Environmental Development 45 (2023) 100812

Contents lists available at ScienceDirect

Environmental Development

journal homepage: www.elsevier.com/locate/envdev

Developing country imperatives in the circular bioeconomy: A review of the South African case

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ARTICLE INFO

Keywords:
Bioeconomy
Circular bioeconomy
Circular economy
Organic waste
Waste management

ABSTRACT

A key principle in the circular bioeconomy is the cascading use of biomass in products that create the most value over its lifetime. For example, the production of fine chemicals or pharmaceuticals are considered high value processes in comparison to energy production or the production of bulk materials such as compost. However, such "low value" applications may be associated with greater environmental and socio-economic benefits depending on the context. This paper explores factors influencing a developing country's transition to a circular bioeconomy. Through a review of the South African case, it was found that national priorities and strategies places emphasis on composting and anaerobic digestion as primary methods for organic waste diversion from landfill. This may in part be attributed to the fact that the technologies can theoretically process a wide variety of waste stocks and they are already commercially established in the country. In addition, the potential sustainability benefits associated with these methods have the potential to mitigate many challenges being faced by the country including job creation, food security, energy security and climate change mitigation. However, to increase circularity whilst adhering to the principle of cascading use, investment in biorefining of organic waste is necessary. Whilst research has been conducted into the biorefining of various waste types including agricultural and industrial waste, the investment cost remains prohibitive. Yet, in the long-term, investment in biorefineries may potentially result in greater socio-economic benefits for the country. Ultimately, to transition towards a sustainable circular bioeconomy, diversification of the industry is essential.

1. Introduction

The circular economy is a concept that is being widely adopted worldwide, with many countries adopting it into their policies and strategies. According to the Ellen MacArthur Foundation (EMF), the circular economy concept can be viewed from two distinct perspectives: technical and biological cycles (EMF, 2013). The biological cycle is commonly referred to as the bioeconomy. In contrast to the technical circular economy, less emphasis has been placed on the circular bioeconomy (CBE). Whilst research has been conducted into the valorisation of biomass and organic waste, the interface between organic waste management and the circular economy has received relatively less attention (Paes et al., 2019).

A key aspect of the circular bioeconomy is the cascading use of biomass materials in products that create the most value over multiple lifetimes (Paes et al., 2019; Philp and Winickoff, 2018; Stegmann et al., 2020; WBCSD and BCG, 2020). In 2020, Stegmann et al. (2020) presented a bio-based value-pyramid depicting the relative value associated with each treatment/manufacturing option

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https://doi.org/10.1016/j.envdev.2023.100812
Received 25 October 2021; Received in revised form 20 June 2022; Accepted 5 February 2023
Available online 9 February 2023

(shown in Fig. 1). The pyramid aims to provide guidance for optimising the value of biomass over time in a circular bioeconomy. Moving down the value pyramid is associated with a decrease in the resource quality with fewer opportunities for further uses of the material. However, the authors acknowledged that "low-value" application may be associated with greater environmental and socio-economic benefits according to the context (Stegmann et al., 2020). In this regard, researchers have explored the potential of the bioeconomy to contribute to meeting the Sustainable Development Goals (Dietz et al., 2018; Heimann, 2019; Mak et al., 2020).

Sustainable organic waste management is an integral aspect in the development of a circular bioeconomy (Maina et al., 2017; Mak et al., 2020; Paes et al., 2019; Venkata Mohan et al., 2016). The South African Bioeconomy Strategy highlights the enhancement of waste management practices to support a green economy as one of the priority areas (DST, 2013). This is further reinforced in the National Waste Management Strategy (NWMS) 2020 which identifies diversion of organic waste from landfill as a key priority area setting national targets; it aims to reduce organic and food waste to landfill by 40% and 30% respectively, within 5 years (DEFF, 2020). The drive to reduce organic waste to landfill may be attributed to a number of reasons including decreasing landfill space. For example, dwindling landfill airspace is a major issue in the Western Cape Province with 22 of 25 municipalities projected to run out of landfill airspace in the next five years (GreenCape, 2020a). To combat this, the province has resolved to divert 50% of organic waste from landfill by 2022, with a total landfill ban in 2027 (GreenCape, 2020b). In addition, the waste economy is gaining more traction as a national imperative as exemplified by the initiation of Operation Phakisa: Chemicals and Waste Economy, a Department of Environmental Affairs and Department of Planning, Monitoring and Evaluation initiated programme aimed at reducing environmental impacts whilst contribution to job creation and GDP (DEA, 2017).

In Africa, the majority of studies focussed on the bioeconomy are from the perspective of technology feasibility. This paper takes a macro perspective to the circular bioeconomy from the viewpoint of a developing country in Africa. More specifically, it explores the key factors influencing a developing country's transition towards a circular bioeconomy. A case study approach is used focused on the Sub-Saharan country South Africa. The country's transition towards a circular bioeconomy is critically analysed in the context of current national goals and priorities. In particular, it reviews current treatment options for organic waste in relation to the principles of a circular bioeconomy, whilst taking into consideration the societal, environmental and economic needs of the nation. It also discusses potential opportunities for growth in the waste bioeconomy.

2. Overview of organic waste management in South Africa

2.1. Organic waste composition

According to the State of Waste Report (SOWR), 19 247 851 tonnes of organic waste was generated in 2017, accounting for 34.6% of total waste (DEA, 2018). Organic waste is categorised into wood waste, (64.8%), food waste (22.1%) and garden waste (13.1%). Wood waste is comprised of waste generated from sawmills, pulp and paper mills, and sugar mills (Fig. 2). The major contributors are sugarcane bagasse (36.5%) and black liquor (39.7%).

The SOWR estimated 19.2 Mt of organic waste generated in 2017 (DEA, 2018). This is significantly higher than the total organic waste reported by the National Waste Baseline Report which estimated 3.0 Mt was generated in 2011 (DEA, 2012). The SOWR only takes into consideration municipal solid waste collected from residences, businesses and institutions. When it comes to food waste, it explicitly excludes waste generated during harvesting based on the assumption that it is commonly diverted as animal feed or used for soil enrichment. It is also important to take into consideration that the SOWR only considers managed waste. According to a survey conducted by Stats SA (2020), in 2019, 30.4% of South African households relied on their own refuse dumps for disposal, whilst 3.2% dumped their waste anywhere. Thus, the reported figures may be considered an underestimate of reality. In comparison, the Food and Agriculture Organization (FAO) reported that 3 Mt of food waste was generated from post-harvest to retail in 2017 (FAO, 2020). Their calculations took into consideration diversion of waste to animal feed, seed and other non-food related uses.

Nahman and de Lange (2013) estimated 10.2 Mt of food waste generated of which 5% was attributed to the consumption phase,

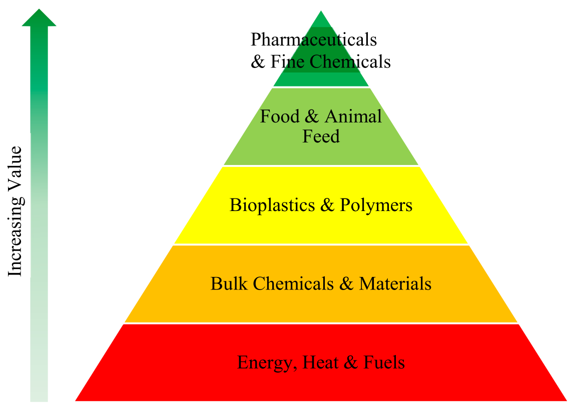

Fig. 1. Bio-based value pyramid adapted from Stegmann et al. (2020).

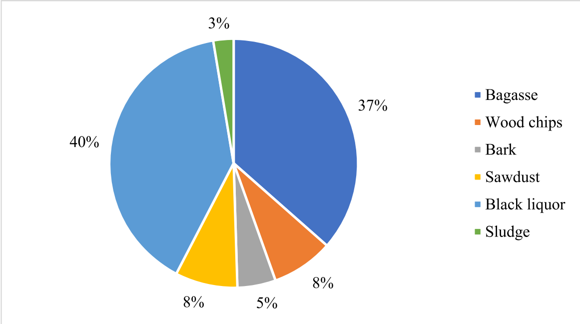

Fig. 2. Composition of wood waste (DEA, 2018).

with agricultural production and post-harvest handling and storage contributing 50%. Their estimate was based on FAO data on food production and waste coupled with estimates of the proportion of food that is lost or waste along the value chain developed by Gustavsson et al. (2013). The study conducted by Nahman and de Lange (2013) estimated total food waste and losses along the value chain but did not take into consideration diversion to other uses such as animal feed. In addition, the estimate was only for edible and thus avoidable food waste which they later assumed to account for 81% of total food waste generated (de Lange and Nahman, 2015).

The study by Nahman and de Lange (2013) found that fruits and vegetables had the highest waste generated across the majority of value chain stages (shown in Fig. 3), excluding post-harvest handling and storage whereby the most waste was associated with cereals. This aligns with a MSW characterisation study conducted in the City of Cape Town, wherein fruit and veg comprised the highest discernible food waste stream (30.6%), whilst the majority (58.6%) was characterised as “mixed” (GreenCape, 2020a).

It is important to make the distinction between food waste and food loss, particularly in the context of waste minimisation and treatment. According to the FAO (FAO, 2019), the distinction is where in the food value chain it occurs, with loss occurring prior to retail and consumption, whereas waste is due to the decisions made by retailers, food service providers and consumers. Furthermore, there is the issue of “surplus” food which has the potential to become lost or waste. Surplus food refers to edible food that is rejected due to a variety of reasons including aesthetic criteria, lack of demand, overproduction, incorrect or damaged packaging and cancelled orders (Facchini et al., 2018). In some instances, this food is diverted to organisations helping disadvantaged people however, potential donors remain wary due to liability concerns should someone get sick.

2.2. Organic waste diversion: uptake of different treatment options

According to the SOWR, in 2017, 49.2% of managed organic waste was recovered/recycled, whilst 0.02% was treated. As shown in Fig. 4, there are a number of potential options for organic waste treatment including composting and anaerobic digestion (i.e. biogas production). In the case of food loss and waste, it may also be redistributed for human consumption (in the case of food surplus), redirected as animal feed or converted to fine chemicals and pharmaceuticals. In South Africa, the main treatment methods for organic waste are landfilling, composting or anaerobic digestion. National strategies and policies for organic waste diversion make specific reference to composting and biogas production as desirable treatment methods (DEA, 2017, n. d.; DEFF, 2020; Schwehn et al., 2014).

The selection of a treatment method is dependent on a number of factors including cost and feedstock composition (discussed further in section 2.3).

2.2.1. Composting

Composting is a biochemical process in which microorganisms decompose organic matter in the presence of oxygen. Specific

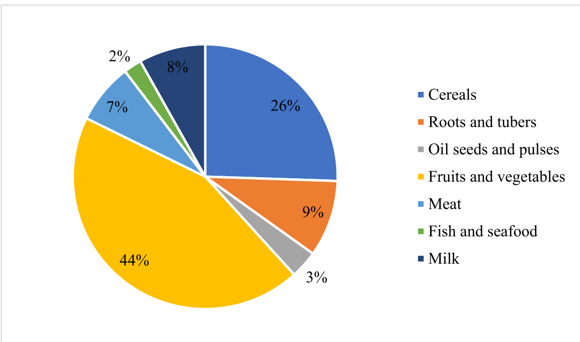

Fig. 3. Composition of food waste across the entire value chain (Nahman and de Lange, 2013).

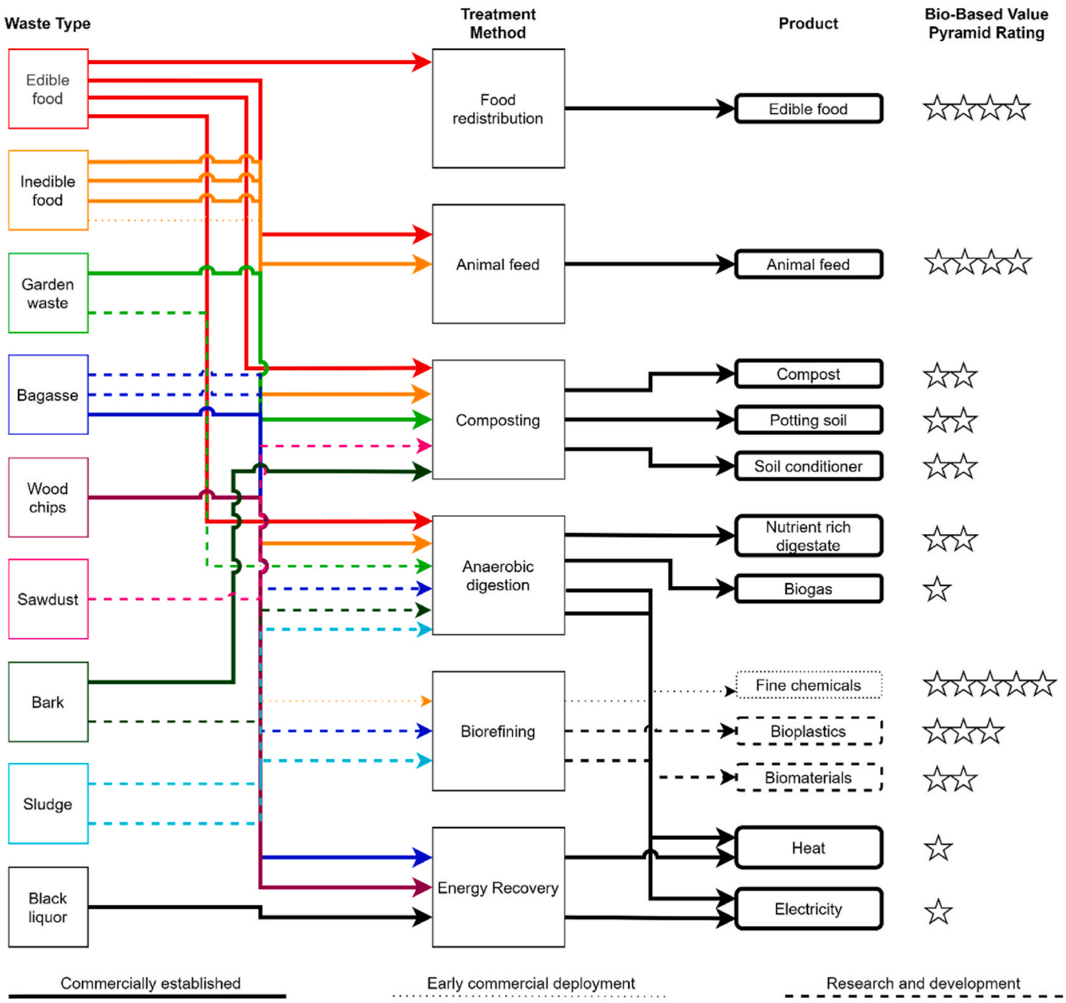

Fig. 4. Organic waste treatment methods in South Africa characterised according to technology maturity and rated according to the bio-based value pyramid proposed by Stegmann et al. (2020).

conditions are required for the microorganisms to grow with their activity influenced by numerous factors including temperature, moisture content, aeration, pH and particle size (Epstein, 2011; Onwosi et al., 2017; Schaub and Leonard, 1996) In addition, the carbon to nitrogen (C:N) ratio of the organic matter is a crucial aspect of microbial activity, with ratios of 20:1 to 40:1 reportedly required for active composting (Epstein, 2011; Onwosi et al., 2017; Schaub and Leonard, 1996). This is important when selecting a feedstock for composting, as different materials have different C:N ratios. As such, co-composting of different materials is common practice to optimise the C:N ratio (Awasthi et al., 2020; Onwosi et al., 2017).

A survey of organic waste disposal methods in South Africa conducted in 2012, found that at least 32% of organic waste was composted (DEA, 2013). A number of composting methods are employed including open windrow, in-vessel and vermicomposting, of which windrow composting was the most popular method reported. This is to be expected as it is relatively low cost, requiring lower capital investment upfront, low technology requirements and low skills requirements (Epstein, 2011; Schaub and Leonard, 1996).

Composting is the primary treatment method for garden waste in South Africa (DEA, 2018). Some municipalities divert garden waste to composting which can be done through various channels. For example, in the Saldanha Bay Municipality garden waste is chipped and composted by a private company whereas the Bergrivier Municipality chips and composts the garden waste in-house (DEADP, 2020). There are also models whereby the municipality chips the waste and either sells the chips for composting by private companies or gives it away to the public for use as fertilizers. The model employed depends on a number of factors including the infrastructure available to the municipality and the costs for treatment (discussed further in section 4.2). Beyond garden waste, composting is used to treat waste from sawmills (e.g. bark and sawdust), food waste as well as manure (DEA, 2018, 2013; DEADP, 2020).

Vermicomposting is a relatively small yet well-established industry in South Africa, whereby the organic material is degraded by earthworms producing vermicast (i.e. earthworm castings) (Furlong et al., 2017). During this process, nutrients in the organic matter (i.e. calcium, phosphorus, potassium and nitrogen) are converted to a more bioavailable form for uptake by plants (Gajalakshmi and

Abbasi, 2008). The combined activity of microorganisms and earthworms results in relatively shorter maturity times in comparison to traditional composting (Singh et al., 2011). Vermicomposting also has the additional benefit of heavy metals removal which are absorbed and saturated within the earthworms, as well as lower pathogen levels (Singh et al., 2011). In South Africa, it is currently used on both commercial and domestic scales for the treatment of food and garden waste (DEA, 2013).

2.2.2. Anaerobic digestion

Anaerobic digestion (AD) is the process by which bacteria degrade organic matter in the absence of oxygen, producing biogas and a nutrient rich digestate. The raw biogas produced primarily comprises of methane (50–75%), carbon dioxide (25–50%) and other gases including nitrogen, oxygen, hydrogen sulphide and ammonia (2–8%) (Wellinger et al., 2013). The produced biogas can be used directly as an energy source or converted to electricity via gas turbines, whilst the digestate can be used as a soil enricher/conditioner.

Anaerobic digestion is a well-established technology in South Africa, with adoption dating back to the 1990s (Greben and Oelofse, 2009). A review conducted in 2018, estimated that there are over 700 biodigester installations in South Africa including domestic and industrial types (Mutungwazi et al., 2018). Biodigesters can process a variety of feedstocks. In South Africa, the majority of installations are in the agricultural sector, processing feedstocks include harvesting and abattoir waste, food processing waste and manure (Nagel, 2019; SABIA, 2016). The biogas plants are commonly co-located on the site of waste generation, with the gas being used to generate electricity to feed the process. Anaerobic digestion has also been used to treat wastewater from breweries and distilleries as well as sludge from wastewater treatment plants.

In South Africa, a number of studies have been conducted into the potential adoption of biogas production for the diversion of organic waste from landfill (Greben and Oelofse, 2009; Masebinu et al., 2018; Matheri et al., 2018a; Msibi and Kornelius, 2017). The heterogenous nature of municipal solid waste means that varying biogas yields can be observed depending on the composition of the stream, with yields ranging from 300 to 500 m^3/ton volatile solids having been observed (Greben and Oelofse, 2009; Kigozi et al., 2014a). Previous research recommends the co-digestion of organic municipal solid waste with other feedstocks (e.g. sewage sludge, agricultural crops and cow manure) to optimise the process (Greben and Oelofse, 2009; Kigozi et al., 2014b; Matheri et al., 2018b).

Some studies have explored the potential for the adoption of anaerobic digestion for energy supply in households. A study conducted by Msibi and Kornelius (2017) found that an average South African household did not produce enough food waste to feed a biodigester that met their energy requirements; the feedstock would need to be supplemented with livestock manure which presents a constraint in urban areas.

2.2.3. Food redistribution

According to the food waste hierarchy developed by Papargyropoulou et al. (2014), redistribution of surplus food for human consumption is the most desirable option following prevention. Food redistribution can occur at various stages of the supply chain after harvesting, dependent on where it is generated. Food redistribution initiatives can take a variety of forms including food banks and kitchens which provide meals (Facchini et al., 2018; Midgley, 2014). Food redistribution in South Africa is dominated by two Non-Profit Organisations (NPOs): Food Forward and SA Harvest. These companies serve as facilitators of food redistribution, obtaining surplus food from supplier (e.g. retailers and farmers) and supplying it to programmes that distribute said food to the public (e.g. food pantries and food kitchens).

2.2.4. Animal feed

Theoretically, all food waste could be diverted to animal feed however, there are concerns about microbial activity (i.e. presence of microorganisms such as *Escherichia coli* and *Salmonella)* and mineral content (e.g. heavy metals) (Dou et al., 2018; García et al., 2005). Thus, all food waste must be heat treated to minimise microbial activity should it be destined for animal feed. An analysis of municipal solid waste in Spain found that fruit and vegetable waste could serve as an appropriate food source for animals (García et al., 2005). A similar result was found by Angulo et al. (2012) when investigating the suitability of food and vegetable waste from a Colombian marketplace for bovine feed. San Martin et al. (2016) investigated fruit and vegetable waste produced in different sectors across the value chain including retail and production, and determined it was suitable for use as animal feed although some fractions may require pre-treatment. Nonetheless, previous studies emphasised the need to detailed characterisation of waste streams to determine its suitability from both a health and safety perspective as well as nutritional content (Angulo et al., 2012; Dou et al., 2018; García et al., 2005; San Martin et al., 2016).

Whilst food waste can be diverted in its original form, it may also be used as a feedstock to produce animal feed. For example, Agriprotein in South Africa, utilises food waste as a feedstock for the commercial production of black soldier fly larvae; these insects provide a source of protein which may be incorporated into an animal's diet as required (Agriprotein, n.d.).

2.2.5. Fine chemicals production

Residue from agriculture and food production can be used as a feedstock in the manufacture of fine chemicals. For example, Brenn-o-kem in the Western Cape uses grape pomace (i.e. skin and seeds) from the wine industry as a feedstock for the production of calcium tartrate, and wine spirits as well as grape seed oil and tannin (Brenn-o-kem, n. d.).

The development of high value biorefineries utilising residues from sugar mills as feedstocks has been identified as an opportunity to develop the South African bioeconomy whilst revitalising the local sugar industry (DST, 2013; Farzad et al., 2017; Görgens et al., 2015; Pachón et al., 2018). Sugarcane bagasse can be utilised as a feedstock for the manufacture of chemicals including bioethanol, lactic acid, sorbitol, glucaric acid, furfural and levulinic acid. Lactic acid is a versatile chemical with a range of uses in food, pharmaceutical and cosmetics industries. In addition, it can be used in the production of polylactic acid, a bioplastic which has been rising in popularity in recent years. South Africa is one of the largest producers of biobased furfural (De Jong and Marcotullio, 2010; Pachón et al., 2018). Illovo Sugar Africa is a notable producer of furfural and its derivatives at its Sezela mill complex in KwaZulu-Natal (Illovo Sugar Africa, n.d.).

2.2.6. Energy recovery

Wood waste is commonly used for energy recovery within industrial processes. In the sugar industry, many sugar mills burn bagasse as a cheap and readily available feedstock to heat boilers to supplement the plant's energy requirements (Pachón et al., 2018). A similar practice is also employed in the forestry and paper and pulp industries, wherein wood offcuts and waste residues are used as a source of process heat (Stafford et al., 2020).

2.3. Factors influencing adoption of treatment methods

The selection of treatment methods is dependent on a variety of factors including feedstock and technology availability, economics and policy and regulatory aspects (Epstein, 2011; Greben and Oelofse, 2009; Kigozi et al., 2014b).

2.3.1. Feedstock availability

Feedstock availability and quality is critical to the development of sustainable industries; different treatment options require different feedstocks and have different tolerances for variations in quality (Paes et al., 2019). High value biomass operations such as biorefining, often require highly specific and high purity feedstocks, with processes that are highly sensitive to the presence of impurities. In contrast, high volume, low value application such as anaerobic digestion and composting can utilise a wider variety of feedstocks. However, the processes still require optimisation according to the feedstock and require a consistent and reliable supply (Awasthi et al., 2020; Greben and Oelofse, 2009; Kigozi et al., 2014b; Matheri et al., 2018b; Onwosi et al., 2017). In the case of anaerobic digestion, the availability of a consistent feedstock is often addressed by co-locating the digester on the waste generation site.

2.3.2. Economics

In general, treatment methods with more advanced technology are associated with higher capital expenditure and operating costs (Epstein, 2011; Greben and Oelofse, 2009; Kigozi et al., 2014b; Soos et al., 2014). In 2014, the South African government in conjunction with the German Ministry investigated alternative solid waste treatment options for South Africa, including the potential costs and job creation opportunities. Similarly to previous studies (Schwehn et al., 2014; Soos et al., 2014), they confirmed that advanced technology options would require higher capital investment and would require a longer timeframe to adopt and implement. A comparison of the methods identified by the NWMS, namely composting and anaerobic digestion, found that the latter was associated with higher capital and operating costs (shown in Table 1). Whilst the estimates from the study are dated, they provide insights into the relative costs associated with the different options.

Biorefineries are associated with high capital and operating costs (Görgens et al., 2015; Kapanji et al., 2021; Padi and Chimphango, 2020). In a study conducted by Görgens et al. (2015), they determined that the economic returns were not "sufficiently robust to attract private investment. Public private partnerships (PPP) may be viewed as an opportunity to increase investment in the industry. In 2014, a PPP (STEP-Bio) was funded by the South African sugarcane milling industry and the Department of Science and Innovation's Sector Innovation Fund ("Moving from Sugarcane Mills to Integrated Sugarcane Biorefineries," n. d.). STEP-Bio focused on short to medium term research and development in the biorefinery industry and supported many projects to that effect. The partnership ended in 2019. Since then there have been limited PPPs in the biorefinery industry. Instead, the government has been focussed on increasing PPPs in the energy sector (Herbert Smith Freehills LLP, 2022).

Costs associated with obtaining feedstock is also a consideration. This can take multiple forms in the organic waste industry depending on the business model. For example, when the waste treatment option forms part of an existing waste generating process there may be no costs associated with obtaining the feedstock. In some cases, waste collection may be an added service or companies

Table 1
Comparison of the economic costs associated with open composting, in-vessel composting and anaerobic digestion (Schwehn et al., 2014; Soos et al., 2014).

	Open composting	In-vessel composting	Anaerobic digestion
Input capacity ranges	5 - 500 kt/a	10 - 500 kt/a	5 - 150 kt/a
Typical outputs	compost	compost	biomethane, heat and electricity, nutrient rich digestate
Indicative capital cost	upwards of R7.75 m for a small-scale windrow system	R62 - R93 for a 30 ktpa facility	R124 - R217 m for a 25ktpa wet AD process
Indicative operating cost	low	low	high
Estimated treatment cost per tonne of feedstock (Rands/t)	300–400	600	700–800
Lifespan (yrs)	15–20	20–30	20–30
Job creation potential	high	low	low
Skills requirement	low	high	high

may charge a gate fee for waste "disposal" providing additional revenue streams. The feedstock quality is also a consideration as there may be additional costs associated with preparation and pre-treatment.

Job creation is a major consideration in the South African context. As shown in Table 1, open composting is considered to have high job creation potential due to the manual labour necessary for the operation. Furthermore, an inverse relationship is suggested between job creation and technological requirements. Fine chemicals production (biorefineries) have the potential to create jobs across the entire value chain from harvest to refinery particularly in the sugar industry. However, the number of jobs created depends on the chemicals in production (Görgens et al., 2015).

3. Discussion

The South African NWMS 2020 strategy highlights composting and anaerobic digestion as the primary diversion techniques to be employed (DEFF, 2020). As shown in Fig. 4, these are considered low value uses of biomass but, the selection of these treatment options may be attributed to their ability to meet the variety of sustainable development needs of the country (Stegmann et al., 2020). This is the case in South Africa whereby these treatment methods address multiple socio-economic needs of the country including job creation, energy provision and food security (discussed further in section 3.1). However, the wider organic waste industry presents opportunities for the development of high value industries which have the potential to contribute to the country's socioeconomic development (section 3.2).

3.1. Potential sustainability benefits

Like many developing countries, South Africa faces many challenges with regards to waste management infrastructure and service delivery. In 2019, only 58.8% of households had access to weekly refuse removal (Stats SA, 2020). Investment in waste management options which have the potential to treat high volumes of waste could contribute to increased service delivery in the waste sector. In theory, composting and anaerobic digestion provide great versatility when it comes to potential feedstocks (shown in Fig. 4). However, as discussed in sections 2.2.1 and 2.2.2, it must be noted that optimisation of each process is necessary to effectively treat the waste. Furthermore, the selection of a treatment method is influenced by a number of factors including technology availability, economics as well as the policy and regulatory environmental environment. Thus, the potential sustainability benefits that may be realised through organic waste valorisation is dependent on the capabilities of the industry.

Energy security is a growing concern in South Africa, which has been experiencing nationwide power outages since 2007 (Salakhetdinov and Agyeno, 2020). According to a recent household survey, 85.0% of households are connected to the national electricity grid (Stats SA, 2020). It was further found that 75.1% of households used electricity as a source of energy for cooking, whilst 7.8% used wood and 4.2% used gas. When coupled with the limited access to waste removal, the development of anaerobic digestion systems has the potential to meet multiple needs: the provision of waste management options and a source of energy (Greben and Oelofse, 2009; Kigozi et al., 2014a; Nethengwe et al., 2018). This would be of particular value in rural communities where 84.0% of households are reliant on their own dumps for waste disposal (Stats SA, 2020).

The contribution of the bioeconomy to food security was proposed as an indicator to measure and monitor a circular bioeconomy by Kardung et al. (2021). As with many other nations, addressing food insecurity is a priority area for the South African government (DAFF, 2014; Hendriks, 2014; Koch, 2011). In 2019, 11.5% of households reported inadequate food access and a further 6.3% reported severely inadequate food access (Stats SA, 2020). The NWMS makes a clear linkage between organic waste diversion from landfill and increasing food security (DEFF, 2020). For example, composting is associated with the potential development of community garden initiatives whereby the resultant soil conditioners are directly used in local food gardens. Similarly, the digestate produced during anaerobic digestion may be used as a soil enhancer increasing productivity during small scale farming. However, a more direct approach to addressing food insecurity is through the promotion of programmes that decrease food loss. Recent years have seen more concerted efforts by the government to facilitate the diversion of edible surplus food to communities in need. This culminated with the launch of the South African Food Loss and Waste Voluntary Agreement in 2020 which is co-led by the Consumer Good Council of South Africa, the Department of Trade, Industry and Competition and the Department of Environment, Forestry and Fisheries (Parfitt and Jenkin, 2020).

The proposed indicator framework for monitoring and measuring a circular bioeconomy by Kardung et al. (2021), also includes contribution to employment as a key indicator. Development of the waste economy is seen as an opportunity for job creation in South Africa (DEA, 2017). However, as shown in section 2, the job creation potential varies according to the method, with high technology requirements generally being associated with fewer job opportunities. In addition, high technology methods require more skilled labour (Schwehn et al., 2014; Soos et al., 2014).

The mitigation of climate change emissions is often cited as a motivation for alternative waste treatments to disposal in landfill (Bogner et al., 2008; Christensen et al., 2009; Friedrich and Trois, 2013), and is thus a potential benefit associated with closing the loop in the bioeconomy (Dietz et al., 2018; Kardung et al., 2021). Methane gas is a potent greenhouse gas which is released as material decomposes in landfills. One of the ways to mitigate its release is landfill gas capturing. However, it is not widely practised in South Africa with a few operations in KwaZulu-Natal and Gauteng provinces (Mutungwazi et al., 2018). Thus, diversion from landfill has the potential to mitigate South Africa's climate change emissions whilst allowing for economic growth.

3.2. Opportunities for growth

As discussed in the Introduction, the South African government recognises the importance of sustainable waste management and the potential sustainability benefits associated with developing the waste economy. However, it can be argued that current strategies fall short in identifying potential opportunities for growth that could result in greater economic returns through the development of high value industries. The focus on composting and anaerobic digestion in the NWMS may be interpreted as trying to maximise on low hanging fruit. As shown in Fig. 4, these technologies are relatively well established in South Africa in comparison to treatment methods such as biorefining which are largely in the research and development stage. However, the question remains as to whether this emphasis will enable the country to meet its goals for organic waste diversion from landfill.

Anaerobic digestion and/or composting can both be effective strategies for the diversion of organic waste. For example, as stated in section 2.2.1, municipalities have been employing composting for garden waste. Composting is also being considered for the diversion of organics in municipal solid waste. However, diverting organics to anaerobic digestion would have the additional benefit of energy production but it is a more complex technology. Thus, the simpler, cheaper and more commercially established method, composting, may be used as a stopgap measure whilst more efficient technologies are being developed. In this way, the country may continue progress towards a circular bioeconomy whilst investing in the development of new technologies.

In order to meet the diversion strategies, there needs to be increased diversion of industrial waste from the sugar and pulp and paper industries. Investment in biorefineries has the potential to develop a bioeconomy based on the production of high value products whilst also addressing the societal needs of South Africa such as job creation. For example, sugarcane bagasse accounted for 23.6% of organic waste in 2017 (DEA, 2018); multiple studies have been conducted investigating the feasibility of different biorefinery configurations for chemical production including ethanol, methanol, furfural, and lactic acid (Farzad et al., 2017; Görgens et al., 2015; Kapanji et al., 2021; Pachón et al., 2018). The study by Görgens et al. (2015) recognised the energy needs of plants and explored the coproduction of chemicals along with electricity generation. The development of biorefineries has the potential to create jobs not only in the refinery itself but upstream, in the agricultural sector for the preparation of the bagasse (Görgens et al., 2015).

Forestry and pulp and paper industries also present opportunities for biorefinery development. A review of biorefining opportunities for waste from these industries identified 129 potential processing pathways for the generation of 78 unique products (Stafford et al., 2020). In 2018, SAPPI approved the construction of a demonstration plant for the production of xylitol and furfural in South Africa (Sappi, 2018). An opportunity also exists for biorefining of starches such as cassava wherein multiple configurations have been investigated (Padi and Chimphango, 2020).

Small-scale biorefineries for the processing of biomass with lower tonnages is an option that should not be ignored. Their size enables them to be located close to the source of raw materials, making them ideal for development in rural areas including at farm levels (Loaiza et al., 2017). It is relatively easier to get investors for technology at a small-scale making innovation faster (Bruins and Sanders, 2012; Clauser et al., 2016). Furthermore, they are more flexible to change of conditions making adaptation a relatively quicker process (Bruins and Sanders, 2012). Biorefining of organic waste at different scales is also a priority research area in South Africa, with the Department of Science and Technology funding a variety of projects investigating different waste streams including fruit, forestry, sugar, poultry and meat (DST, n.d.).

4. Conclusions

For a developing country such as South Africa, the transition towards a circular bioeconomy is underpinned by the socio-economic needs of the country. The National Waste Management Strategy 2020 promotes the diversion of organic waste to well established treatment methods: composting and anaerobic digestion. The potential sustainability benefits associated with these methods could potentially address many challenges being faced by the country including food security, energy security, job creation and climate change mitigation.

When selecting a treatment method to promote, trade-offs are seemingly inevitable. Composting has the potential to create many jobs, contribute to food security and is the most commercially established. In comparison, anaerobic digestion contributes to both food and energy security but, it has a lower job creation potential than composting as well as higher capital and operating costs. Ultimately, the choice of treatment method is dependent on the context within which it will operate.

Whilst the potential for the development of high value industries such as biorefineries has been investigated, the investment cost remains prohibitive for the country. However, in the long-term, investment in biorefining is necessary to achieve a circular bioeconomy which not only “closes the loop” but optimises the value of biomass. Furthermore, these industries could lead to greater economic growth potentially resulting in more socio-economic benefits.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

This work was funded by the National Research Foundation of South Africa (Grant Number: 128149).

References

Agriprotein, n.d. Recycling food waste into sustainable insect protein using biotechnology [WWW Document]. URL https://www.agriprotein.com/(accessed 2.11.21)..
Angulo, J., Mahecha, L., Yepes, S.A., Yepes, A.M., Bustamante, G., Jaramillo, H., Valencia, E., Villamil, T., Gallo, J., 2012. Quantitative and nutritional characterization of fruit and vegetable waste from marketplace: a potential use as bovine feedstuff? J. Environ. Manag. 95, S203–S209. https://doi.org/10.1016/j.jenvman.2010.09.022.
Awasthi, S.K., Sarsaiya, S., Awasthi, M.K., Liu, T., Zhao, J., Kumar, S., Zhang, Z., 2020. Changes in global trends in food waste composting: research challenges and opportunities. Bioresour. Technol. 299, 122555 https://doi.org/10.1016/j.biortech.2019.122555.
Bogner, J., Pipatti, R., Hashimoto, S., Diaz, C., Mareckova, K., Diaz, L., Kjeldsen, P., Monni, S., Faaij, A., Qingxian, G., Tianzhu, Z., Mohammed, A.A., Sutamihardja, R.T.M., Gregory, R., 2008. Mitigation of global greenhouse gas emissions from waste: conclusions and strategies from the intergovernmental panel on climate change (IPCC) fourth assessment Report. Working group III (mitigation). Waste Manag. Res. 26, 11–32. https://doi.org/10.1177/0734242X07088433.
Brenn-o-kem, n.d. Our range of products [WWW Document]. URL https://www.brenn-o-kem.co.za/products/(accessed 2.11.21)..
Bruins, M.E., Sanders, J.P.M., 2012. Small-scale processing of biomass for biorefinery. Biofuels, Bioprod. Biorefining 6, 135–145. https://doi.org/10.1002/bbb1319.
Christensen, T.H., Simion, F., Tonini, D., Møller, J., 2009. Global warming factors modelled for 40 generic municipal waste management scenarios. Waste Manag. Res. 27, 871–884. https://doi.org/10.1177/0734242X09350333.
Clauser, N.M., Gutiérrez, S., Area, M.C., Felissia, F.E., Vallejos, M.E., 2016. Small-sized biorefineries as strategy to add value to sugarcane bagasse. Chem. Eng. Res. Des. 107, 137–146. https://doi.org/10.1016/j.cherd.2015.10.050.
DAFF, 2014. The National Policy on Food and Nutrition Security for the Republic of South Africa. Department of Agriculture Forestry and Fisheries.
De Jong, W., Marcotullio, G., 2010. Overview of biorefineries based on co-production of furfural, existing concepts and novel developments. Int. J. Chem. React. Eng. 8 https://doi.org/10.2202/1542-6580.2174.
de Lange, W., Nahman, A., 2015. Costs of food waste in South Africa: incorporating inedible food waste. Waste Manag. 40, 167–172. https://doi.org/10.1016/j.wasman.2015.03.001.
DEA, 2012. National Waste Information Baseline Report. Department of Environmental Affairs, Pretoria, South Africa.
DEA, 2013. The National Organic Waste Composting Strategy - Final Status Quo Report. Department of Environmental Affairs, Pretoria, South Africa.
DEA, 2017. Operation Phakisa: Chemicals and Waste Economy Lab Outcomes. Department of Environmental Affairs.
DEA, 2018. South Africa - State of Waste Report. Department of Environmental Affairs, Pretoria, South Africa. https://doi.org/10.18041/2382-3240/saber.2010v5n1.2536.
DEADP, 2020. Provincial Organic Waste Strategy. Western Cape Government Department of Environmental Affairs & Development Planning, Cape Town, South Africa.
DEFF, 2020. National Waste Management Strategy 2020. Department of Environment, Forestry and Fisheries, Pretoria, South Africa.
Dietz, T., Börner, J., Förster, J.J., von Braun, J., 2018. Governance of the bioeconomy: a global comparative study of national bioeconomy strategies. Sustain. Times 10. https://doi.org/10.3390/su10093190.
Dou, Z., Toth, J.D., Westendorf, M.L., 2018. Food waste for livestock feeding: feasibility, safety, and sustainability implications. Global Food Secur. 17, 154–161. https://doi.org/10.1016/j.gfs.2017.12.003.
DST, 2013. The Bio-Economy Strategy. Department of Science and Technology, Pretoria, South Africa.
EMF, 2013. Towards the Circular Economy: Economic and Business Rational for an Accelerated Transition. Ellen MacArthur Foundation.
Epstein, E., 2011. Industrial Composting: Environmental Engineering and Facilities Management. CRC Press, Florida, United States of America.
Facchini, E., Iacovidou, E., Gronow, J., Voulvoulis, N., 2018. Food flows in the United Kingdom: the potential of surplus food redistribution to reduce waste. J. Air Waste Manag. Assoc. 68, 887–899. https://doi.org/10.1080/10962247.2017.1405854.
FAO, 2019. The State of Food and Agriculture 2019. Moving Forward on Food Loss and Waste Reduction. Food and Agricultural Organization of the United Nations, Rome, Italy. https://doi.org/10.4324/9781315764788.
FAO, 2020. Food Agric. Organ. United Nations. New food balances [WWW Document]. URL. http://www.fao.org/faostat/en/#data/FBS, 10.24.20.
Farzad, S., Mandegari, M.A., Guo, M., Haigh, K.F., Shah, N., Görgens, J.F., 2017. Multi-product biorefineries from lignocelluloses: a pathway to revitalisation of the sugar industry? Biotechnol. Biofuels 10, 1–24. https://doi.org/10.1186/s13068-017-0761-9.
Friedrich, E., Trois, C., 2013. GHG emission factors developed for the recycling and composting of municipal waste in South African municipalities. Waste Manag. 33, 2520–2531. https://doi.org/10.1016/j.wasman.2013.05.010.
Furlong, C., Rajapaksha, N.S., Butt, K.R., Gibson, W.T., 2017. Is composting worm availability the main barrier to large-scale adoption of worm-based organic waste processing technologies? J. Clean. Prod. 164, 1026–1033. https://doi.org/10.1016/j.jclepro.2017.06.226.
Gajalakshmi, S., Abbasi, S.A., 2008. Solid Waste Management by Composting: State of the Art, Critical Reviews in Environmental Science and Technology. https://doi.org/10.1080/10643380701413633.
García, A.J., Esteban, M.B., Márquez, M.C., Ramos, P., 2005. Biodegradable municipal solid waste: characterization and potential use as animal feedstuffs. Waste Manag. 25, 780–787. https://doi.org/10.1016/j.wasman.2005.01.006.
Görgens, J., Mandegari, M., Farzad, S., Dafal, A., Haigh, K., 2015. A Biorefinery Approach to Improve the Sustainability of the South African Sugar Industry: an Assessment of Selected Scenarios. https://doi.org/10.4324/9780429201998-6.
Greben, H.A., Oelofse, S.H.H., 2009. Unlocking the resource potential of organic waste: a South African perspective. Waste Manag. Res. 27, 676–684. https://doi.org/10.1177/0734242X09103817.
GreenCape, 2020a. Waste: 2020 market intelligence report. Cape Town, South Africa 33.
GreenCape, 2020b. Food loss and waste: a case for reduction, recovery and recycling. Cape Town, South Africa 8.
Gustavsson, J., Cederberg, C., Sonesson, U., Emanuelsson, A., 2013. The methodology of the FAO study : " Global Food Losses and Food Waste - extent , causes and prevention " - FAO , 2011. SIK report No. 857.
Heimann, T., 2019. Bioeconomy and SDGs: does the bioeconomy support the achievement of the SDGs? Earth's Future 7, 43–57. https://doi.org/10.1029/2018EF001014.
Hendriks, S., 2014. Food security in South Africa: status quo and policy imperatives. Agrekon 53, 1–24. https://doi.org/10.1080/03031853.2014.915468.
Kapanji, K.K., Haigh, K.F., Johann, F.G., 2021. Biomass and Bioenergy Techno-economics of lignocellulose biorefineries at South African sugar mills using the biofine process to co-produce levulinic acid , furfural and electricity along with gamma valeractone 146. https://doi.org/10.1016/j.biombioe.2021.106008.
Kardung, M., Cingiz, K., Costenoble, O., Delahaye, R., Heijman, W., Lovrić, M., van Leeuwen, M., M'Barek, R., van Meijl, H., Piotrowski, S., Ronzon, T., Sauer, J., Verhoog, D., Verkerk, P.J., Vrachioli, M., Wesseler, J.H.H., Zhu, B.X., 2021. Development of the circular bioeconomy: drivers and indicators. Sustainability 13, 413. https://doi.org/10.3390/su13010413.
Kigozi, R., Aboyade, A., Muzenda, E., 2014a. Biogas production using the organic fraction of municipal solid waste as feedstock. Int. J. Res. Chem. Metall. Civ. Eng. 1.
Kigozi, R., Muzenda, E., Aboyade, A.O., 2014b. Biogas technology: current trends, opportunities and challenges. In: 6th International Conference on Green Technology. Renewable Energy & Environmental Engineering, Cape Town, South Africa.
Koch, J., 2011. The Food Security Policy Context in South Africa, Country Study, No. 21, Country Study. International Policy Centre for Inclusive Growth, Brasilia.

Loaiza, S.S., Aroca, G., Cardona, C.A., 2017. Small-scale biorefineries: future and perspectives. In: Torres, I. (Ed.), Biorefineries: Concepts, Advancements and Research. Nova Science Publishers, Inc, New York, pp. 1–38.

Maina, S., Kachrimanidou, V., Koutinas, A., 2017. A roadmap towards a circular and sustainable bioeconomy through waste valorization. Curr. Opin. Green Sustain. Chem. 8, 18–23. https://doi.org/10.1016/j.cogsc.2017.07.007.

Mak, T.M.W., Xiong, X., Tsang, D.C.W., Yu, I.K.M., Poon, C.S., 2020. Sustainable food waste management towards circular bioeconomy: policy review, limitations and opportunities. Bioresour. Technol. 297 https://doi.org/10.1016/j.biortech.2019.122497.

Masebinu, S.O., Akinlabi, E.T., Muzenda, E., Aboyade, A.O., Mbohwa, C., 2018. Experimental and feasibility assessment of biogas production by anaerobic digestion of fruit and vegetable waste from Joburg Market. Waste Manag. 75, 236–250. https://doi.org/10.1016/j.wasman.2018.02.011.

Matheri, A.N., Mbohwa, C., Ntuli, F., Belaid, M., Seodigeng, T., Catherine Ngila, J., Kinuthia Njenga, C., 2018a. Waste to energy bio-digester selection and design model for the organic fraction of municipal solid waste. Renew. Sustain. Energy Rev. 82, 1113–1121. https://doi.org/10.1016/j.rser.2017.09.051.

Matheri, A.N., Sethunya, V.L., Belaid, M., Muzenda, E., 2018b. Analysis of the biogas productivity from dry anaerobic digestion of organic fraction of municipal solid waste. Renew. Sustain. Energy Rev. 81, 2328–2334. https://doi.org/10.1016/j.rser.2017.06.041.

Midgley, J.L., 2014. The logics of surplus food redistribution. J. Environ. Plann. Manag. 57, 1872–1892. https://doi.org/10.1080/09640568.2013.848192.

Moving from Sugarcane Mills to Integrated Sugarcane Biorefineries [WWW Document], n.d. . Sugar milling res. Inst. URL https://www.smri.org/sugarfacts/Pages/sugarcanebiorefineries.aspx (accessed 6.19.22)..

Msibi, S.S., Kornelius, G., 2017. Potential for domestic biogas as household energy supply in South Africa. J. Energy South Afr. 28, 1–13. https://doi.org/10.17159/2413-3051/2017/v28i2a1754.

Mutungwazi, A., Mukumba, P., Makaka, G., 2018. Biogas digester types installed in South Africa: a review. Renew. Sustain. Energy Rev. 81, 172–180. https://doi.org/10.1016/j.rser.2017.07.051.

Nagel, B.M., 2019. An Update on the Process Economics of Biogas in South Africa Based on Observations from Recent Installations. University of Cape, Town.

Nahman, A., de Lange, W., 2013. Costs of food waste along the value chain: evidence from South Africa. Waste Manag. 33, 2493–2500. https://doi.org/10.1016/j.wasman.2013.07.012.

Nethengwe, N.S., Uhunamure, S.E., Tinarwo, D., 2018. Potentials of biogas as a source of renewable energy: a case study of South Africa. Int. J. Renew. Energy Resour. 8, 1112–1123.

Onwosi, C.O., Igbokwe, V.C., Odimba, J.N., Eke, I.E., Nwankwoala, M.O., Iroh, I.N., Ezeogu, L.I., 2017. Composting technology in waste stabilization: on the methods, challenges and future prospects. J. Environ. Manag. 190, 140–157. https://doi.org/10.1016/j.jenvman.2016.12.051.

Pachón, E.R., Vaskan, P., Raman, J.K., Gnansounou, E., 2018. Transition of a South African sugar mill towards a biorefinery. A feasibility assessment. Appl. Energy 229, 1–17. https://doi.org/10.1016/j.apenergy.2018.07.104.

Padi, R.K., Chimphango, A., 2020. Feasibility of commercial waste biorefineries for cassava starch industries: techno-economic assessment. Bioresour. Technol. 297 https://doi.org/10.1016/j.biortech.2019.122461.

Paes, L.A.B., Bezerra, B.S., Deus, R.M., Jugend, D., Battistelle, R.A.G., 2019. Organic solid waste management in a circular economy perspective – a systematic review and SWOT analysis. J. Clean. Prod. 239, 118086 https://doi.org/10.1016/j.jclepro.2019.118086.

Papargyropoulou, E., Lozano, R., K Steinberger, J., Wright, N., Ujang, Z. Bin, 2014. The food waste hierarchy as a framework for the management of food surplus and food waste. J. Clean. Prod. 76, 106–115. https://doi.org/10.1016/j.jclepro.2014.04.020.

Parfitt, J., Jenkin, N., 2020. South Africa's Food Loss and Waste Voluntary Agreement: Implementation Plan. Consumer Goods Council of South Africa.

Philp, J., Winickoff, D., 2018. Realising the circular bioeconomy. OECD Sci. Technol. Ind. Policy Pap. 1–74.

SABIA, 2016. Biogas Industry in South Africa - an Assessment of the Skills Need and Estimation of the Job Potential.

Salakhetdinov, E., Agyeno, O., 2020. Achieving energy security in Africa: prospects of nuclear energy development in South Africa and Nigeria. African J. Sci. Technol. Innov. Dev. 1–9. https://doi.org/10.1080/20421338.2020.1799538.

San Martin, D., Ramos, S., Zufía, J., 2016. Valorisation of food waste to produce new raw materials for animal feed. Food Chem. 198, 68–74. https://doi.org/10.1016/j.foodchem.2015.11.035.

Sappi, 2018. Sappi approves construction of demonstration plant for Xylitol & Furfural production in line with strategic biorefinery plans [WWW Document]. URL. https://www.sappi.com/sappi-approves-construction-demonstration-plant-xylitol-furfural-production-line-strategic, 2.21.21.

Schaub, S.M., Leonard, J.J., 1996. Composting: an alternative waste management option for food processing industries. Trends Food Sci. Technol. 7, 263–268. https://doi.org/10.1016/0924-2244(96)10029-7.

Schwehn, E., Whiteman, A., Frith, P., Gower-Jackson, S., 2014. Appropriate Technology for Advanced Waste Treatment. Department of Environmental Affairs, Pretoria, South Africa.

Singh, R.P., Singh, P., Araujo, A.S.F., Hakimi Ibrahim, M., Sulaiman, O., 2011. Management of urban solid waste: vermicomposting a sustainable option. Resour. Conserv. Recycl. 55, 719–729. https://doi.org/10.1016/j.resconrec.2011.02.005.

Smith Freehills Llp, Herbert, 2022. A general introduction to public-private partnerships in South Africa [WWW Document]. Law Rev. URL. https://www.lexology.com/library/detail.aspx?g=53749261-0103-47c2-b667-24704aaf37b9, 6.19.22.

Soos, R., Whiteman, A., Gheorghiu, D., 2014. Financial Implications of Advanced Waste Treatment. Department of Environmental Affairs, Pretoria, South Africa.

Stafford, W., De Lange, W., Nahman, A., Chunilall, V., Lekha, P., Andrew, J., Johakimu, J., Sithole, B., Trotter, D., 2020. Forestry biorefineries. Renew. Energy 154, 461–475. https://doi.org/10.1016/j.renene.2020.02.002.

Stats SA, 2020. General Household Survey 2019. Department: Statistics South Africa, Pretoria, South Africa.

Stegmann, P., Londo, M., Junginger, M., 2020. The circular bioeconomy: its elements and role in European bioeconomy clusters. Resour. Conserv. Recycl. X 6, 100029. https://doi.org/10.1016/j.rcrx.2019.100029.

Illovo sugar Africa, n.d. Products overview [WWW Document]. URL https://www.illovosugarafrica.com/Products (accessed 2.18.21)..

Venkata Mohan, S., Nikhil, G.N., Chiranjeevi, P., Nagendranatha Reddy, C., Rohit, M.V., Kumar, A.N., Sarkar, O., 2016. Waste biorefinery models towards sustainable circular bioeconomy: critical review and future perspectives. Bioresour. Technol. 215, 2–12. https://doi.org/10.1016/j.biortech.2016.03.130.

WBCSD, BCG, 2020. Circular Bioeconomy: the Business Opportunity Contributing to a Sustainable World. World Business Council for Sustainable Development.

Wellinger, A., Murphy, J., Baxter, D., 2013. The Biogas Handbook: Science, Production and Applications, the Biogas Handbook: Science, Production and Applications. https://doi.org/10.1533/9780857097415.