The hydrolysis phase of anaerobic digestion is where complex biopolymeric compounds (lipids, carbohydrates, and proteins) are converted to water-soluble compounds by degradation through Bacteroides, Clostridia, and Bifidobacteria and sometimes Streptococci and Enterobacteriaceae [52]. This step is relatively slow and can limit the rate of the overall digestion, mainly when solid material is used as a substrate. As seen in Equation (1), cellulose ($C_6H_{10}O_5$) is hydrolyzed to generate glucose ($C_6H_{12}O_6$) and hydrogen (H_2). This reaction is catalyzed by homogeneous/heterogeneous acids yielding the fermentable monosaccharide ($C_6H_{12}O_6$). The products ($C_6H_{12}O_6$ and H_2) are used by the fermentative microorganisms in the next phase to form higher-chain organic compounds, such as volatile fatty acids [53,54].

$$(C_6H_{10}O_5)_n + nH_2O \rightarrow n(C_6H_{12}) + nH_2 \tag{1}$$

4.2. Acidogenesis

This is the second phase, known as the fermentation stage, where the acidogenic bacteria *Streptococcus*, *Escherichia*, *Staphylococcus*, *Pseudomonas*, *Bacillus*, *Sarcina*, *Desulfovibrio*, *Lactobacillus*, and others are active [55]. These bacteria degrade amino acids, lipids, and glucose into volatile fatty acids, organic acids, carbon dioxide, and hydrogen gas (as illustrated in Equations (2)–(7) below [53]). Acetic acid (CH_3COOH) is the most important organic acid produced in this stage, which serves as the substrate for methanogenic microorganisms [16]. It is worth noting that volatile fatty acid production is favored when pH is above 5, while ethanol production (CH_3CH_2OH) is favored by pH lower than 5, with reactions stopping at a pH level that is less than 4 [50].

$$C_6H_{12}O_6 \leftrightarrow 2CH_3CH_2OH + 2CO_2 \tag{2}$$

$$C_6H_{12}O_6 + 2H_2 \leftrightarrow 2CH_3CH_2COOH + 2H_2O \tag{3}$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \tag{4}$$

$$C_3H_7O_2N + 2H_2O \rightarrow C_2H_4O_2 + NH_3 + CO_2 + 2H_2 + ATP \tag{5}$$

$$C_4H_9O_3 + NH_3 + CO_2 + H_2 + ATP \tag{6}$$

$$4CH_3COCOO^- + 4H_2O \rightarrow 5CH_3COO^- + 2HCO_3{}^- + 3H^+ \tag{7}$$

4.3. Acetogenesis

At this stage, the reactions are reversible with a release of hydrogen. Volatile fatty acids, specifically acetic acid and butyric acid, are converted into carbon dioxide gas, hydrogen, and acetate, as shown in Equations (8)–(10). The active bacteria in this stage are *Clostridium*, *Syntrophomonas wolfeii*, and *Syntrophomonas wolinii* [55]. This conversion of volatile fatty acids is enabled by the presence of water molecules (acting as electron sources) from the previous stages of anaerobic digestion. Equation (9) converts the phase product to acetate and hydrogen, used in the next stage [56]. This stage is equally important since it reflects the biogas production efficiency, given that the reduction of the acetate ion forms about 70% of methane. Acetate is a primary intermediary product of this phase and it accounts for 25% of the products formed together, with approximately 11% of hydrogen [57].

$$CH_3CH_2COO^- + 3H_2O \leftrightarrow CH_3COO^- + H^+ + HCO_3{}^- + 3H_2 \tag{8}$$

$$C_6H_{12}O_6 + 2H_2O \leftrightarrow 2CH_3COOH + 2CO_2 + 4H_2 \tag{9}$$

$$2CH_3CH_2OH + 2H_2O \leftrightarrow CH_3COO^- + 2H_2 + H^- \tag{10}$$

4.4. Methanogenesis

In the final phase of the methanogenesis stage, acetic acid is converted into methane and carbon dioxide using bacteria called methanogens, which are anaerobes with a high vulnerability to limited amounts of oxygen. In addition, carbon dioxide is a product that reacts with hydrogen gas to produce more methane. On the other hand, ethanol undergoes decarboxylation to form methane. Two types of bacteria—the acetophilic methanogenic (with *Methanosarcina* and *Methanosaeta* active specie) and the hydrogenophilic methanogenic (with *Methanospirilum*, *Methanobacterium formicicum*, *Methanoplanus*, and *Methanobrevibacterium* as the dominant specie)—exist in this stage [55]. The former is responsible for the decarboxylation of acetate to methane and the latter for methane formation through a reaction of carbon dioxide and hydrogen [53]. The final product of the anaerobic digestion process is biogas, which is composed of methane and carbon dioxide.

$$CH_3COOH \rightarrow CH_4 + CO_2 \tag{11}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{12}$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \tag{13}$$

5. Factors Affecting the Anaerobic Digestion Process and Biogas Production

Biogas production is influenced by different factors, such as substrate type, temperature, pH, organic loading rate, hydraulic retention time, etc. [58].

5.1. Substrate Type

Numerous biomass feedstocks can be used for biogas production, depending on their nutritional composition. Accordingly, these compositions influence biogas yield, methane content, degradation kinetics, and biomass biodegradability [59]. The critical nutritional compositions of biomass substrates suitable for biogas production are carbohydrates, protein, and fats. Theoretical estimations of biogas percentage and methane yield from these nutrients have been reported in the literature and are calculated using the Buswell formula [60]. Protein-rich substrates have a high potential for methane yield, but their degradation gives off ammonium ions, leading to an alkalinity increase in the AD process. The increase in alkalinity improves the digest value as fertilizer while preventing the activities of methanogens. This inhibition occurs during the equilibrium shift from ammonium to ammonia, typically in changing concentrations. In addition, literature remarks suggest that microorganisms can acclimatize to environments with high ammonia concentrations while efficiently producing biogas [61,62].

Lipid-rich substrates, such as fats, possess great methane yield potential, such as animal and plant tissue waste, biodegradable kitchen and canteen waste, grease and oil mixture, etc. [63]. These substrates release long-chain fatty acids during their degradation, which are typically toxic to the microbial environment and cause a drop in pH [64–66]. There are several other types of biomass that are used for biogas production apart from the protein and lipid-rich substrates, for example, substrates with a high degree of lignocellulose (wheat straw, sorghum, rice straw, etc.) [67]. This type of biomass is hard to degrade due to these three reasons: (i) recalcitrant nature, (ii) heterogeneous structure, and (iii) low accessibility by enzymes, such as carbohydrate polymers [68–70]. However, pre-treatment mechanisms can help break down the heterogeneous matrix, thus, increasing the porous and surface area of the lignocellulose biomass and enhancing biogas production.

Characterization of the waste substrates is performed to ascertain the composition of each substrate. This is generally physical and chemical composition regarding volatile solids, total solids, C/N ratio as well as elemental analysis for carbon, nitrogen, hydrogen, and sulfur [71,72]. During substrate characterization, the place (source) where the substrate was collected is vital, as waste chemical content is affected by many factors, such as weather conditions and the type of soil where the original substances were grown [73,74]. Physical and chemical compositions depend on the type of substrate, for example, carbohydrates have carbon and hydrogen while proteins and lipids have nitrogen as part of their composition [75,76]. These substrate compositions can be analyzed using different analytical techniques.

5.2. Anaerobic Digestion pH

The operational pH directly affects both the digestive progress and products formed in the AD process. Literature findings show that the ideal comprehensive pH range for AD should be between 4.0 and 8.5, as per the requirement for the fermentative bacteria, although the limiting range of 6.5–7.2 is favorable for the growth of methanogens [77,78]. The microorganism growth rate is significantly affected by the change in pH and, as such, each microbial group has a specific optimum pH. A comparative abundance of microbial species increased from 6 to 14 at pH 4.0 and 7.0, respectively [79]. Bacterial population dominance differs with changing pH, for example, at pH 6.0, *Clostridium butyricum* is dominant, while the *Propionibacterium* spp. thrives during anaerobic acidogenesis at pH 8 [80].

When the pH level is controlled for the optimal growth of microorganisms, reductions in toxicity, generally from increased concentration of free ammonia (FA), are also achieved. Similarly, pH significantly affects volatile fatty acid (VFA) composition [79]. In an anaerobic reactor, instability typically leads to the accumulation of VFAs, leading to a drop in pH and, therefore, acidification. Nonetheless, this accumulation of VFAs does not always exemplify a pH drop, owing to the buffer capacity of some waste forms. There is an excess of alkalinity in manure, denoting that the VFA growth shall surpass a certain point before it can be determined as a significant change in pH [81]. When the pH in the reactor drops, the concentration of VFAs is possibly very high, and the process may previously have been affected [82]. Hydrogen sulfide and phosphate are other compounds contributing to the buffering capacity [83]. To counteract this pH imbalance, a buffer solution may be added to the bioreactor [78].

5.3. Temperature

As this is one of the critical parameters influencing AD, temperature influences the activity of enzymes and co-enzymes and the methane yield and digestate (effluent) quality [84,85]. Anaerobic bacteria generally grow at three temperature ranges, namely the psychrophilic

(10–30 °C), mesophilic (30–40 °C) as well as thermophilic (50–60 °C) range [86,87]. Generally, AD performance increases with an increasing temperature [88]. There has been an emphasis on the advantages of the thermophilic operation, which has high metabolic rates, higher rates of destroying pathogens, and higher specific growth rates, collectively leading to higher biogas production [85–88]. Gallert, et al. [89] demonstrated that ammonia accumulation inhibition affects thermophilic digestion less than mesophilic digestion.

Biogas production under thermophilic conditions (55 °C) has been reported to give more than double the amount produced under psychrophilic conditions (15 °C) by Wei, et al. [90]. Furthermore, other studies show that phosphorus assimilation and organic nitrogen degradation increase with temperature too [85]. Thermodynamically higher temperatures benefit endergonic reactions, such as the breakdown of propionate into acetate, CO_2, and H_2, though that is not favorable to exergonic reactions, such as hydrogenotrophic methanogenesis [84]. Further, the temperature may influence the passive separation of solids with considerable improvement under thermophilic compared to psychrophilic conditions [91]. There are, however, some shortfalls in thermophilic conditions, for instance, being sensitive to environmental changes compared to the mesophilic process [92,93].

5.4. Organic Loading Rate

This is another crucial operational parameter in the biogas production process. This parameter is defined as a measure of the substrate's amount being added to a constant digester system per unit of volume per day. OLR is frequently presented as grams of total solids, chemical oxygen demand, or volatile solids per litre digester volume per day [94]. This parameter can be calculated according to Equation (14)

$$\mathrm{OLR} = \frac{\mathrm{COD}_{\mathrm{feed}} \times \mathrm{Q}}{\mathrm{V}_{\mathrm{r}}} \tag{14}$$

where $\mathrm{COD}_{\mathrm{feed}}$ is the substrate strength in terms of COD concentration (mg/L), Q is the flow rate of the substrate (L/day), and V_{r} (L) is the working volume of the reactor [95].

Literature studies have looked at how this factor affects the biogas production process, for example, Jiang, et al. [96] explored its effects on the acidogenesis of food waste. This study was focused on the OLR effects at individual AD steps and it illustrated that high OLR favoured the acetate and valerate percentages while propionate and butyrate percentages were low under the same OLR conditions. Similarly, Lim, et al. [97] conducted a comparable study for three OLR 5, 9, and 13 g/L d and observed that the highest OLR led to a very vicious fermentation broth and reactor became unstable with a lesser yield compared to the lower OLR values in the same study. Both studies agree that higher OLR may lead to an accumulation of unused solid food waste in the reactor and, therefore, lead to a reactor failure.

5.5. Hydraulic Retention Time (HRT)

This parameter measures the average retention time of a liquid or dissolved component in a reactor in a biogas study. This parameter is calculated as the tank volume divided by the influent flow rate. HRT is used to approximate the time a substrate is treated in a process. The mixing controls HRT and the biogas yield greatly depends on how the digester is mixed. Other factors that affect the HRT are substrate type used and different processes, with effects observed from a few days to a couple of months [94]. There has been contradicting data on the effects of HRT on anaerobic acidogenesis, for example, some researchers found that acidification increased with the HRT [98]. Demirel and Yenigun [99] studied the effects of variations in HRT with no control of pH and their findings revealed that a high degree of acidification was obtained at low HRT. However, the effect of HRT in the overall AD process has been observed to be similar, while longer HRT leads to higher methane content [100].

5.6. Effect of Inoculation on AD Process Parameters

The use of inocula positively reinforces sustainability through the recovery of material and reduced energy consumption [101,102]. Research has been found that the use of inocula is more significant than alkaline pre-treatment of raw material substrates since inocula have sufficient bacterial content and increase active microorganisms [103]. Since inoculum is highly cellulosic, it is unable to be digested by itself; accordingly, it is suitable to be reused in AD with other substrates. Types of inocula used in biogas production include sludge from wastewater treatment plants, digested silage, paper mill wastewater, digested sewage sludge, etc. [104,105]. Depending on the composition of each inoculum, the influence on biogas production will vary. For example, palm oil mill effluent has been used as an inoculum with cow manure biogas production, resulting in higher biogas production [106]. Activated digestate from an anaerobic digestion plant that treats crop and agriculture waste was used as an inoculum by Fabbri, et al. [107], where the best biogas production was obtained with an inoculum/substrate ratio of 2:1. Some studies have investigated the effects of different inocula types on specific substrates while others have looked at the effects of mixed inoculation and data that show a positive influence of inoculation are available in literature [108,109].

5.7. Co-Digestion of Two Substrates

In a biogas production process, anaerobic microorganisms have different requirements of organic and micronutrients for their growth and degradation of substrates. These nutritional requirements of microorganisms are usually not satisfied by the digestion of single substrates. As a result, a combination of two or more substrates can be co-digested. The suitability of substrates for biogas production is determined by their primary nutritional composition, including carbohydrates, proteins, and lipids [61]. This nutritional composition greatly influences biogas yield and methane content produced. Suppose a substrate has an imbalance in carbon to nitrogen ratio, such as animal manure. It can be co-digested with a carbon-rich substrate to reimburse for the imbalance, thus, obtaining improved process stability and biogas production [49]. Thus, co-digestion of sugar industry wastewater and Tunisian green macroalgae has been conducted to enhance biogas and methane production [110]. Further, Matheri et al. optimized biogas production through co-digestion of the organic part of municipal solid waste and chicken manure [111]. Other examples of substrates used in co-digestion are listed in Table 1.

Table 1. Previously reported studies on biogas and methane production through a co-digestion of different types of feedstocks at diverse operating parameters.

Feedstock 1	Feedstock 2	Temperature (°C)	Optimal pH	HRT (Days)	Biogas/Methane Yield (L)	Reference
Fruit and vegetable waste	Sewage sludge	20–30	4.1	105	331	[112]
Leather flashing (LF)	MSW	-	6.5	30–35	6.518	[113]
Taihu algea	Kitchen waste	35	-	1	0.388.6	[114]
Horse dung	Cow dung	28–33	-	30	0.360	[115]
Dairy manure	Food waste	35	-	20–30	0.311	[116]
Whole stillage	Cattle manure	37	5.9–6.6	640	0.310	[117]
Coffee-pulp	Cow dung	35	7.0	240	-	[118]
Food waste	Straw	35	7.0–7.5	-	0.580	[119]
Municipal wastewater	Poultry waste	35	7.3	34	0.88	[120]
Fruit vegetable waste	Sugarcane bagasse	-	3.9–7.0	30	2.600	[121]
Water hyacinth	Sugar mill effluent	30, 40	6.4–8.8	15	6.771	[122]

The above table clearly shows that not only in SA but around the globe too there has been a lack of co-digesting sugarcane process effluent and municipal solid waste for biogas production. This shows that there is a gap in the research regarding the use of these two substrates as co-substrates, both locally and all around the world.

6. Microorganism Selection, Culturing, and Inhibition

In many instances, microorganisms have proven far more cost effective than hydrolytic enzymes. Microorganisms can convert the substrates' high-molecular-weight compounds into lower-mass compounds through fermentation. Microorganisms involve the synthesis of enzymes and the multiplication of decomposing microorganisms [123]. In this process, it is necessary to consider the conditions of survival and growth of valuable microorganisms, for example, nutrients, inhibitors, pH, temperature, oxygen concentration, etc. [124]. Changes in the structure of the populations of microorganisms used in the substrate decomposition are affected by adjusting these parameters. The changes can be made based on the desire and requirements of the biogas process [123]. However, microorganisms usually involve a longer retention time, the possibility of growth of unwanted microorganisms, and stricter operating conditions [125]. Therefore, the value of the generation time for the given conditions must be considered for each species. It is also acknowledged that the doubling time for bacteria is a lot shorter than for fungi; thus, microorganisms ought to be used after prior studies [123].

Lastly, as suggested by Sawyerr, Trois, Workneh, and Okudoh [54], it is essential to have continued research on the evaluation of different types of biomass feedstock and waste streams, as substrates are critical for developing processes that lead to kinetic reactions and increasing methane yield. This is crucial because AD provides multiple advantages over other waste-management methods, such as the technology can be used on both small and large scales, low operating costs, low energy consumption, and reduced environmental impacts through the excess digestate produced, since it can be used to enhance soil fertility [54,126]. The digestate can work as a biofertilizer, as it is rich in nitrogen, phosphorus, and potassium, with traces of some elements and heavy metals. The fertiliser value differs according to the nutrients present in the feedstock [127].

7. Types of Digesters Used

A variety of digesters exist for the anaerobic digestion of organic waste material. These digester types depend on operational factors and the nature of waste to be treated, for instance, its solid content. These are classified as covered lagoon digesters (used for treating liquid manure with less than 2% solids), complete-mix digesters (treating manure with 2–10% solids), upflow and downflow fixed-bed biodigesters, batch biodigester, and continuously stirred tank reactors (low solid digesters), as presented in Table 2 [128]. UASB is the most commonly used digester for municipal and industrial wastewaters and it is suitable for both small- and large-scale biogas production. This biodigester has proven to be energetically efficient while it provides operational stability [129]. UASB can also be used for the co-digestion of sugar process wastewater and municipal solid waste as some studies have confirmed it suitable for digestion of more than one substrate [130].

Table 2. Advantages and disadvantages of various digester types used in AD process when one or more feedstocks are used.

Biodigester Type	Feedstocks	Advantages	Shortcomings	Ref
Continuous Stirred-Tank Reactor (CSTR)	Ulva slurry + whey	Enhanced mass transfer, improved temperature control, facile reaction optimization, easy automation	usage or generation of solids during the reaction, plugging problems	[131,132]

Table 2. *Cont.*

Biodigester Type	Feedstocks	Advantages	Shortcomings	Ref
Batch	Thickened sludge	simple and flexible in configuration and operation, low installation and operation cost, higher biomass retention	long run times, and difficulty in defining initial conditions	[133,134]
Upflow Anaerobic Sludge Blanket (UASB)	Recycled and synthetic wastewater containing methanol	no need for temperature control as heat is released during methanogenesis	delay in start-up and granule formation, inability to remove pathogens and coloring agents from the wastewater	[129,135,136]
Anaerobic Sequencing Batch Reactor (ASBR)	Synthetic wastewater	relatively cheap, their stepwise nature allows observation of dynamic, repeatable behavior	heavy computational requirements for multiple cycles, difficulty in establishing the correct biomass concentration in the reactor	[137]
Covered lagoon	Palm Oil Mill Effluent	easy to build, operate, and maintain	needs hydraulic maintenance from 20 to 90 days and wide areas, easy to leak out	[138]

8. Discussion

Generally, South Africa faces challenges when it comes to biogas production. Around 200 biodigesters have been installed in the last decade, with about 90% of them being for small-scale use. Nonetheless, lack of local research in this field leads to unresolvable failures of the installed biodigesters. Mukumba, et al. [139] explained how research lacks in SA regarding biogas generation and alluded to how there is an absence of data, even from the currently installed biodigesters. The main reason for this is the lack of financial assistance while data collection from the field biodigesters is hindered by some other measures.

From the available literature, it can be deduced that thorough characterization of waste substrates must be performed to ascertain the composition of each substrate. This generally gives information on physical and chemical composition regarding volatile solids, total solids, C/N ratio, and elemental analysis for carbon, nitrogen, hydrogen, and sulfur [71,72]. During substrate characterization, the place (source) where the substrate was collected is vital, as waste chemical content is affected by factors, such as weather conditions and the type of soil where the original substances were grown [73,74]. Further, chemical compositions differ greatly depending on the type of substrate. For example, carbohydrates have carbon and hydrogen, while proteins and lipids have nitrogen as part of their composition [75,76].

9. Conclusions

This review can be summarised through the following statements. There is a lack of literature regarding the usage of sugar wastewater as a substrate for biogas production compared with municipal solid waste. It is, therefore, necessary to explore the potential of this substrate and its co-digestion compatibility, particularly in South Africa, as the country is a big sugar producer, making it a hub generating volumes of sugar wastewater in the production process. Anaerobic digestion of single substrates does not lead to maximum biogas generation; hence, two or more substrates need to be co-digested for better biogas yield and high methane content. Efficient biogas production can be achieved only if there is an excellent synergistic effect between the co-digested substrates. This means an excellent overall balance of nutrients from each substrate, leading to the correct microbial community and aiding an enhanced AD process. Different parameters affect biogas production differently; therefore, special attention must be paid to such parameters for thorough parametric analysis. For example, when exploring the hydraulic retention time on biogas generation, analysis must be conducted periodically in 3–5 day intervals to investigate if the AD process is affected thoroughly. Regarding temperature studies, it can be concluded that the thermophilic range leads to higher biogas yields than the psychrophilic and mesophilic ranges. However, the mesophilic range is deemed the best since the thermophilic microorganisms are sensitive to environmental changes. Biogas production is favored by pH in a range of 6.0–8.5, meaning that there should be continuous monitoring of this parameter throughout the process. This study also found that a good balance of OLR may help avoid reactor failures. The type of reactor/digester employed for biogas production depends mainly on the type of substrates treated. Finally, sugar wastewater and the municipal solid waste can be considered as good substrates for biogas production in SA due to their enormous availability and the potential to turn their negative impacts into value addition. Biogas production is a viable alternative, among others, to boost the country from its current energy issues.

The study was limited regarding available literature in the South African context, which shows that there is a huge gap in the area of waste valorisation in South Africa, even though the country is struggling with waste management. This opens up space for more research to be conducted in this area using two of the country's most abundant feedstocks, sugarcane wastewater and municipal solid waste. The specific parameters to be considered for this waste valorisation are highlighted in this review as a foundation.

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