

Review

Methodological Approaches to Optimising Anaerobic Digestion of Water Hyacinth for Energy Efficiency in South Africa

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Abstract: Anaerobic digestion has been identified as a feasible fragment of a bioeconomy, yet numerous factors hinder the adoption of the technology in South Africa. Apart from its energy recovery, other nonmarket advantages support the technology. Though it may be challenging to have a price tag, they provide clear added worth for such investments. With a growing energy demand and global energy transitions, there is a need to sustainably commercialise the biogas industry in South Africa. Most studies are at laboratory scale and under specific conditions, which invariably create gaps in using their data for commercialising the biogas technology. The key to recognising these gaps depends on knowing the crucial technical phases that have the utmost outcome on the economics of biogas production. This study is a meta-analysis of the optimisation of anaerobic digestion through methodological approaches aimed at enhancing the production of biogas. This review, therefore, argues that regulating the fundamental operational parameters, understanding the microbial community's interactions, and modelling the anaerobic processes are vital indicators for improving the process stability and methane yield for the commercialisation of the technology. It further argues that South Africa can exploit water hyacinth as a substrate for a self-sufficient biogas production system in a bid to mitigate the invasive alien plants.

Keywords: biogas; energy transition; water hyacinth; anaerobic digestion; optimisation; sustainable cities



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1. Introduction

South Africa's energy is generated predominantly from coal and is rated as the 12th dominant contributors of greenhouse gas (GHG) emissions in the world and the first in Africa [1]. However, attempts at diversifying the energy mix with renewable energy sources such as bioenergy, solar energy, and hydropower are being made, as they are essential contributors to the country's energy supply portfolio and national development. Renewable energy has the potential to contribute to the world energy security and significantly reduce dependency on fossil fuels—oil, coal, and gas [2–4]. They have also provided opportunities for mitigating the devastating effects of greenhouse gases [3,5]. One of the principal renewable energy sources, in the long run, is bioenergy, because it presents a wide range of possibilities such as pyrolysis, anaerobic digestion (AD), and gasification. From a feasibility perspective, each bioenergy technology demonstrates various advantages and disadvantages. For instance, incinerators are frowned upon because of the harmful products such as furans and dioxins released, if not appropriately managed [6,7].

Therefore, consideration for any will be for the availability of feedstock, proximate obtainable infrastructure, and market need. AD has received attention because of its adaptation to a broad spectrum of feedstocks, nutrient recovery, and net energy output [8–10].

AD is described as a biological degradation of organic materials without the presence of oxygen, thereby resulting in methane-rich biogas and an enriched digestate [11]. The methane generated during AD can be converted to different energies depending on indigenous needs; it can be compressed and liquefied as a transportation fuel [12], generation of electricity [13], heat and cooking [2], while the digestate improves the soil structures and reduces the use of chemical fertilisers as shown in Figure 1. AD is considered a flexible technology as its scale of operation can vary from a small size to a much bigger size. It can be integrated with other waste-to-energy technologies such as pyrolysis. AD helps solve societal problems, by creating a sustainable waste management opportunity—mostly by reducing organic wastes on landfills, and economically feasible wastewater treatment.

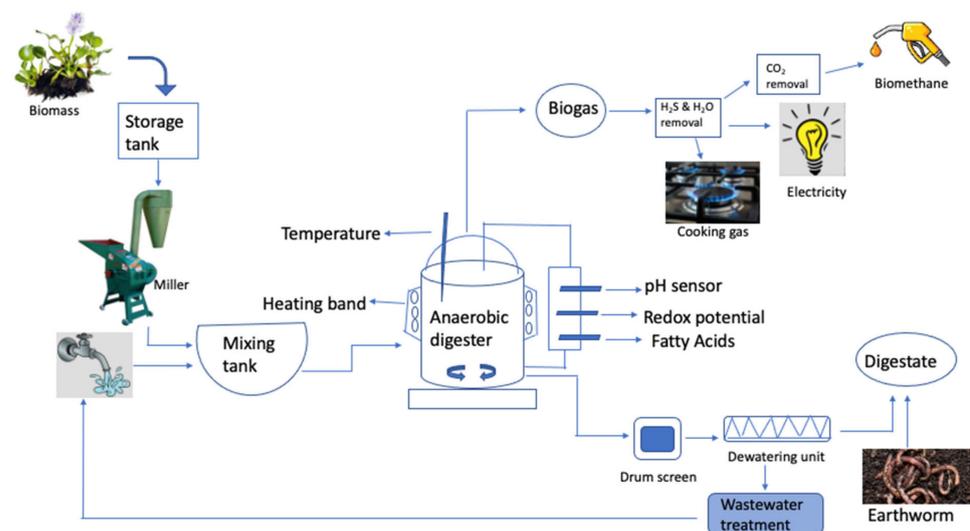


Figure 1. The process flow of anaerobic digestion. Source: Based on personal notes (2021).

In South Africa, AD technology is still considered to be at its inception, even though the technology was first utilised as far back as in the 1950s [14]. The lackadaisical adoption of the technology compared to other countries is ascribed to inadequate feedstocks, lack of institutional support, research output communication, bureaucratic issues such as streamlining the application procedure, and shift of interest to other renewable energy sources [15,16]. According to Tiepelt [17], the number of AD plants in South Africa is not more than 400. Some of the plants are owned by Bio2Watt, WEC/Northern Waste Water Treatment Works, BiogasSA, iBert, and SANEDI. The viability of the biogas industry is largely a function of the cost of feedstock. While most of the deployed biogas plants in the country have concentrated mainly on using animal waste and wastewater as feedstock, there is a broad spectrum of feedstocks and each is dependent on accessibility.

WH (*Eichhornia crassipes*), an invasive alien plant, has gained attention as a promising feedstock for AD because of its high proliferation rate, no threat to food security globally, efficiently hydrolysable sugars, low lignin content, and energy obtained efficiencies. *Eichhornia crassipes* is a native of the Amazon Basin of South America but has spread vastly worldwide. According to Yan and Guo [18], the pervasive occurrence of WH is because of its distinctive biological features, global warming, and intensified eutrophication of surface waters. The prevalence of the aquatic plant in South Africa is attributed to the nutrient enrichment of dams because of the poor treatment of sewage of the heavily populous metropolitans [19]. Its invasion is known to affect sustainability, economic growth, biodiversity, and human health, and the control methods utilised are either not sustainable (chemical), not cost-effective (mechanical), or take a longer time (biological). The expendi-

ture on the control of invasive species in the country is valued to surpass 70 million U.S Dollars annually, which is almost 0.3% of the republic's gross domestic product [20].

WH has been utilised in phytoremediation, compost, animal feed, enzyme production, and bioenergy. Ilo et al. [21] compared the techno-economic feasibility of utilising the aquatic plant to the control methods and reported that utilising *E. crassipes* is economically feasible and sustainable, as most of the cost–benefit analysis for the control methods used models that were based on postulations of market prices. However, the fiscal viability models applied in valuable resource recovery of *E. crassipes* were more genuine and adaptive to likely variations in impending cashflows and discount rates. Therefore, its use in AD is a sustainable method of mitigating its adverse impacts in South Africa. However, the AD process is considered unstable, with a high cost of investment and low return on investment [22]. Optimising the AD process is significant and can considerably add to the decrease of the economic and environmental cost.

This review, therefore, presents WH as a promising and sustainable source of feedstock and aims to provide a comprehensive overview for methodologically improving the efficiency of AD of WH. It further accentuates AD of WH as an economically feasible energy alternative that would sustainably alleviate South Africa's energy crisis. Studies on the effectiveness of a specific methodology recommended by scientists regarding the relationship between the quantity of biogas produced in a laboratory and the possible efficacy when used on an industrial scale are seldom provided [23–25], suggesting a dearth of clarity in methodology. The key to recognising the gaps from laboratory scale to industrial scale of AD depends on knowing the crucial technical phases that have the utmost outcome on the economics [26]. This review consequently describes the strategies for optimising the AD process as (1) regulating the fundamental process parameters, (2) high-throughput molecular tools in understanding the structure of the microbial consortium in AD expose the ecology of unidentified unculturable anaerobic microorganisms, and (3) models and simulations that help comprehend and envisage the AD process for optimisation. Hence, the review envisages that the result of the interpretations would help biogas plant operators improve the operations of AD of WH for optimal energy recovery and help relevant stakeholders understand and facilitate the adoption of the technology in the country.

2. Materials and Methods

This paper is based on a meta-analysis of several empirical works, which aimed at (1) laboratory analysis of AD of WH as both mono- and co-digestion and (2) the process parameters for optimal performance and process stability of AD. An automated search using different databases was executed among which included EBSCOhost, Google Scholar, and Scopus. The following terms were used to search for the relevant studies/and or articles: “biogas”, “methane yield”, “water hyacinth or *Eichhornia crassipes* “process stability”, “co-digestion”, “laboratory analysis”, “system analysis”. The scope of the study was limited to articles published in the past ten years because of the large number of articles retrieved. Furthermore, supplementary investigations were made by studying references of publications and grey literature for more articles that were not retrieved during the search. A total of 1209 records were retrieved and thoroughly examined based on inclusion and exclusion criteria. Excluded articles are (1) articles not available in the English language, (2) unpublished thesis and reports, and (3) articles that are not directly related to the subject areas. The title, abstract, and full-text articles were assessed based on their significance to the objectives stated above; this exercise resulted in the selection of 52 papers. The ROSES flow diagram of the number of studies retrieved is presented in Figure 2. The review made efforts for the search to be all-inclusive.

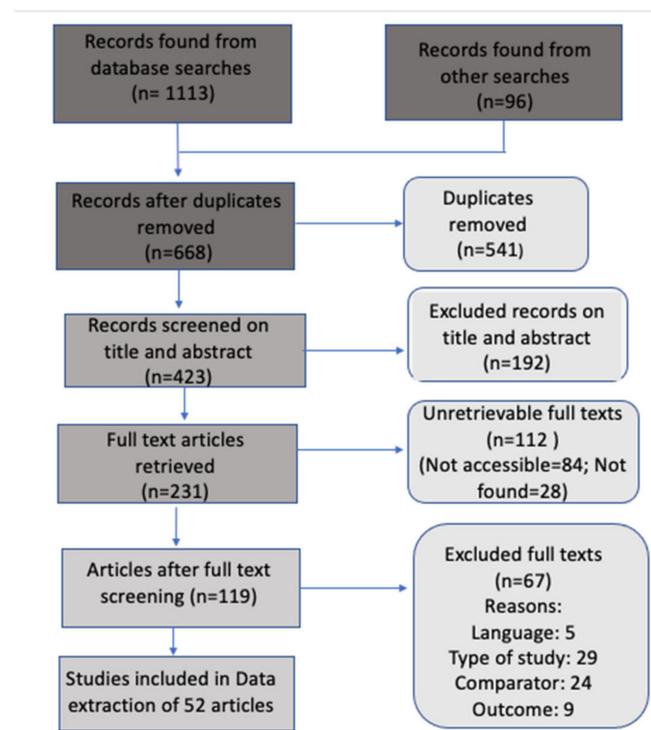


Figure 2. Methodological approach using a rapid appraisal in selected peer-reviewed articles. Source: Adapted from [27].

3. Process Parameters for Optimal AD Performance

Operational and environmental factors are the two sets of parameters that affect AD performance [8]. Attaining an optimum method of AD through regulating the fundamental operational parameters, understanding the microbial community's interactions, and modelling of the anaerobic processes necessitates an assessment of the consequential trade-off between the additional cost of optimisation techniques and improvement in biogas yield. In other words, the basis of optimisation of AD is a favourable relationship between methodological improvements and economic feasibility. While the purpose of improving the technical process comprises optimising biogas production and enhancing process stability, the financial incentive is, therefore, to increase the return on investment. Table 1 represents studies on AD of WH. The studies revealed the effects of pretreatment, mono and co-digestion, temperature, and HRT on biogas and methane yield. This segment presents the methodological review of the AD to highlight the varying biogas yields that are attributed to operational and environmental factors to help scholars greatly comprehend their interactions for optimisation.

Table 1. Studies on AD of WH evaluating numerous process conditions.

S/N	Reference	Digester Type	Substrate	Pretreatment	Temperature (°C)	Inoculum to Substrate Ratio	Methane Yield (%)	Biogas Yield (mL g ⁻¹ vs)	Hrt (Days)
1	[28]	Batch reactors	WH (Untreated) WH (Pre-treated)	Microbial (<i>Citrobacter werkmanii</i> VKVVG4)	-	-	57 ± 0.2 59.99 ± 0.3	156 ± 11	50
2	[29]	Laboratory scale digester	WH + <i>V. dysplasia</i> WH+ <i>P. chrysosporium</i> WH	Fungal (<i>Volvariella dysplasia</i> and <i>Phanerochaete chrysosporium</i>)	-	-	64 66 60	99.45 243.66 100	60
3	[30]	ALBR and UASB (20 L)	WH WH + WAS WH + FW	Mechanically crushed	30 ± 3	1:2	63–68	142.8 ± 10 148 ± 5 394.6 ± 12	10
4	[31]	Lab-scale digester	CM + SS + WH	Cut and mashed	37	-	65	81.2	12
5	[32]	Lab-scale digester	WH Salvinia	Blended	37 ± 2	2:1	62 63 47.67 67.66 47.73 42.89 68.3	552 221 69 96.99 70 62 370.85	60
6	[33]	Lab-scale anaerobic digester	<i>Prosopis juliflora</i> pods + dry leaves + WH	Crushed with blender	35 ± 2	-	65.4 58.2 52.1	320.54 286.50 298.83	40
7	[34]	Batch type anaerobic digester (60 L)	FW WH FW + WH (15:2) FW + WH (8:3)	Dried and pulverised	3243	1:2	64.4	42.40	-
8	[35]	Laboratory digester	WH (pretreated)	Cut, blended, and treated with H ₂ SO ₄	28–30	-	57.65 ± 0.2 65.65 ± 0.5	253 ± 3 296 ± 9	50
9	[36]	Glass batch reactors	WH + BP (untreated) WH (Pre-treated) + BP	Thermal (Hot air oven)	-	-	37.2 23.5 37.8 39.7	419 285.21 387.53 382.46	20
10	[37]	0.5 L bioreactor vessels	YP + WH, CaP + WH, CoP + WH, PP + WH	Heat dried and milled	37 ± 1	1:2			

Table 1. Cont.

S/N	Reference	Digester Type	Substrate	Pretreatment	Temperature (°C)	Inoculum to Substrate Ratio	Methane Yield (%)	Biogas Yield (mL g ⁻¹ vs)	Hrt (Days)
11	[38]	Continuous mode two-stage reactor with stage separation (20 L)	WH (untreated) WH (pre-treated) WH + FW	Macerated and preheated WH at 90 °C for 1 hr	35 ± 1	-	57–61 68–71 60–63	-	20
12	[39]	Dry fermentation reactor (5 L)	WH	-	Ambient	1:1 0.25:1	69 61 ± 1.5	41.79 -	30
13	[40]	2 L Glass batch reactors	WH	-	37 ± 2	0.5:1 1:1 3:1	58 ± 0.33 57 ± 0.67 63 ± 1.4	406 - 383	30
14	[41]	500 mL Duran glass bottles	WH WH + Fruit and vegetable waste	-	37	-	57.5 60.5	114 141	15

WH—Water hyacinth, ALBR—Anaerobic Leaching Bed Reactor, UASB—Upflow Anaerobic Sludge Bed Reactor, FW—Food waste, CM—Cow manure, BP—Banana peels, YP—Yam peels, CaP—Cassava peels, CoP—Cocoyam peels, PP—Plantain peels, WAS—Waste Activated Sludge, SS—Sewage sludge.

The biogas yields of the fourteen studies (Table 1) were converted to mL g^{-1} vs for uniformity and ease of comparison. Most of the studies adopted the mesophilic temperature [30–35,37–41] while the rest did not disclose the temperature used [28,29,36]. Furthermore, 35.7% of the studies that used mechanical pretreatment produced a higher biogas yield at the range of 62–552 mL g^{-1} vs [30–34] than those that used other pretreatment processes. Although the chemical process of pretreatment is not popular among the studies, biogas yield was 42.40 mL g^{-1} vs [35]. While 21.4% did not specify the pretreatment used but had biogas yield between 41.79–406 mL g^{-1} vs [39–41], the biological and thermal pretreatment had a biogas yield between 99.45–243.66 mL g^{-1} vs [28,29] and 253 ± 3 –419 mL g^{-1} vs [36–38], respectively. Mathew et al. [32] compared the AD of WH to that of *Salvinia* and reported a high biogas yield of 552 mL g^{-1} vs to 221 mL g^{-1} vs. The study also revealed a lower volatile fatty acid accumulation (VFA) during the degradation of WH compared to *Salvinia*.

It can be deduced from Table 1 that co-digestion of WH with other organic materials such as food waste, sewage sludge, and peels produced more methane yield than mono-digestion. In addition, 57.1% of the studies produced more methane yield at an average of 65% than mono digestion at 62%. However, other factors could have either promoted or inhibited the methane and biogas yield in these studies.

3.1. Operational Factors

3.1.1. Effect of Digester Design

The design of a digester is one prominent feature of a cost-effective AD process. The assessment of digester design is dependent on various factors such as cost of installation and maintenance, performance, energy recovery, and discharge of effluents [42]. The different digesters that are commonly constructed are single- or multi-stage, dry or wet, and batch or continuous mode. The single-stage reactor is reported to have fewer technicalities and operational costs; however, the microbial consortiums growth rate is limited as they perform in the same environmental conditions. On the other hand, the multi-stage offers a favourable condition to the microorganisms, but are more complex, necessitate more space, and are not economical [43,44]. Although the multi-stage reactors are considered to improve process stability, it is not factual to state that the single-stage reactors are unreliable. The continuous stirred tank reactor (CSTR) is deemed to be easier to operate than other reactors such as up-flow anaerobic sludge bed reactors (UASB). A digester design should be simple, effective, and economically feasible. Its suitability rating should address parameters such as mixing, temperature, retention time, and the feedstock's quantity and quality, mostly by total solid (TS) basis [45,46].

3.1.2. Mixing

The effects of mixing in AD are to guarantee sufficient access to organic materials for the dynamic microorganisms and to proficiently circulate the heat inside the reactor, thereby inhibiting temperature gradients, dead zones, and hot spots. There are various techniques of mixing, i.e., propellers, recirculation, and each is selected by the type of digester, the TS of the feedstock, and the agitator type. Mechanical mixing has been criticised because of its energy consumption that directly increases operational cost. Mixing is done intermittently so as not to disturb syntrophic activity. Intermittent mixing improves biogas yield because the digestion by-products are degraded better by slower hydrolysis and fermentation [47]. Constant vigorous agitation influences the methane content negatively [48] and the insertion of propellers could trigger an influx of oxygen into the reactor [49]. Of the various mixing techniques, recirculation methods have been proven to be the most economical and efficient in enhancing AD's performance. Ni et al. [50] studied the effect of liquid digestate recirculation on methane yield, and the system balance of AD of pig manure. Under the same operational conditions, the methane yield from the reactors was comparable in phase 1. When the organic loading rate (OLR) was below 5 g vs L^{-1}

in phase 2, there was an increase in Reactor 2 (with recirculation) compared to Reactor 1 (without recirculation), which signified that under comparative OLRs, liquid digestate recirculation stimulated process stability [50].

3.1.3. Hydraulic Retention Time (HRT)

It is an essential factor to consider during the design of a digester as well as for the growth rates of hydrogen- and methane-forming bacteria. It regulates the delivery of substrates to microorganisms. A longer HRT gives the microorganism adequate contact time to degrade the substrates, thereby increasing biogas yield; however, it is considered to increase the operational cost. On the other hand, a shorter HRT is interrelated with volatile fatty acids (VFA) accumulation and washing out of methanogens. The different studies on AD of WH presented in Table 1 were further analysed for the effect of HRT on methane yield and presented in Figure 3. While the analysis illustrates that the highest methane yield of 71–68.3% is at HRT of 20–40 days [34,38,39], nonetheless, at the same HRT of 20 days, the study of Longjan and Dehouche [37] revealed a low methane yield of 23.5–39.7%. A low HRT is considered attractive as it is directly related to a lower investment cost and enhanced process stability [51,52]. The study of Tasnim et al. [31] on co-digestion of cow manure, sewage sludge, and WH revealed a high methane yield of 65% at a 10-day HRT, and Hernández-Shek et al. [41] reported a high methane yield of 60.5% at HRT of 15 days in the co-digestion of WH with fruit and vegetable waste.

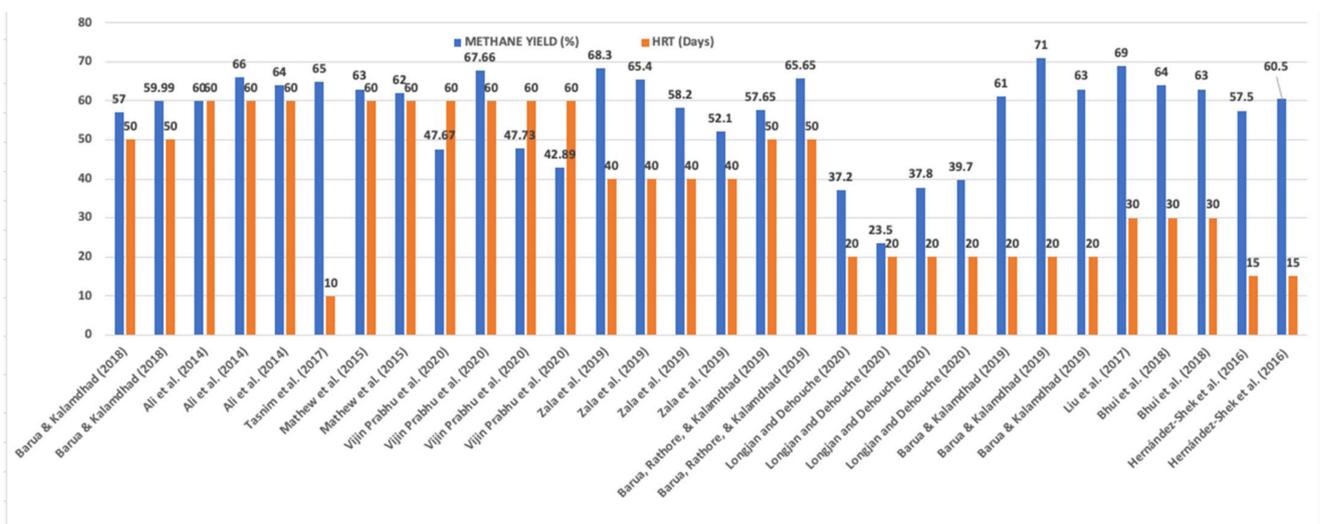


Figure 3. Effect of HRT on methane yield. Source: Based on personal notes (2021).

3.2. Environmental Factors

3.2.1. Effect of Inhibition

AD is a delicate process, where the presence of inhibitory compounds such as ammonia and VFA cause system imbalance resulting in low biogas and methane yield [9]. This is because the microbial consortium in each biochemical stage is susceptible to numerous inhibitory matters in the feedstock or produced during the anaerobic process.

Ammonia

Ammonia, which is formed during the biological breakdown of nitrogenous material, is an important function in AD performance and stability. It exists in two basic forms: Ammonium ion (NH_4^+) and free ammonia Nitrogen (NH_3), and a combination of both forms is known as Total Ammonia Nitrogen (TAN). Free ammonia has much higher toxicity and a more significant effect on AD than ammonium ion because it can penetrate cells and disturb microorganisms' metabolism [42,53]. Ideally, ammonia concentration guarantees the methanogenic medium's buffer capacity, but it becomes toxic above a threshold

concentration. There are various reports of these threshold levels of toxicity and most do not differentiate between free ammonia and TAN. While Yenigün and Demirel [53] revealed that free ammonia's threshold for toxicity is between 150 to 1200 mg L⁻¹, Rajagopal et al. [54] reported a range of 1500 to 7000 mg L⁻¹.

Studies have shown that methodologies such as pretreatment of feedstocks, co-digestion, air stripping, alteration of pH and temperature, a decrease of OLR, and the addition of support media have been applied in mitigating the inhibitory effect of ammonia [53–55]. Zhang et al. [56], who investigated the effect of air stripping in removing ammonia in AD of piggy wastewater, disclosed that the elimination of ammonia was reliant on pH and aeration rate. Based on their findings, air stripping at alkaline pH is feasible for averting system imbalance in AD of WH.

Volatile Fatty Acids

VFAs are molecular entities formed during the hydrolysis phase, as a result of the degradation of more complex structures. Accumulation of VFA, which causes inhibition, occurs when there is an increase in the OLR. This increase leads to a faster hydrolysis rate that disrupts the acetogen's and methanogens' adaptation, resulting in a drop in pH and a low methane yield [10]. VFA concentrations are used as indicators of process imbalance; however, there are debates on the exact concentration as numerous experiments reveal that process stability occurred at different levels. Mathew et al. [32] reported a total VFA in the AD of WH to be lower than 22 mg L⁻¹. The use of the propionic acid to acetic acid ratio as a sign of process instability is recommended because propionic acids are inhibitory to methanogens [40].

Several approaches can prevent process instabilities as a result of the accumulation of VFA. Rocamora et al. [10] recommended increasing the inoculum: substrate (I:S) ratio and percolate recirculation; however, the study of Bhui et al. [40], which aimed at exploring the effect of VFA in different I:S ratios to biogas production from batch-scale AD of WH, reported maximum VFA accumulations at 1084 mg L⁻¹ for WH at 0.25:1 ratio and lowest values at 158 mg L⁻¹ for WH at a rate of 3:1. The study revealed that the total VFA drastically affected methane content in 3:1 (WH). Anukam et al. [13] opined for the use of non-biological conductive materials that absorb toxins, which calls for further research.

3.2.2. Organic Loading Rate (OLR)

OLR determines the biogas and methane yield. The kilograms of volatile solids are loaded per volume of the reactor per day [57]. An OLR and the I:S ratio mainly on TS contents simplify the operation process because TS is more realistic than the study of other parameters [47]. Barua and Kalamdhad [38] reported a stable pH when the OLR was increased from 0.625 kg COD m³⁻¹ to 1.35 kg COD m³⁻¹; however, the process became unstable when it was further increased to 4.55 kg COD m³⁻¹. The change in pH indicates that the discharge Chemical Oxygen Demand (COD) mainly constitutes the unutilised VFA formed in the reactor at an increased OLR. OLR should be gradual to permit suitable acclimatisation of the microorganism because an abrupt change disturbs them. Nkuna et al. [58] studied the consequences of uneven OLR on microbial communities and AD of WH (mono- and co-digestion) and pointed out that unstable OLR affected the process performance, system balance, and the composition of microorganisms of mono- and co-digestion, but it was dominant in co-digestion.

3.2.3. Temperature

Temperature controls the rates of the enzymatic reaction and substrate diffusion. Most digesters function at either mesophilic (30–40 °C) or thermophilic temperatures (45–60 °C); each temperature has a different active microbial consortium. A slight change in temperature of an anaerobic digester affects the microorganisms' activities, resulting in a low biogas yield. While the thermophilic phase enhances the complex substrate's solubilisation rate, the mesophilic stage provides a stable methane production process [59]. An AD operated

in thermophilic temperature has a higher reaction rate, thereby leading to a lesser HRT and digester volumes. It requires high energy for maintaining the reactor at such a high temperature. However, with a slow reaction rate and high HRT, mesophilic digesters are commonly used because of their low energy cost, stable operational process, and less critical ammonium inhibition. Recently, attention has been drawn to the Temperature Phased Anaerobic digesters (TPAD), which involves two-phase systems, both thermophilic and mesophilic phases.

3.2.3.1. pH

pH reveals the approximate condition of a digester, and a drop in pH results in low biogas yield and methanogenesis inhibition. Barua and Kalamdhad [38] noted that a pH of 6.5–7.5 is best for microorganisms to thrive in a digester. However, multi-stage digesters are recommended as the biochemical stages require different optimal pH values. At the same time, Rocamora et al. [10] reported an optimal pH of hydrolysis and acidogenesis to be within the range of 5.5 and 6.5, and Mao et al. [60] opined that methanogenesis occurs at a higher pH of 6.5 and 8.2, with an optimum at 7.0.

Studies have shown that it is not ideal to use pH as a first pointer for process stability because it relies on buffering capacity. For instance, Yi et al. [61] analysed the role of increasing total solids on the performance of AD of food waste at mesophilic temperature. Digesters with higher TS had higher VFAs accumulation, but digester R3, which had the highest VFAs accumulation, did not indicate a low pH. The study of Widyarani et al. [62] on the effect of pH on biogas generation of tofu wastewater revealed that low pH did not negatively affect the batch AD of the Tofu wastewater system. The outcome of their study implies that ensuring there is buffer capacity is imperative in comparison to adjusting pH.

3.2.4. Co-Digestion

The anaerobic mono-digestion of *E. crassipes* is rate-limiting because the hydrolysis of the lignocellulosic structure takes a long time and reduces biogas yield [36]. Co-digestion is an efficient and commercially feasible method to improve methane production and system stability [63]. The essence of co-digestion is to adjust the carbon/nitrogen (C/N) ratio of the feedstocks for efficient microbial growth. C/N ratio shows the nutrient levels of feedstocks. A high C/N ratio results in a shortage of nitrogen and dormancy of methanogens, reducing methane yield. In contrast, a low C/N ratio leads to carbon shortage, thereby causing the accumulation of VFA, which has a negative effect during methanogenesis.

Priya et al. [30] tested practical solutions to enhance biogas production from the AD of WH. They reported a biogas yield from the co-digestion of WH, with activated sludge and food waste as $\sim 150 \text{ mL g}^{-1}$ vs and $\sim 400 \text{ mL g}^{-1}$ vs, respectively. In contrast, mono-digestion of WH yielded $\sim 140 \text{ mL g}^{-1}$ vs of biogas. However, Zala et al. [34] reported a higher biogas yield of 320.5 mL g^{-1} vs in mono-digestion of WH compared to the biogas yield of 286.5 mL g^{-1} vs and 298.8 mL g^{-1} vs in co-digestion of WH and food waste, but the difference in pH rate displayed process stability in co-digestion than in mono-digestion.

3.2.5. FOS/TAC

Several parameters such as methane yield, pH, or VFA are used as indicators for process stability in AD; however, the FOS/TAC is extensively reflected as the most imperative and express marker [64]. The titration method, which represents the ratio between volatile organic acids (FOS) and total inorganic carbonate (buffer capacity) (TAC), is an easy and continuous method for determining AD process stability [58,65]. The composition of feedstock for AD affects the FOS/TAC value. Nkuna and Roopnarain [58] reported process stability and high biogas yield from the AD of WH at FOS/TAC ratio of 0.4–0.6. A high FOS/TAC value (>0.6) implies system overload, and this results in a low yield of methane, whereas a low FOS/TAC value indicates a low OLR, which causes process imbalance.

3.3. Other Factors

3.3.1. Pretreatment

Production of biogas from lignocellulosic biomass is demanding because its structure and composition makes it recalcitrant to microbial or enzymatic degradation. However, pretreatment is an efficient approach to breaking down the organic molecules' covalent bonds, decreasing the recalcitrance, and increasing biodegradability. It exposes the lignocellulosic polymers into hexoses and pentoses, helps microorganisms access the cellulose, and hastens the hydrolysis stage. There are different pretreatment methods; however, the choice for pre-treatment should be sustainable, cost-effective, and not yield inhibitory compounds.

A lack of empirical consensus still exists in the literature over an established single pretreatment method that is the most effective for high methane yield. Sarto et al. [35] examined the effect of chemical pretreatment (H_2SO_4) in facilitating the production of biogas from WH, and although the cellulose content was broken down significantly to glucose, the lignin composition slightly decreased. Barua et al. [28] investigated the effect of microbial (*Citrobacter werkmanii* VKVVG4) pretreatment on WH. The study showed that, although microbial pretreatment consumed time to improve the solubility and breakdown of WH's lignocellulosic cell wall, it enhanced the biogas yield. In recent time, the use of integrated pretreatment methods has been utilised for optimal methane production.

3.3.2. Inoculum

Inoculum with the balanced microbial consortium is an important factor that reduces the acclimatisation period for process stability and efficiency of AD performance [66]. It is a proficient method of delivering the essential microorganisms to the AD process. In recent times, specific microorganisms are used as inoculants to increase degradation rate, unlike previously, where indigenous microorganisms conducted the degradation. The presence of key members of the anaerobic microbial consortium in an inoculum strongly influences the AD process's performance [38]. A suitable I/S ratio circumvents process instability in a digester by creating a conducive atmosphere for microbial activities. A high I/S ratio enhances the efficiency of removing COD as it hastens COD's breakdown to biogas [40]. COD is a suitable indicator that reveals the extent the degradation process has taken to be completed; the higher the COD removal, the more stable the process is.

Examining how microbial consortium change at the start-up phase increases the microbial community's relationship to AD performance, thereby improving the process economics. Studies have engaged in using high-throughput methodologies such as 454 pyrosequencing, quantitative Polymerase Chain Reaction (qPCR), and fluorescent in situ hybridisation (FISH) for such investigations [67,68]. The use of support media (immobilisers) stimulates methanogenic reactions by creating opportunities on feedstock's surface area for microbial attachment. Although there is limited literature on the consequences of these support media to the microorganisms, the study of Poirier et al. [69] emphasised that immobilisers such as zeolites and activated carbon aided the AD process under high ammonium stress and also improved the growth of the microorganisms.

4. Modelling of AD Process

Although it is imperative to acquire knowledge from conducting tests, a theoretical evaluation must propose a hypothesis and establish a linkage for knowing and optimising the AD process. According to Kucharska et al. [70], modelling is used in optimising the process parameters, thereby saving time and increasing the efficacy of utilising resources. Mathematical models aid in investigating phenomena during the AD process; they are also used to transfer experiments from pilot-scale to industrial scale. International Water Associations' Anaerobic Digestion Model No 1 (ADMI) is the most generally known model in AD studies; however, its intricacy had steered the inclusion of the latest empirical understanding or simpler algorithms [71]. Other modeling approaches utilised on the AD optimisation process are classified by Kucharska et al. [70] as Kinetic models such as

Gompertz and Monod models; black-box models such as Response Surface Methodology (RSM) and Artificial Neural Networks (ANN) and Substrate conversion-based models such as First-order, Logistic and Boltzmann [72] and AD model No. 2 (AM2) [71] have also been applied for fitness.

The black-box models predict complicated processes with unspecified input and output data correlation. It does not require an antecedent understanding of the mechanism. The model is applied when a reaction is influenced by numerous variables; it assesses the relationship between biogas yield and independent parameters. ANN is considered to have a higher prediction capability that is close to measured gases compared to RSM [70]. Chanathaworn [73] improved the biogas production from the AD of WH and earthworm bedding wastewater using the RSM model approach, and TS, pH, and particle size as the model variables. The study confirmed the fitness of the model at a coefficient of determination (R^2) of 96.1%

The kinetic models consider microbial consortium as an essential component of the digester. For instance, the modified Gompertz equation reveals the correlation between methane yield and microbial growth pattern [28]. On the other hand, the substrate conversion-based models aim at the substrate decomposition or biogas yield and not on microbial growth rate. For instance, the First-order Kinetics provides changes in volatile solids during biodegradation, although it is considered to have an extensive latency period [74] and not predict process failure [75].

The R^2 and root of the mean of the squares (RMSE) are usually used to compare fitting errors of models. Sarto et al. [35] compared the simulation of biogas production from *E. crassipes* with a modified Gompertz, First-order kinetics, and Cone model, and reported that all the proposed models fitted the determined biogas yield with fitting inaccuracy that is below 10%. The variation between determined and theorised biogas yield for modified Gompertz was 0.271–9.78%, 3.491–5.424% for First-order Kinetic, and 0.032–8.743% for the Cone model, while the R^2 was 0.964–0.995 (modified Gompertz), 0.977–0.985 (First-order Kinetic), and 0.980–0.994 (Cone), respectively.

5. Outlook of Biogas Technology in South Africa's Energy Transition

The Energy sector of South Africa contributed to nearly 80% of the nation's Greenhouse gas (GHG) emissions in 2019, of which half originated from petrol production and power generation [76]. Consequently, South Africa has pledged in the Integrated Resource Plan 2019 to a low-carbon economy to address climate change. However, there is a need for this transition to be timely as the country is facing the menace of climate change. The present COVID-19 pandemic is an avenue for the energy transition to achieve the climate targets and promote socio-economic development [77–79]. The three priority areas for energy transition for sustainable cities are buildings, transport, and integrated energy systems; this makes AD an integral technology for South Africa's bioeconomy because it is multifaceted.

The use of biomethane in the transport sector is promising, though it is still at the infant level in the country. Biomethane can be compressed and utilised in passenger vehicles or liquefied and used in heavy-haul vehicles and ships. Its utilisation as a transport fuel is considered to have limited environmental concerns, such as GHG emissions, compared to fossil-derived fuels [12,80]. In addition, compared to other biofuels, biomethane is unique in blending wholly with natural gas without requiring the engine to be changed. For example, the blending of bioethanol with petrol is usually at portions of 5, 10, and 85% quantities, and while the portions of 5 and 10 do not require amendment of vehicle, the use of an 85% ratio does [81]. This amendment of the vehicle (Flexi-Fuel vehicles) is reported to possibly release unburned ethanol, acetaldehyde, and acetic acid in the environment [82] and also gives rise to disastrous engine failure because the bioethanol is corrosive and it forms films as it is mixable in water and non-mixable in oil [79,83].

A fundamental question is whether the numerous valuable functions linked to the AD technology can be significantly realistic and sustainable. One of the constraining facets of

AD is the availability of feedstocks. While the energy crops are frowned at as unsustainable, agricultural residues and organic fraction of municipal solid waste are gaining attention. The lignocellulosic feedstock trade is liable to develop quickly in the long run when compared to conventional feedstocks. Other limitations of the biogas industry's growth ultimately rely on sound policy and institutional framework, market players, and technical expertise. In the global energy market, the biofuel markets are in poor trade patterns against fossil fuel markets notwithstanding the tariffs and no-tariff trade difficulties. The South African government had introduced a renewable energy feed-in-tariffs (REFiTs) program, which had poor implementation and was substituted by an auction-based tariff under the Renewable Energy Independent Power Producer Procurement (REIPP) program [84]. Its sustainability is questionable as it is considered to have an expensive transaction fee, and the monitoring and assessment procedure are not accessible to the public. With the growing energy demand in the country, there is a need to scale up the biogas industry, which, even now, has not been adopted fully; however, one needs to certify the production approach and the kind of feedstocks used.

6. Conclusions

High energy demand and accessibility of ample feedstocks have made AD a promising business opportunity. The AD technology decreases carbon emissions, offers energy security, and creates green jobs. Commercialisation of biogas production has not been adopted to its full potential in South Africa due to sound policy and institutional framework, a market economy, technical expertise, and sustainable feedstocks. While research and investments in biogas production are strongly recommended for upscaling biogas production to a commercial level, there are, however, substantial gaps in the literature due to disagreements over the most economical methods or combination of methods that generates optimal biogas yield. Attaining an optimum method of AD of WH through regulating the fundamental operational parameters, understanding the microbial community's interactions, and modelling of the anaerobic processes necessitates an assessment of the consequential trade-off between the additional cost of optimisation techniques and improvement in biogas yield. It was deduced from the studies that co-digestion of WH and other organic materials such as food waste and sewage sludge produced more methane yield of 65% than mono digestion of 62%. Furthermore, 35.7% of the studies that used mechanical pretreatment produced a higher biogas yield at the range of 62–552 mL g⁻¹ vs than those that used other pretreatment processes. These methods could be extended to the utilisation of other feedstocks notwithstanding that the present review focused on WH as they share operational similarities. It is envisaged that the thematic issues addressed in this paper will contribute to policy discourse and scholarly deliberations that would engender more research and investments towards upscaling biogas production to the commercial phase.

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Abbreviations

AD—Anaerobic Digestion, WH—Water hyacinth, LCFA—Long-chain fatty acids, CSTR—Continuous stirred tank reactor, ALBR—Anaerobic leaching bed reactor, UASB—Upflow anaerobic

sludge bed reactor, TPAD—Temperature phased anaerobic digester, VS—Volatile Solids, FW—Food waste, HRT—Hydraulic retention time, C/N—Carbon-Nitrogen ratio, VFA—Volatile fatty acids, I/S—Inoculum-Substrate ratio, TS—Total solids, CH₄—Methane, OLR—Organic loading rate, TAN—Total Ammonia Nitrogen, COD—Chemical Oxygen Demand, GHG—Greenhouse gas.

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