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Review Article

Anaerobic Codigestion of Sludge and Food Waste for Enhanced Resource Recovery

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ABSTRACT

Resource oriented management of organic waste streams, such as waste-activated sludge and food waste, presents an opportunity to recover energy and nutrients while mitigating climate change. The characteristics of sludge, including low nutrient and high solid contents, limit its treatment through anaerobic digestion. Anaerobic co-digestion of sludge with an abundant organic-rich substrate such as food waste can overcome the limitations of sludge mono-digestion. The sustainability of the codigestion approach is due to the ability to subsidise the energy demand of the entire wastewater treatment system with the bioenergy produced. Moreover, other resources, namely, struvite, liquid fertiliser, and compost, can be recovered. The present study reviews the anaerobic codigestion of sludge with food waste, focusing on the waste substrates produced in South Africa.

KEYWORDS

Waste-activated sludge, Food waste, Anaerobic codigestion, Biogas, Bioresource

INTRODUCTION

Air, water, and food are crucial to the survival of any living being on Earth. Human activities pose a threat to the quality of air and water since most of the activities are not of a closed-loop nature. The lack of adequate treatment for the wastes produced, particularly those containing organic matter, leads to air and water pollution [1]. For instance, food waste and wastewater sludge that are inappropriately discarded rot and release greenhouse gases (GHG) into the atmosphere, contributing to global warming, while leachates seep and pollute underground water bodies [2]. Organic waste is a resource that can aid in producing food and provide renewable fuel. Furthermore, the reliance on fossil fuels also contributes significantly to air pollution through GHG emissions. The anaerobic digestion (AD) of waste-activated sludge (WAS) with food waste (FW) has gained much attention as a successful technology to remedy organic waste streams [3]. This treatment method reduces the amount of GHG released into the atmosphere while producing carbon-neutral biogas and biofertiliser. Biofertilisers can be used in agriculture for food production, and the biogas harvested can be used to heat, generate electricity, or fuel vehicles. Biogas in itself can be converted to other renewable chemicals [4].

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South Africa's growing population and urbanisation have led to the increased generation of FW and sewage sludge (SS), as well as an increased electricity demand [5]. Most wastewater treatment plants (WWTPs) and food supply chains are not effectively treating their solid waste for full nutrient and energy recovery [6]. The common practice of disposal in sea or landfills causes secondary pollution, which includes the leaching of nitrogen (N), phosphorus (P) and heavy metals [5]. South Africa relies primarily on coal for energy production, which is responsible for 70% of its carbon dioxide emissions, making it the 12th highest emitter globally [7]. According to Statistics South Africa [8], almost 90% of 236 TWh of electricity is generated in coal-fired power stations, 5% from nuclear, 0.5% from hydroelectricity, 2.3% from natural gas, 0.01% from wind and 1.3% from pumped storage schemes [8]. The national landfill methane emission is equivalent to 101 TWh of electricity, half of South Africa's energy generation.

Currently, the cost of treating water is escalating, threatening the effective treatment of wastewater. By the year 2025, the cost of treating wastewater in terms of WWTP electricity bill is expected to increase by almost 40% [9]. A large-scale WWTP in South Africa has an annual electricity budget averaging 5 million USD, which is expected to be 7 million USD by 2025 [10]. AD in WWTP can help reduce their electrical bill, even offset it by 100% and feed excess energy to the national grid. In the recent past, a local WWTP has fully utilised the mono-digestion of WAS and converted the produced biogas to electricity, leading to 10% energy savings [10].

This body of work reviews the production and characteristics of FW and WAS. An evaluation of the mono-digestion technology currently used for FW and WAS and its limitations are discussed. The potential of the anaerobic co-digestion (ACD) of WAS with FW technology as a sustainable method for municipal solid waste management is reviewed. Lastly, the conversion of biogas to electricity is evaluated. Part of this work is derived from the authors' PhD [11] and Masters [12] dissertations focused on the anaerobic treatment of WAS and FW, respectively.

MUNICIPAL WASTEWATER TREATMENT AND WASTE-ACTIVATED SLUDGE GENERATION

South Africa produces a total of 0.310 million tons of dry sludge annually, and only 28% of it is applied to agricultural lands [13]. According to a study conducted by Apollo [14], on the sludge potential of the Midvaal, Emfuleni, and Lesedi municipalities in Gauteng, South Africa, sludge amounts between 5 and 23 tons/day are being produced by the WWTPs in the three municipalities [14].

Characteristics of waste-activated sludge

WAS in its original form emits a bad odour and consists of biomass and bacterial culture produced during the ASP stage. Furthermore, WAS contains harmful heavy metals (Cd, Cr, Hg, Pb), refractory organic compounds (chlorophenols, pesticides, nitro-aromatic compounds), and nutrients such as N and P [15]. Moreover, hazardous pollutants, including endocrine-disrupting compounds, nonylphenol, and bis (2-ethylhexyl) phthalate, are retained in the sludge and may cause severe environmental risks [16]. The biomass consists of 30% proteins, 40% carbohydrates, and 30% lipids in particulate forms [17]. The general physicochemical properties of WAS are presented in Table 1.

WAS consists of large amounts of water and extracellular polymeric substances (EPS) as presented in Table 2 [11]. The EPS constitutes a major part of the WAS organic fraction and is likely sourced from the ASP microbial activity or the influent wastewater. Polysaccharides (PS), proteins, and humic substances account for up to 80% of the EPS composition, in addition to lipids, nucleic and uronic acids, and some inorganic complexes [17]. EPS occurs in the

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interior part of microbial aggregates and outside of cells and is divided into three categories consisting of tightly bound (TB-), loosely bound (LB-), and slime (S-) EPS [18]. A representative diagram of the EPS structure is depicted in Figure 2.

The LB-EPS (loosely bound polymers, sheaths, and condensed gels), which extends from TB-EPS, have a porous dispersible structure, while the TB-EPS (attached organic materials) comparatively adheres to the bacterial cell surface inside the sludge flocs [19]. The S-EPS, which consists of slimes, colloids, and soluble macromolecules, is uniformly distributed in the aqueous phase. The surface physical and chemical properties of WAS matrices are governed by the gel-like, three-dimensional EPS biopolymers, which provide protective shielding. The shielding prevents cell lysis and rupture, thereby influencing the functional integrity, flocculation, strength, biodegradability, and dewaterability of the sludge [20].

Table 1. General characteristics of waste-activated sludge.

Parameter	Units	Value
pH		6.6
TS	%	2.6
VS	%TS	65.2
Alkalinity	$mgCaCO_3/L$	4000
TVFA	$mgCH_3COOH/L$	47400
NH_4-N	mg/L	650
C	%TS	37.6
N	%TS	6.9
H	%TS	5.7
S	%TS	0.6
O	%TS	21.5
C/N	ratio	5.4

Key: **TS** – total solids, **TVFA** – total volatile fatty acids, **VS** – volatile solids.

Table 2. Special characteristics of waste-activated sludge.

Parameter	Units	Concentration
VSS/SS		0.75
Proteins	mg/g SS	346
Polysaccharides	mg/g SS	101
Humics	mg/g SS	58
Total EPS	mg/g SS	130
Iron	mg/L	213
Calcium	mg/L	362
EPS surface charge	meq/g SS	0.33
Zeta-potential	mV	-29.6
Floc size	µm	53
Surface area Cs	(m^2/g SS)	15.6

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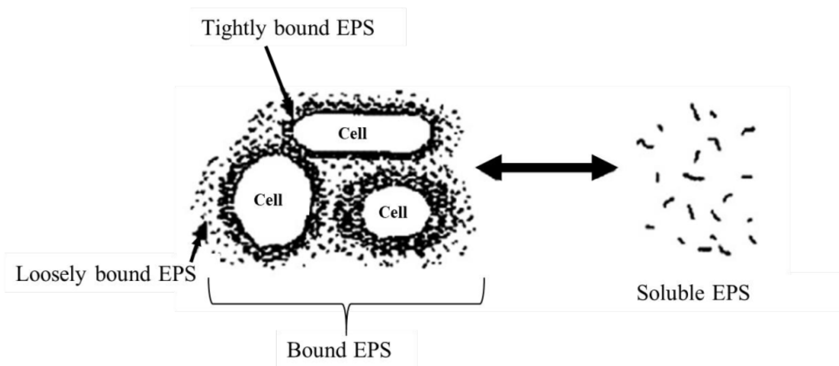

Figure 1. A sketch of EPS structure [18]

Waste-activated sludge disposal and associated challenges

The redress of the excess WAS to reduce environmental pollution poses a major challenge to wastewater treatment plants [11]. Costs for treating and disposing of WAS account for up to 60% of the total operation cost, and in terms of greenhouse gas emissions (GHG), sludge management accounts for >40% of GHG emissions from wastewater treatment plants (WWTPs) in South Africa [21]. A survey conducted by Snyman [22] on 72 large WWTPs in South Africa revealed that final disposal methods of WAS are frequently on-site, with the majority of sludge used/disposed of from AD. Sludge on-site disposal means the direct application on land and stockpiling. Local municipalities, farmers, and other businesses might benefit from the filtrate and/or dewatered sludge (if the technology is available). Dewatering is done by centrifuge, drying beds, or mechanical belt filter presses. The sludge can be used in several ways, including converted to compost for crops, applied at the bottom layer for golf courses, or used to grow instant lawns. The sludge can alternatively be exchanged for bulking agents with local contractors [22]. A sustainable treatment method for the WAS is thus needed.

FOOD WASTE GENERATION AND MANAGEMENT IN SOUTH AFRICA

South Africa produced an average of 28 million tons of food per year from 2007 to 2009 according to Faostat [23] records. The production amounts for each commodity group are listed in Table 3. Cereals, fruits, and vegetables account for most of the produced commodities, averaging 13.2 and 8.2 million tons, respectively, which is a combined 74% of total production. The remaining 26% is made up of the rest of the commodities, with the least produced being fish and seafood, oil seeds, and pulses.

Table 3. Food production per commodity group in South Africa [24].

Commodity Group	**Production (1000 tons)**			
	2007	**2008**	**2009**	**Average**
Cereals	9514	15363	14586	13154
Roots and Tubers	2023	2147	1882	2017
Oil seeds and Pulses	261	535	563	453
Fruits and Vegetables	8109	8417	8162	8229
Meat	2138	2179	444	1587
Fish and seafood	673	No data	No data	224
Milk	3066	3200	3091	3119
Total Production	**25785**	**31841**	**28729**	**28785**

The total food waste generated is estimated to be a third of the total amount of food produced in South Africa [24]. Food waste is generated at different stages of the supply chain, consisting of five categories; agriculture, consumption, distribution, processing packaging, and post-harvest handling and storage. A staggering 95% of FW is generated during the pre-consumption stages, as outlined in Table 4, equivalent to 10 million tons of foods wasted which are still edible and by incorporating the inevitable 2.4 million tons of inedible losses, the total FW generated in South Africa could be calculated to be 12 million tons [25]. Losses during processing and packaging, post-harvest handling and storage and agricultural production share similar splits of about 25%, with distribution accounting for 20% of the 95% [24]. At the consumption stage, only 4.9% of the agricultural production is lost, equivalent to 0.5 million tonnes. Fruits and vegetables contribute a large portion of the total waste per commodity group (44%), while the rest of the commodities make up the other half. Lastly, the majority (73%) of the fruits and vegetable is wasted during the pre-distribution stages.

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Table 4. South Africa's food waste by weight and percentage for each step of the food supply chain for selected commodities [25]

Commodity	Waste 1000 tons (%)					
	Agriculture	**Post-harvest handling and storage**	**Processing and packaging**	**Distribution**	**Consumption**	**Total waste per commodity group**
Cereals	788	989	398	289	142	**2605**
Roots and tubers	282	312	213	107	41	**955**
Oil seeds and pulses	144	84	78	27	13	**346**
Fruits and vegetables	846	685	1733	986	241	**4491**
Meat	382	15	108	196	52	**753**
Fish and seafood	38	38	54	85	10	**225**
Milk	186	321	3	318	3	**831**
Total per stage of food supply chain	**2 667**	**2 444**	**2 585**	**2 008**	**501**	**10 205**

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Characteristics of food waste

FW contains both high moisture and organic content. The moisture content ranges from 80 to 91%, while the pH is typically acidic and ranges from 4 to 6.5, as characterised in Table 5 and Table 6. The decrease in pH value is greatly affected by the amount of time FW is stored [26]. The general characteristics of FW, outlined in Table 6, show that FW is acidic upon receipt and has a high moisture content of 82.5%. The VS/TS ratio above 90% and C/N values of approximately 18.3 confirm its biodegradability, making it highly suitable for anaerobic digestion [27]. FW generally constitutes 0.5 of carbon, 0.07 of hydrogen, 0.3 of oxygen, 0.028 of nitrogen, and 0.007 of sulphur.

Table 5. Typical domestic food waste characteristics [12]

Parameters	**Yirong *et al.*** [28]	**Zhang *et al.*** [29]	**Zhang *et al.*** [30]	**Zhang *et al.*** [27]	**Kuczman *et al.*** [31]
pH	-	-	6.5	4.2	5.98
TS (%)	23.9	30.9	18.1	23.1	15.3
VS (%)	21.6	26.4	17.1	21	13.0
VS (% TS)	90.5	85.3	94	100	85.2

Table 6. General characteristics of food waste [32]

Parameter	**Units**	**Value**
Physical characteristics		
pH		5.0
Moisture content	%	82.5 ± 3.0
Bulk density	kg/m3	892.5 ± 22.5
VS (% TS)	%	94 ± 0.02
Composition		
Grains	%TS	35.7 ± 6.5
Vegetables	%TS	47.1 ± 7.4
Meat	%TS	17.2 ± 5.3
Chemical characteristics		
C	%TS	51.2 ± 6.5
N	%TS	2.8 ± 0.6
H	%TS	7.2 ± 1.3
S	%TS	0.7 ± 0.1
O	%TS	38.1 ± 5.1
Total carbohydrate	g/l	25 ± 4.8

C/N	ratio	18.3 ± 2.4

Food waste disposal and its effects on the environment

In South Africa, landfilling is considered low-cost and the most practical food waste management method [33]. However, factoring in the lack of land near areas of waste generation makes landfilling expensive, and with the forecast of the closure of many landfill sites in South Africa, landfilling is not a sustainable solution [33]. Furthermore, organic waste in landfills undergoes anaerobic digestion and consequently releases GHG emissions, high in concentration of methane and carbon dioxide [34]. The decomposition of FW results in leachate that can potentially seep into water bodies and pollute them [35]. The increased costs of landfilling have also made landfilling a financially wasteful exercise [36]. Landfilling is banned in Canada, Germany, Sweden and many other countries; the banning of these practices is becoming a priority in South Africa as well [24] [37].

The average GHG emissions in the food supply chain are 2.8 to 4.14 tonnes of CO_2e per tonne of food, according to Oelofse and Nahman [24]. Agricultural production, manufacturing and processing stages contributed between 1.95 and 2.29 tCO_2e per tonne of food, distribution and retail: between 0.1 and 0.8 tCO_2e per tonne of food, consumption: between 0.3 and 0.6 tCO_2e per tonne of food and end-of-life (landfill): For every tonne of food, 0.45 tCO_2e is produced indicating that the inefficiencies in the supply chain could contribute 4.14 tCO_2e per tonne of wasted food which would have a considerable impact on South Africa's greenhouse gas emissions footprint [24]. According to the DEA [38] report, 9.3 % and 4.3 % of South Africa's greenhouse gas emissions can be attributed to agriculture and the disposal of organic waste, including FW.

Municipalities must adopt technologies and processes that convert organic waste to biogas and fertiliser. Given the Circular Economy and Sustainable Processes, it is important to use waste produced as a resource. For several technologies, anaerobic digestion is considered for the recovery of energy and may be used to convert organic waste into biogas or fertilisers that can be used in agriculture [39].

ANAEROBIC DIGESTION FOR WASTE-ACTIVATED SLUDGE AND FOOD WASTE MANAGEMENT

In wastewater treatment plants, anaerobic digestion (AD) has been widely used in the last few decades to treat sludges successfully [40]. AD is a well-studied biological process that converts the chemical energy of WAS into methane-rich biogas and bio-fertiliser while destroying pathogens and removing odours [41], [42]. The recovered bioresources can be used as alternatives to fossil fuels. In addition, AD has been recognised as an environmentally friendly technology for the conversion of waste into renewable energy [43]. FW has now gained global attention as a high-moisture, energy-rich, and widely available feed for AD [44]. The AD technology for FW management has been applied gradually at a pilot scale in households and restaurants [31]. The majority of large-scale applications of the anaerobic digestion of FW are based on co-digestion with either sewage or animal excreta [45]. As FW amounts increase, considerable consideration should be given to the large-scale application of AD as a management tool.

Limitations of anaerobic mono digestion of waste-activated sludge and food waste substrates

Whereas anaerobic digestion has become an indispensable process in modern wastewater treatment plants, limitations are inherent due to the WAS properties [46]. The limitations include low hydrolysis efficiency and long hydraulic retention time (HRT) [47]. The low hydrolysis efficiency is attributed to the complex structure of EPS in the WAS. In particular,

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the walls of microbial cells are sufficiently thick to impede effective biodegradation in internal organics via normal AD processes [48]. Therefore, pre-treatment is necessary to break down cell walls to free intracellular organics. The solubilized cell components are much more biodegradable; thus, the HRT of the AD process is reduced and the efficiency is improved when they are released [48].

To improve AD efficiency and accelerate the rate-limiting hydrolysis, various pre-treatment technologies including advanced oxidation processes, chemical and physical, have been developed [11]. Most methods are energy-intensive, and thus, their application requires careful economic feasibility analysis [48]. Anaerobic co-digestion (AcD) of FW with other waste streams has gained attention as an effective waste management treatment method for WAS because it can counter-balance nutrient deficiency, promote economic feasibility, and introduce a waste management solution to more than one waste stream. Moreover, the high acidity of FW makes its mono-digestion unfavourable.

Codigestion of sludge and food waste

Anaerobic codigestion in a WWTP is the addition of organic-rich waste materials to the sludge during digestion for improved efficiency [49]. The AcD offers one of the most important advantages of having the potential to increase the efficiency of organic waste degradation and thus methane production. A case study on the benefits and disadvantages of the codigestion of food and dairy waste at high organic loading rates with sludge sewage was conducted by Sembera *et al.* [50]. They found that the potential increase of methane was 300%. Co-substrates are positively synergised in the digestive medium, thus serving as a source of lost nutrients. The yield of biogas from mono-digestion to AcD is increased [49]. Additionally, the diverted waste disposal route reduces the need for more landfill space and potentially aids municipalities in achieving their waste management goals.

WWTPs and municipalities are now expected to have cost savings from the use of wastes integrated into their existing anaerobic mono-digestion systems. With increased biogas production, there is a reduction in the plant's grid energy costs resulting from excess generation of electricity at the site, which can be sold and fed into the national grid; this upgrades the WWTP to a power supplier as well. Sembera *et al.* [50] report that from 2014 to 2015, at the Moosburg WWTP, there was an increase in hourly electricity production because of increased methane yield, which resulted in energy neutrality. Further economic gains were from gate fees. The co-substrates can supply micronutrients and alkalinity, overcoming limitations of mono-digestion of each substrate, resulting in more efficient use of equipment by improving process performance [44].

Although AcD studies have shown that it has advantages over mono-digestion and its effective result in treating waste, there is limited research comparing the feasibility of various co-substrates due to their influential factors on digestion and best operating conditions [49]. Also, although AcD offers a lot of advantages, many researchers continue to be plagued by problems in their performance; this often leads to system malfunction largely as a result of an inappropriate ratio of substrates and operating conditions [51], [52]. The disadvantages that have been seen by Sembera *et al.* [50] are that solids concentration tends to increase within the digester, higher nitrogen backloading, lower retention time and reduced digestion efficiency. Consequently, a good understanding of AcD is required for a successful outcome. Previous research in Table 7 shows varying applications and improvements of AcD of wastewater sludge with organic-rich FW and organic fraction of municipal solid wastes (OFMSW) at mesophilic temperatures.

Improvements in methane yield (MY) as low as 16% and as high as 122% may be obtained from Cabbai *et al.* [54] and Cavinato *et al.* [53], respectively. Cavinato et al. [53] co-digested WAS with OFMSW at a 50:50 mixing ratio by substrate volume at an OLR of 1.6 gVS/L/day and obtained 0.09 LCH_4/gVSadded for monodigestion and 0.2 LCH_4/gVSadded for co-digestion. Cabbai *et al.* [54] digested SS with FW at a ratio of 1:0.23 as per VS obtained higher MYs than

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Cavinato *et al.* [53] of 0.25 LCH4/gVSadded during mono-digestion and 0.29 LCH4/gVSadded for AcD. It was found that when compared with lower amounts of FW, higher concentrations of FW were responsible for increasing the methane yield in the substrate mixture. In particular, FW contains a higher amount of biodegradable volatile organic matter for AD compared to sludge, which is quite resistant to hydrolysis [59]. Various other factors, such as reactor size, contaminants in OFMSW, and OLR, affect the throughput of the process, as seen in Table 7.

Table 7. Summary of studies applying anaerobic codigestion of wastewater sludge with FW or OFMSW

Mixture	Ratio[1]	Reactor size (L)	OLR (gVS/L/d)	Methane yield (LCH4/gVSadded) Mono	Co	Increase (%)	Reference
WAS:OFMSW	50:50 V	380	1.6	0.09	0.20	122	[53]
SS:FW	1:0.23 VS	1.2	-	0.25	0.29	16	[54]
	1:2.09 VS				0.37	48	
PS:FW	22:78 TS	3	3.8	0.3	0.36	20	[55]
SS:OFMSW	46:54 VS	5.5	1.7	0.249	0.42	69	[56]
SS:FW	100:20 V	100	2.1	-	0.38	-	[57]
SS:FW	60:40 VS	4	3.5	-	0.18	-	[58]

Digester type used for wastewater sludge and food waste

Various types of digesters are used to treat wastewater sludge and food waste; however, they all perform the same basic function. Digesters of all types hold organic substrate in the absence of oxygen and facilitate suitable conditions for the growth of methanogens [60]. Digester applicability is based on the technical suitability, cost-effectiveness and availability of local skills and materials. Though a specific design may have proven successful for treating a range of feedstock, it still depends on the prevailing climatic and economic environment the installer faces. Conventionally, wastewater treatment plants in South Africa apply a variety of layouts for the complete-mix/fixed-dome type digester for sludge stabilisation, as depicted in Figure 2. This type of digester provides excellent mixing and heated conditions, moreover, a cylindrical tank with a conical top and bottom is recommended [61]. Due to the heating and mixing provided, the digester enables operation at higher total solids of 3 to 10%, allowing for organic loadings of 1.5 to 3 kgVS/m^3/day [62] and reduced retention times from 50 to 80 days to 20 to 30 days [61]. Digester heating may be carried out using external or internal heat exchange coils heating water or steam in a boiler. Mixing may be through draft tubes (internal or external), gas-mixing, mechanical mixing, or jet- or nozzle-mixing [63].

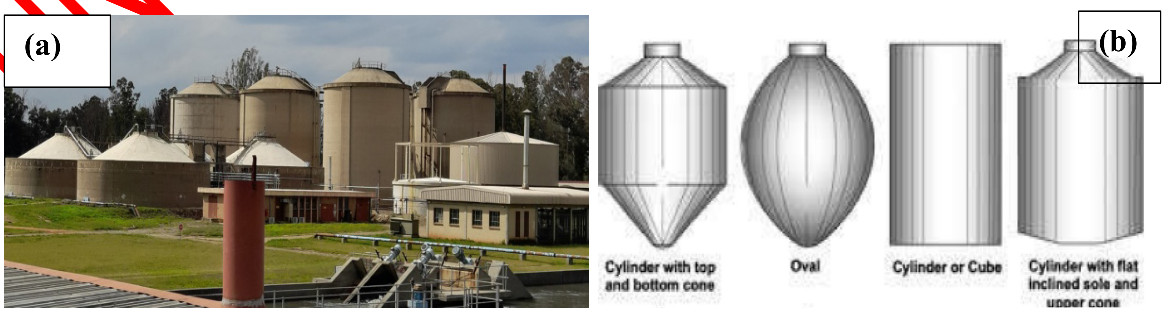

Figure 2. Conventional digester types (a) at a wastewater treatment plant and (b) schematic representation of the digesters [65]

The high-rate characteristic of the complete-mix digester makes it equally suitable for the digestion of FW. All 420 digesters at 108 WWTPs in South Africa use a variation of the

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complete-mix digester [63]. Thus, the municipal WWTP digesters are already equipped for introducing food waste as a co-substrate in that regard [64]. Additional equipment is, however, required for food waste handling before digestion and power generation.

Equipment required for codigestion at a wastewater treatment plant

WWTPs are equipped for the mono-digestion of sludge. To enable anaerobic co-digestion with FW, a preliminary FW pre-treatment unit is required, known as the materials recovery facility (MRF) depicted in Figure 3. The MRF facilitates sorting organic waste from foreign objects and the crushing of whole foods into smaller particle sizes that can be easily fed to the anaerobic digesters at a total solids concentration acceptable by the existing pumps and downstream equipment. Furthermore, conventional WWTPs in South Africa are not designed to make use of the produced biogas except for digester heating through water boilers, where excess biogas is flared [63]. In that regard, equipment is required to manage biogas conversion to electricity and heat.

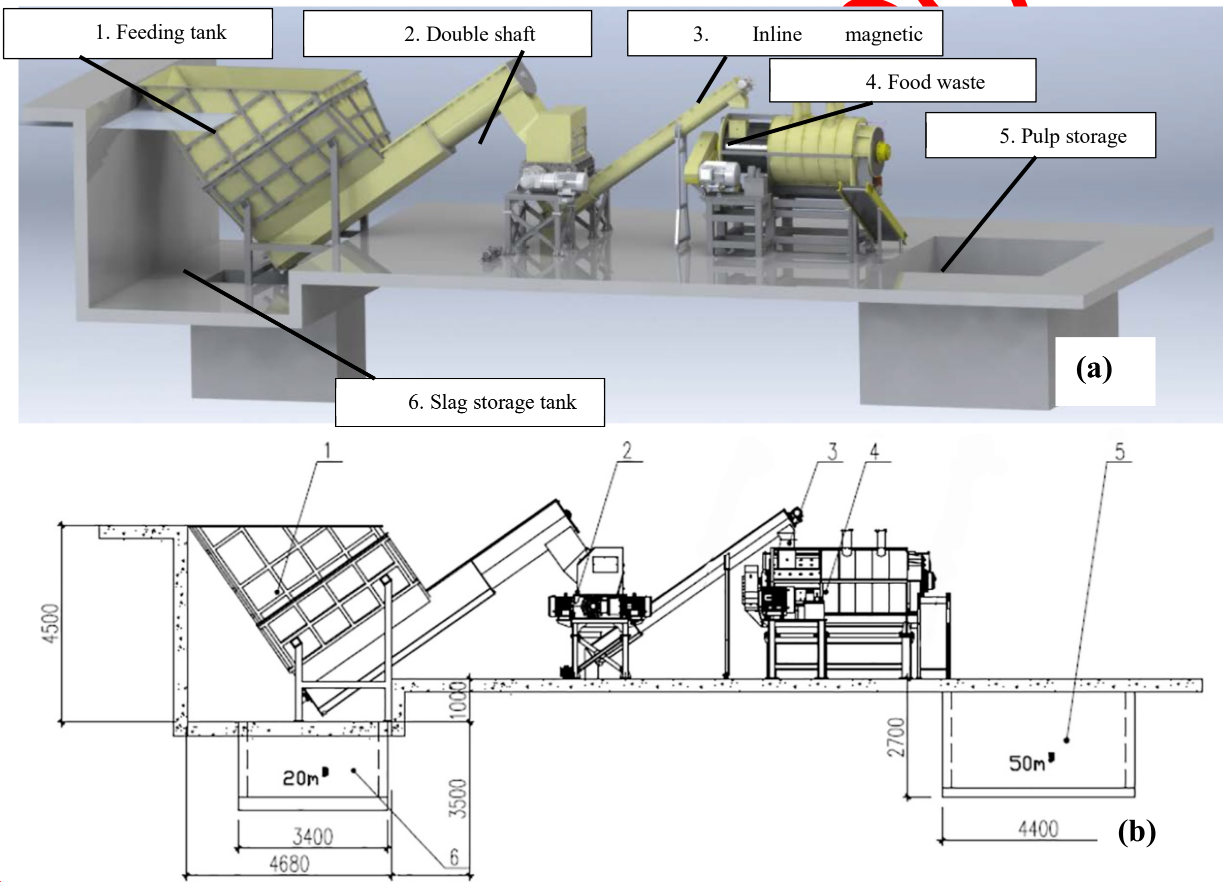

Figure 3. Pictorial (a) and schematic (b) representation of the materials recovery facility for food waste pre-treatment [66].

BIOGAS CONVERSION TO ELECTRICITY

Biogas production is considered to be among the most important future renewable energy sources since a continuous power supply from organic waste can be guaranteed [67]. Methane has a calorific value of 36 MJ/m^3, and biogas has a calorific value of 22 MJ/m^3 at 60% methane composition [68]. Purification may increase the calorific value of biogas. Assuming a mechanical efficiency of 35% for the generator, 1 m^3 of biogas may generate 2.1 kW of electricity. According to records of Statistics South Africa and the CSIR, South Africa's energy mix is still heavily reliant on coal, with its contribution to the national mix decreasing from

92.8% in 2006 to 80.1% in 2021 as shown in Table 8. Renewable energy contribution has increased from 0.4% in 2013 to 21% in 2021.

Table 8. Electricity available for distribution in the electricity, gas and water supply industry; 2013, 2016 and 2021

Source of electricity	**2013** [69]	**2016** [8]	**2021** [70]
		Gigawatt-hours (%)	
Coal	215 691	203 054	176 600
Natural gas	8 410	7 573	-
Nuclear material	11 954	12 305	10 100
Diesel	1 904	4 007	3 600
Wind	18	2 126	16 200
Sun (solar electricity)	0	2 151	
Electricity generated from pump storage stations	3 006	2 934	
Waste material (e.g. bagasse and wood waste)	2 304	2 073	30 200
Water (hydroelectricity)	1 077	783	
Total electricity generated	**244 364**	**237 006**	**-**

Equipment required for combined heat and power recovery at a wastewater treatment plant

The conversion of biogas into electricity is carried out by internal combustion engines known as combined heat and power (CHP) units that are paired with a set of biogas scrubbers employed to remove any impurities hazardous to the generators' internal components, such as sulfur and condensation (Figure 4). The requirements for Genset, a typical generator used, are listed in Table 9 [66]. In this large-scale application, the CHP units are used to convert biogas into electricity and heat. Heat can be mainly used to heat the anaerobic digesters to mesophilic and even thermophilic temperatures, while excess heat and power may be sold to the public [71].

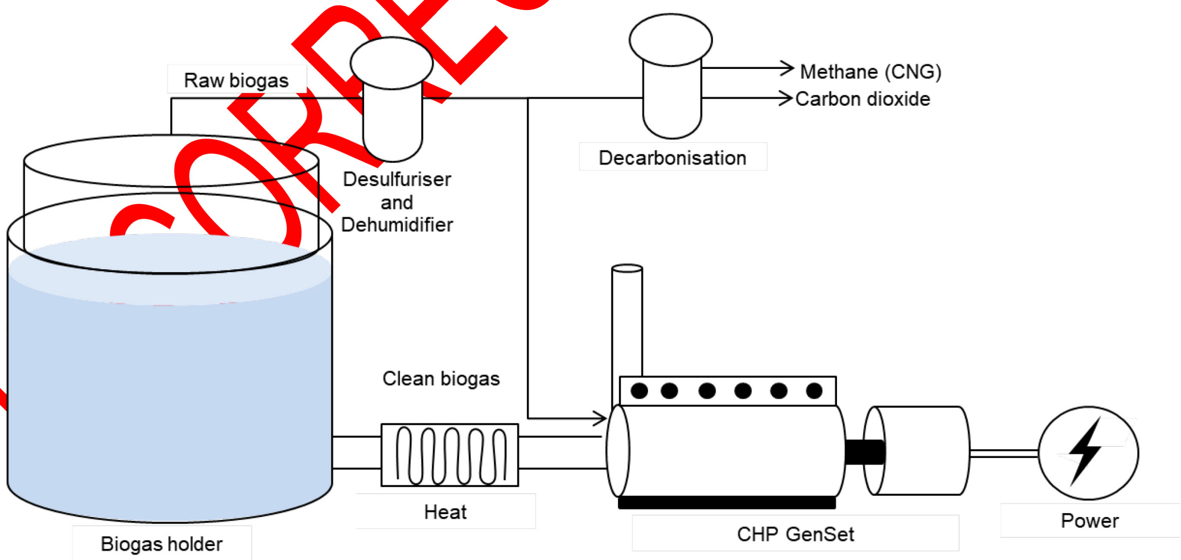

Figure 4. Schematic representation of the CHP module and CNG process flow.

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Table 9. Genset biogas requirements

Parameter	**Limit**
Methane (CH_4) content	>55%
Temperature	≤ 40 °C
Intake pressure	> 20 Kpa with a pressure change of ≤ 1 Kpa/min
H_2S content	≤ 50 mg/Nm3
Total sulfur content	≤ 100 mg/Nm3
Ammonia (NH_3) content	≤ 20 mg/Nm3
Impurity Granularity	≤ 5 µm
Impurity content	≤ 30 mg/Nm3
Moisture content	≤ 40 mg/Nm3; no free water

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Electricity potential from food waste and waste-activated sludge

South Africa produces 12 million tons of FW per year [25]. This amount of FW can yield a significant amount of biogas. The biogas potential of this food waste can be calculated using eq. (1) and (2). An anaerobic digester treating FW and operated at mesophilic optimal conditions obtained a biogas yield (BY) of 879 L/kgVS$_{added}$, as reported by Xu *et al*. [44]. In the 12 million tons of FW, volatile solids VS is assumed to be 95% and TS 15%; thus, the total VS (TVS) available would be 1 854 125 918 kgVS. The total biogas production potential is 1 629 776 682 L.

$$TVS = (FW \times TS\%) \times VS\% \tag{1}$$

$$\text{Ebiogas} = \text{BY} \times \text{TVS} \tag{2}$$

Biogas can be converted into electricity through small and large combustion engines. Larger engines have a combined heat and power (CHP) capacity to provide heat to the anaerobic digester and other processes. Typically, small engines have a conversion efficiency of 25% and 35 - 40% for larger engines [68].

This analysis uses an engine conversion efficiency of 25 and 40% to predict energy potential for small and large-scale electricity generation, respectively. Equation (3) with the conversion efficiencies may be used to calculate the energy potential from the biogas:

$$e_{biogas} = E_{biogas} \times \text{CV} \times 0.277778 \times \eta \tag{3}$$

where e$_{biogas}$ is the total electricity in kWh generated from biogas, E$_{biogas}$ is the available raw biogas in m^3, CV is the calorific value 22 MJ/ m^3 of biogas at 60% methane, 0.277778 kWh/MJ is a unit conversion from MJ to kW and the overall conversion efficiency of the generator is represented by the symbol η [72].

Therefore, the annual biogas electricity potential of South Africa based on their FW amounts is 3 485 914 025 975 kW, which is 3% of the target for new electricity production from renewable energy to contribute to the national 227 TWh energy mix which is set by the Integrated Resource Plan of South Africa and initiated by the Department of Energy [73].

One of the first commercial anaerobic digesters to produce biogas and generate electricity in South Africa was John Fry, who built it in 1957 at his pig farm [74] (Figure 6). Currently, there are about 300 different-sized operating biogas plants in South Africa. Johannesburg Waters (JW), a municipality based in Gauteng province, has four working anaerobic digesters to reduce the total organic load on their wastewater treatment plant and stabilise the sludge before disposal (Figure 7b). JW is producing approximately 2 million m^3/yr of biogas from wastewater sludge. WEC Projects uses biogas produced from JW WWTP and runs a set of three generators, each with a power output of 300 kW and instantly feeds approximately 5 MW of electricity annually to the grid.

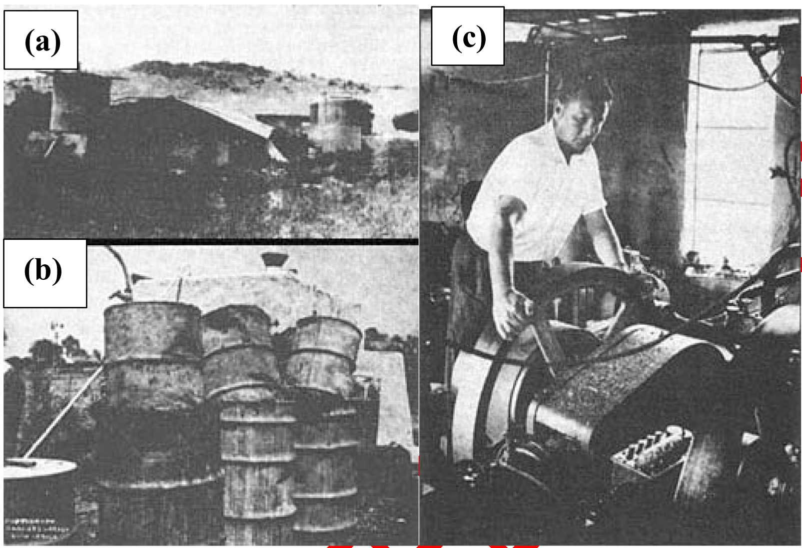

Figure 5. Original digester tanks [(a) and (b)] used at Fry's pig farm and a diesel engine (c) converted to run on methane gas [74].

Bio2watt in Bronkhortspruit, South Africa, runs a 4.6 MW biogas power plant from about 120,000 tons of organic waste from a Beef Farm per year. Companies such as Botala Energy Solutions and Biogas SA can be hired to install small- to large-scale plants around South Africa. One of Botala's biogas plants depicted in Figure 5a has a 100 kV combined heat and power plant for a local village in Tshwane with fresh produce as digester feedstock. The community benefits from the electricity and fertiliser produced from their fresh produce waste material. Nationally with only 108 WWTPs out of 824 utilising AD for sludge stabilisation, there is an annual biogas production potential of 103 174 915 m^3 and 240 084 225 kWh of electricity from 1 291 735 ML of sludge [63].

Figure 6. Demonstration of the large-scale biogas plants in South Africa built by (a) Botala Energy Solutions and (b) WEC Projects

Even though biogas in South Africa was first produced in the 1950s [74], [75] its use remains very low. According to Mukumba, Makaka and Mamphweli [75], this is due to the lack of research work on biogas technology and purification processes, which leads to the low

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efficiency of biogas compared to conventional fuels such as diesel and petrol. Other factors contributing to the low uptake of AD technology include low electricity costs from coal-fired thermal power stations, education, awareness of biogas in general, and funding for establishing and maintaining biogas digesters. The lack of a generic solution to run a digester was one of the main challenges reported on biogas development in South Africa. Most of the data available are based on research in other countries and cannot be used directly in South Africa. Thus, more South African anaerobic digestion research needs to be conducted to promote biogas utilisation locally [75].

OTHER BIORESOURCES FROM ANAEROBIC DIGESTATE

There is a high demand for agricultural nutrients such as phosphorus and nitrogen. Currently, phosphorus is mainly obtained through extractive activities from nature reserves [76]. The extractive peak of phosphatic rock will be reached in the following decades and thus a decrease in natural reserves may be seen in the coming century [76].

The breakdown of the WAS and FW, during AcD, releases nutrients in excess. Several studies (Table 10) have reported a significant increase in the concentration of phosphorus and nitrogen in the liquid phase during anaerobic digestion [77]–[80]. Therefore, for sustainable development and food security, it is crucial to enhance the recovery of the nutrients contained in the supernatant after dewatering the anaerobic digestate [81].

Table 10. Concentration of nutrients in WAS supernatant before and after anaerobic digestion.

	Before AD	**After AD**
Li et al. [78]	PO_4^{3-} - 1.14 mg/L	PO_4^{3-} - 181.2 mg/L
	NH^{4+} - 1.21 mg/L	NH^{4+} - 318.86 mg/L
Cheng et al. [77]	Aqueous P – 0 mg/L	Aqueous P – 316 mg/L
Liu et al. [79]	OP – 0 mg/L	OP – 787.47 mg/L
Xu et al. [80]	TDP – 1.99 mg/L	TDP – 7.30 mg/L
	PO_4^{3-} - 0.52 mg/L	PO_4^{3-} - 3.19 mg/L
	OP – 0.63 mg/L	OP – 4.77 mg/L

Two sustainable ways to recover nitrogen and phosphorus are through the struvite precipitation of the liquid digestate (supernatant) and composting the remaining sludge cake. The liquid anaerobic effluent filtrate (supernatant) can be precipitated to obtain magnesium ammonium phosphate ($MgNH_4PO_4 \cdot 6H_2O$) called struvite, while the dewatered sludge cake is aerobically treated in self-heating windrows with bulking agents providing a pasteurised saleable product called compost. Thus, the annual 0.3 million tons of dry sludge if properly composted may be used for agricultural applications.

The removal of struvite is crucial for preventing struvite buildup in pipes, increasing sludge dewaterability and reducing polymer consumption [63]. During digestate dewatering, the phosphate-rich filtrate is returned to the head of works, which leads to an increased phosphate loading. At the right conditions and concentration, struvite may form on any surface, including pipes and mechanical parts causing restriction and damage, respectively. During the controlled struvite precipitation process a high-quality, environmentally benign fertiliser is produced, that is low in heavy metal concentration and has a slow rate of nutrient release giving it a low application frequency [82].

The composting treatment process of sewage sludge lowers pathogen content, reduces vector attraction, stabilises organic matter and reduces heavy metals and pollutants while yielding a humic-like substance [83]. The composted sewage sludge has a wider land

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application due to its characteristics of available nutrients and stabilised organic matter [84]. Studies show that the use of composted sewage sludge provides equal and in some instances better yield in crop growth compared to synthetic fertiliser [85].

CONCLUSION

The current review has outlined the generation and management of sludge and food waste in the WWTPs and food sectors in South Africa. The sludge and food waste characteristics were shown, and the challenges with sludge mono digestion were outlined while showing the high biodegradability of food waste and its suitability for codigestion with sludge. The uncontrolled disposal of food waste has been shown to harm the environment. The codigestion approach has the potential to generate income for WWTPs through the reduced cost of their electricity usage, feeding excess generated electricity into the national grid, and selling biofertiliser.

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NOMENCLATURE

Symbols

BY	biogas yield	[L_{biogas}/gVS_{added}]
CV	calorific value	[MJ/m^3]
MY	methane yield	[L_{CH4}/gVS_{added}]
OLR	organic loading rate	[$kgVS/m^3/day$]
TS	total solids	[%]
VS	volatile solids	[%]
e_{biogas}	electricity	[kWh]

Greek letters

ρ	density	[kg/m^3]
η	efficiency	[%]

Abbreviations

AD	Anaerobic digestion
AcD	Anaerobic co-digestion
ASP	Activated sludge process
BOD	Biochemical oxygen demand
CD	Cow dung
EPS	Extracellular polymeric substances
FW	Food waste
GHG	Greenhouse gas
HRT	Hydraulic retention time
MWW	Municipal wastewater
OFMSW	Organic fraction of municipal solid wastes
OLR	Organic loading rate
PVC	Polyvinyl chloride
WAS	Waste activated sludge

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WWTP	Wastewater treatment plant
TS	Total solids
VFA	Volatile fatty acids
VS	Volatile solids

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