Towards Sustainability in Municipal Solid Waste Management in South Africa: A Survey of Challenges and Prospects

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In most developing countries, the huge amount of unmanaged municipal solid wastes and the inefficiency of the current waste management system has resulted in an unprecedented effect on human health and the quality of the environment. The drive towards sustainability in solid waste management in South Africa has led to the promulgation of several legislations and policies directed towards increased efficiency of solid waste management strategies. However, despite the progress in South Africa's waste management systems over the years, it is still being constantly faced with some challenges and shortcomings. To achieve sustainable development through the transition from a linear economic model to a circular economy, there is a need to revamp the waste management sector. This study presents a survey of the key physical elements of integrated waste management in South Africa. The study further discusses the challenges with major emphasis on the future directions of integrated waste management. Waste management decisions are data-driven decisions. This study identifies the lack of accurate and reliable waste-related data as one of the major factors that impede the fast-track growth towards sustainable waste management in South Africa. A data-mining approach that emphasizes intelligent modeling of waste management systems is recommended to support the national waste database which will aid waste management decisions and optimizes waste management facilities and investments. Sustainability in waste management in South Africa requires a multi-sector intervention and involvement to stimulate sustainable development in waste management.

Keywords: intelligent modeling, circular economy, sustainability, South Africa, waste management

1. Introduction

Municipal Solid waste management has both environmental and economic consequences. It is a crucial challenge of the environment globally and in most African countries. The huge volume of unmanaged solid wastes and the inefficiency of the current waste management system in most developing countries has resulted in an unprecedented effect on human health and the quality of the environment. Deficient waste collection and disposal system, inappropriate location of facilities affects human health and affects the environment negatively by contributing to climatic change, pollution of air, soil, and water. There is a prediction of an increase in the trend of waste generation globally from 3.5 million tonnes daily in 2010 to above 6 million tonnes daily in 2025 (Hoornweg and Bhada-Tata, 2012). However, globally, about two billion population do not have access to a proper waste collection system (UNEP, 2015). Few among the problems inhibiting integrated waste management in developing countries are lack of proper planning, economic barrier, deficient recycling facilities, and public passivity to waste management (Gupta and Misra, 2014). A major method of waste disposal is still the landfill method in developing countries which produces methane gas, a greenhouse gas 21 times weightier than carbon dioxide (Couth and Trois, 2012) which affect the quality of the groundwater (Olusheyi *et al.*, 2020), and form a threat to human and the environment (Adegoke *et al.*, 2017). The deficiency in the collection and disposal of waste has led to waste accumulations on the street, public places, and other illegal dumpsites.

Sustainability is achieved in waste management when material resources are utilized efficiently to reduce the quantity of generated waste, in a manner that promotes sustainable development goals. It is important to study waste management in terms of sustainability by all stakeholders and practitioners. Bui *et al.*, (2020) identified some of the barriers to achieving sustainability in solid waste management and transformed the factors into comparable scales using the fuzzy Delphi technique. The study identified the most important of these barriers; lack of sufficient funds, hazardous waste, lack of staff capacities, and deficient and less-standard data collection and analysis. Solid waste management plays a vital role in the drive towards achieving sustainable development (Ikhlayel, 2018). However, management shortcomings that have overwhelmed solid waste management have resulted in the loss of resources and lean waste management approaches to emergencies and response maintenance (Galante *et al.*, 2010).

According to Campitelli & Schebek (2020), different waste management assessment methods that aid decision making have been identified in previous researches namely; material flow analysis (MFA), multi-criteria-decision-making (MCDM), risk assessment (RA), simulation models, life cycle Assessment (LCA), clean development mechanism (CDM), cost-benefit analysis, energy analysis, among others. However, it has been observed that the practical applications of comprehensive assessment tools are limited owing to the complexities of these methods (Campitelli & Schebek, 2020; Zurbrügg et al., 2014). Campitelli & Schebek (2020) further identified the challenge of non-availability of reliable and accurate waste-related data in most developing countries as a major factor which impedes the application of these assessment methods

South Africa is a developing country with nine provinces and a total population of 58.78 million (StatsSA, 2019). The upsurge in population and urbanization has placed a burden on the waste management system in South Africa (Friedrich and Trois, 2010). In South Africa, like most developing countries, waste management is an urban issue due to the non-stop urbanization and the increase in the population. The population of individuals in South Africa residing in the urban areas is expected to grow by 71.3% and 80% in 2030 and 2050 respectively (DEA, 2018). According to the Department of Environment (DEAT, 2000), reliable and accurate data on the current waste situation including waste quantities and characteristics is a vital first step towards planning an integrated waste management plan.

According to a waste report in the third National Waste Baseline published by the Department of Environmental Affairs, South Africa revealed that about 108 million tonnes of waste were generated in 2012, which comprised of both general waste and hazardous waste. A larger percentage of the waste, about 98 million tonnes was disposed of in the landfill and less than 10% of the total generated waste was recycled (DEA, 2012a). By 2017, general waste generation has increased to 54.2 million tonnes and hazardous waste to 66.9 million tonnes (DEA, 2018). The drive towards sustainability in solid waste management in South Africa has led to the promulgation of several legislations and policies directed towards increased efficiency of solid waste management strategies. However, despite the progress in South Africa's waste management systems over the years, it is still being constantly faced with some challenges and shortcomings. Strategic planning of environmental and economically sustainable waste management is urgently essential in the waste management sector of South Africa.

Achieving optimal goals targeted at improvements in waste management strategies, efficient utilization and allocation of resources, effective collection, disposal, and treatment of waste has been very challenging in South Africa owing to the complex interconnections between the physical and non-physical elements of integrated waste management. Deficiency of any of these elements; collection, disposal, treatment, material recovery will affect the overall performance of the waste management system. This study presents a survey of key elements of integrated waste management in South Africa. This is achieved by evaluating the trend, progresses, shortcomings, and possible areas of improvement in each of the components towards sustainable waste management. The status quo waste management was evaluated holistically to identify the challenges and future directions of waste management.

Subsequent sections in this paper are structured as follows; section 2 describes the methodology used in this study to evaluate the waste management system, section 3 discusses the significance of integrating the circular economy model in waste management to achieve sustainable development. Section 4 presents integrated solid waste management and discusses briefly the key elements of integrated solid waste management in South Africa. Some of the shortcomings with major emphasis on the future directions of integrated waste management in South Africa were discussed in section 5. This section emphasizes the application of artificial intelligence techniques for reliable estimation of waste characteristics. Section 6 concludes this paper.

2. Methodology

The methodology used in this study is a desktop literature survey of articles relevant to South Africa waste management, reports of the Department of Environment Affairs, South African Waste Information Centre (SAWIC), and reports from the South Africa national database (StatsSA). Also, reports and bulletin from globally recognized databases were reviewed. The popular trend of waste generation, collection and disposal, and treatment were reviewed and compared to the South Africa case study to identify areas of improvement. An extensive literature review of relevant articles from reputable journal in the space of municipal solid waste management was also done to find useful information on waste management scenarios locally and internationally

3. Waste Management, Circular Economy and Sustainable Development

Circular economy (CE) suggests the upper ranks in the waste hierarchy scales namely; prevention, reuse, and recycling, thereby promoting a cleaner production where waste production is minimal (Luttenberger, 2020). CE adoption has been gaining traction globally because of the abrupt depletion of resources and the harmful environmental consequences of climatic changes (Priyadarshini and Abhilash, 2020). It has been adopted as an alternative to the existing production and consumption model of “take, make, and dispose” which constitutes the linear economy (Ghisellini *et al.,* 2016). The linear economy is characterized by waste generation by the consumer from manufactured products that are disposed of, thereby posing challenges of pollution and depletion of resources (Ogunmakinde, 2019). The trend which the CE model depicts is a “resource-product-waste-regenerate resource”, through effective use and re-use, minimization of waste generation, pollution reduction, thereby reserving resources, boosts sustainable development, and protect the environment (Guohui and Yunfeng, 2012). CE is mainly targeted towards a greater equilibrium between economy, environment, and society and in the improvement of the efficiency of resource consumption, to preserve the value of resources and material and minimize waste through a closed-loop pattern of production in economic development (Ghisellini *et al.*, 2016). An important tool that is vital to determine the course of action to achieve system sustainability is the sustainability assessment tool (Ness, 2006). According to Ness 2006, sustainability assessment tools are categorized as follows:

- A quantitative tool which measures the economic, social, and environmental development based on a long-term history of the trend of sustainability
- Product or service tool which is aimed at assessing the environmental impact of materials flow and energy in its cradle-to-grave life cycle
- Integrated assessment tool for future predictions, projects evaluations which will aid decision making

To achieve sustainable development through the transition from a linear economic model to a circular economy, there is a need to revamp the waste management sector. This can be achieved through a paradigm shift to a more sustainable and resource-efficient ecosystem (Zhang *et al.*, 2019). According to UN (2019), the following sustainable development goals are related to solid waste management: SDG 4 –Inclusive quality education for all, SDG 8 - Productive job and sustainable economic growth, SDG 9 - Industrialization and infrastructure, SDG 11 - Safe and sustainable cities and human settlements, SDG 12 - Sustainable consumption and production and SDG 17 – reinforce Partnerships for the sustainable development goals. Sustainable development is achieved when present needs are satisfied without compromising the capacity of meeting future needs (Johanna, 2018). Sustainability is a subject which interacts the economic, environmental, and social aspect of an event (Kate, 2012). CE synergizes resource consumption, waste generation, and emissions and integrates economic and environmental policies (Mayer *et al.*, 2019). A set of action plans were recommended by the EU in 2015 which is targeted towards the transition from a linear economy to a circular economy to foster sustainable consumption and production, economic growth, job creation, and enhances of supply of raw material to industries in alignment with the 2030 EU sustainable development agenda (European Commission, 2015).

The future of the waste sector is a circular economy where a sustainable and zero waste society is realized. Zero waste society is achieved when resources are conserved through production, consumption, re-use, product, and materials recovery without contamination of the environment that can risk human life and health. CE can be implemented in several stages such as the design, production, and consumption stages, and waste management to achieve sustainable development (Zhijun and Nailing, 2007). In the waste management sector, CE can be implemented at three levels (i) micro-level which involves product recycling and reuse system, scavenger, and decomposers at the consumer level (ii) Meso-level such as in waste trade market and renewable resources, and (iii) macro-level which features zero waste management strategy at the city or regional scale. Figure 1 presents the conceptual framework of the CE

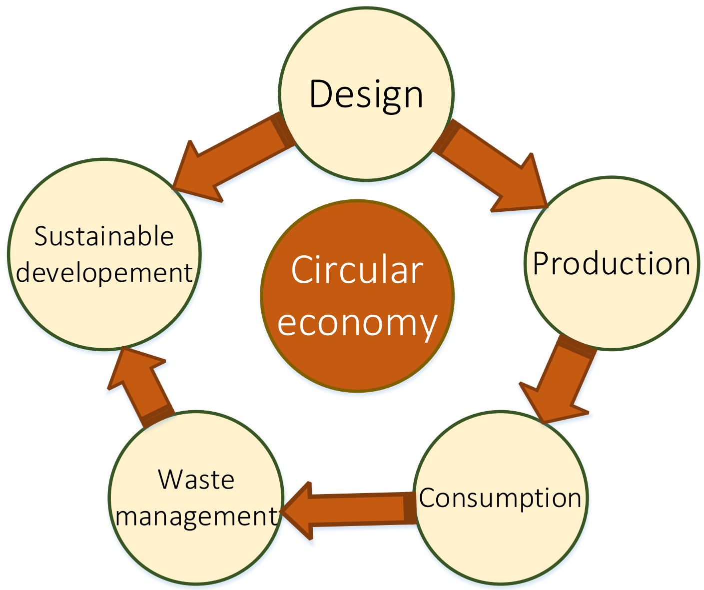

Figure 1 Circular Economy development model structure (Ogunmakinde 2019)

The state-of-the-art solid waste management systems are no longer the oversimplified method of collecting, sorting, and disposal. It is experiencing a transformation to a more sustainable system which through conformity to waste hierarchical steps balances product or service, system designs, materials, and energy recovery and end-of-life management of presently wasted resources (Jacobsen *et al.*, 2018). The waste hierarchy is a set of steps, which sets out the preference order for waste management with a core objective of reducing was and divert a reasonable quantity of waste that is disposed of in landfills. The highest and the most preferred priority in the waste hierarchy is the prevention of waste through avoidance and reduction while the least preferred option is the final disposal of non-recyclable and non-biodegradable wastes as depicted in an inverted pyramid in Figure 2. Avoidance and reduction of waste involve an effort to prevent the production of materials that become waste and prevent them from entering waste streams. Where it is impossible to prevent, avoid, and reduce waste, it is then re-used for the same, similar, or different purpose without altering its properties or form. The same or different products can be made from recyclable waste using recycling facilities rather than ending up in landfills, organic waste streams can be recovered through composting. Recovery of energy and materials embedded in waste not appropriate for reuse and recycle would be the next priority

These key elements of the waste hierarchy have been promoted by the South Africa Waste Management Strategy (NWMS) and National Environmental Management: Waste Acts and equally influenced the South Africa Waste Legislations (DEA, 2012a). Prioritization of waste management through the waste hierarchy model is a recognized practice in South Africa towards reducing the landfill waste disposal

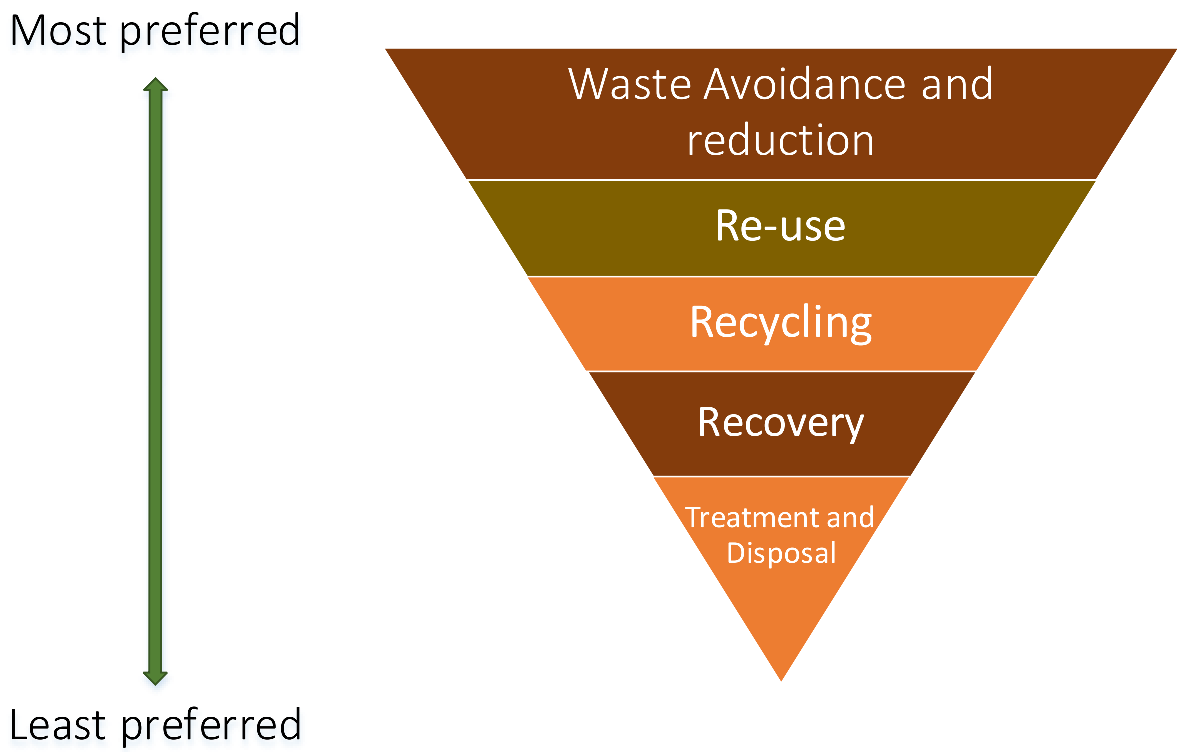

Figure 2 Hierarchical approach in Waste Management

4. Integrated Waste Management in South Africa

Integrated municipal solid waste management (IMSWM) is a structure which gives considerations for waste prevention, recycling, recovery, controlled and supervised disposal to efficiently manage waste to safeguard the health of human and environment. The major focus of IMSWM is to achieve sustainable development environmentally, socially, and economically through environmental protection, pollution mitigation, minimization, re-use and recycling of waste, the establishment of targets for collection, setting out of approaches for planning any new facilities (IWMP, 2016). An integrated waste management strategy should incorporate the enactment of hierarchical techniques. Just as the waste hierarchy alluded, more attention should be given to waste avoidance and reduction more than storage, collection, and disposal. After all, attempts to reduce and prevent waste production, then consideration is given to re-use and recycle and, finally, the treatment and disposal of non-recyclables options is the least preferred option in the integrated waste management scheme. Strategies and practices that promote waste reduction include; unwanted goods like old clothing and household items donated or sold, re-use of empty packaging items by household, plastic shopping bag levies imposition, public awareness and encouragement on the use of recyclable materials in households, businesses, and industries

There are two major components of integrated sustainable waste management; they are physical components and the governance aspect of waste management. The physical components include waste generation, collection, disposal, treatment, resource value recovery through materials recycling, and energy recovery. The governance aspect includes the involvement and roles of the stakeholders, public and private sectors, municipalities, financial sustainability, sound policies, and institutional aspects of waste management. Integrated and sustainable waste management should explicitly attend to both the physical components and the governance aspects to achieve the long-term sustainability of the system. Figure 3 presents the framework of integrated municipal solid waste management showing its components.

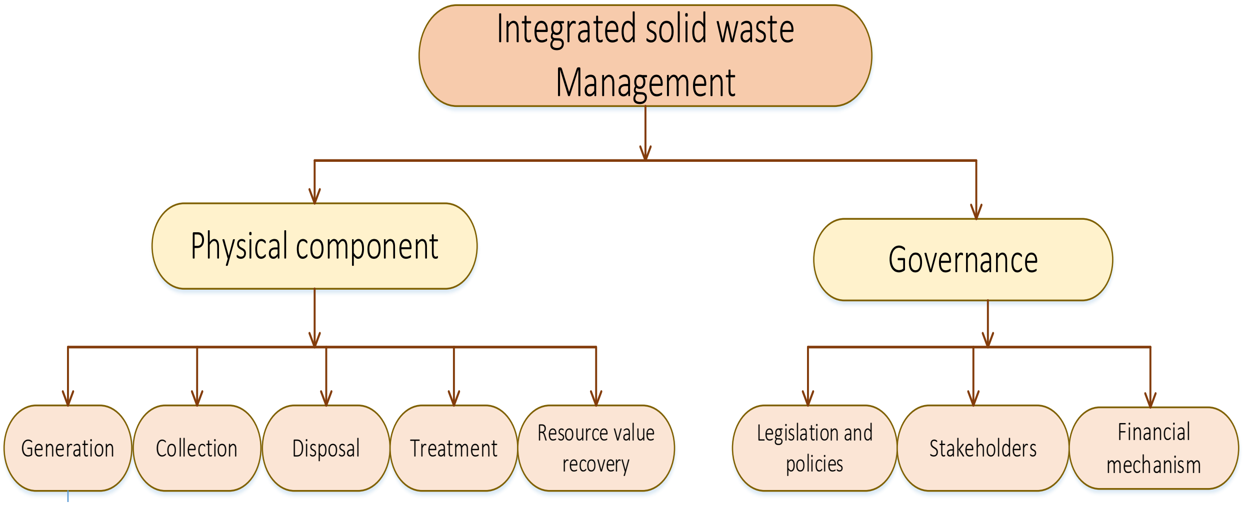

Figure 3 Components of Integrated Waste Management

Integrated Waste Management Planning was introduced in South Africa to maximize the efficiency of management at reduced cost and lowest environmental impact. According to Waste Act, No 59 of 2008, each municipality is obliged to develop an integrated Municipal Solid Waste Plan (IMWP) under the framework of the National Waste Management Strategy (IWMP, 2016). In South Africa, the following key components are involved in integrated solid waste management; waste generations, source separation, waste storage, collection and transport, transfer, materials recovery, treatment, processing, and disposal. Figure 4 represents the flow diagram of an integrated municipal solid waste management system which depicts the flow of materials through the components of waste management

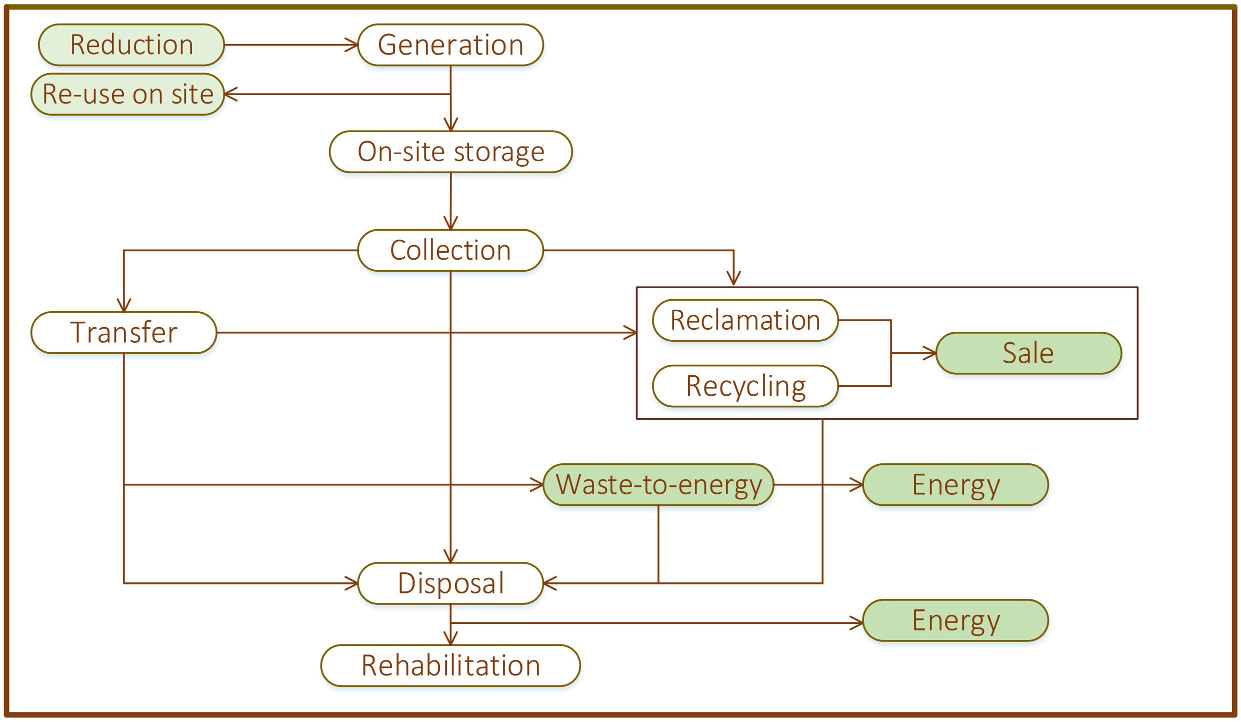

Figure 4 Flow diagram of an integrated waste management showing flow of materials in each components and process output (DEA 2012b)

There are policies and laws in South Africa that are relevant to waste management which imposes legislations for stakeholders at the national, provincial, and municipal levels for ensuring sustainable waste management. Few among these legislations include; National Environmental Management Act 107 of 1998, Environmental Conservation Act 73 of 1989, National Water Act 36 of 1998, hazardous substance Act 15 of 1973, Development Facilitation Act (Act 67 of 1995), local government Municipal structure act (117 of 1998), the constitution of the Republic of South Africa (Act 108 of 1996) (City of Johannesburg, 2011). Several domestic projects have been engaged in South Africa at different hierarchical levels to enhance the shift from the traditional disposal system to the more preferred options in the waste hierarchy. A report by the South Africa Cities Network (SACN, 2014) identified some of these activities by the public, private, public-private partnership at different hierarchical levels as presented in Table 1. It can be observed from the table that most of these activities focus on energy recovery most especially the recovery of energy from landfill methane gas. Details of these energy recovery projects are discussed in subsequent sections.

Table 1 Identified Domestic activities that enhanced the scale-up in the waste hierarchy

S/N	Waste Hierarchy category	Source Separation	Recycling	Energy Recovery	Disposal	Total
1	Public	2	1	1	0	4
2	Private	1	3	5	1	10
3	Public-Private	3	0	5	1	9
4	Total	6	4	11	2	23

4.1 Solid Waste Generation and Composition

Waste, according to the National Environmental Management: Waste Act 59 of 2008 is legally defined as any substance that can be reduced, reused, recycled, and recovered and considered surplus, rejected, discarded, and abandoned or disposed of in which the generator has no further used of it for production. (IWMP, 2016). Waste in South Africa is generated from a wide range of activities such as mining, manufacturing, commercial, and construction by individuals, businesses, institutions, and Industries daily. The rate of waste generation in South Africa relies on several factors such as population size, growth and density, income level, literacy level, and rate of urbanization. A pragmatic increase in population size and an improved standard of living results in an increase in the rate of generation. The direct correlation between the rate of generation and population size and growth rate is observed in the South Africa case study. A decline was recorded in the average population growth rate of South Africa from 2.3% to 0.9% in 2013 and 2017 respectively (StatsSA, 2018).

The provincial growth rate in the same period does not follow the same trend as revealed in Figure 5. Population density varies in an almost similar manner as the population in the provinces with Gauteng Province having the highest $785.5/km^2$ and Northwest Province with the lowest $3.3/km^2$. For future planning of solid waste management, allocation of collection, transportation, disposal, and treatment facilities, the prediction of waste generation is important (Kumar and Samadder, 2017). However, this may be difficult in the absence of sufficient and reliable waste data and more importantly due to rapidly changing variables and defiant parameters. A projection of greater waste generation presently and in the future can be made in the province with a higher growth rate and higher population density.

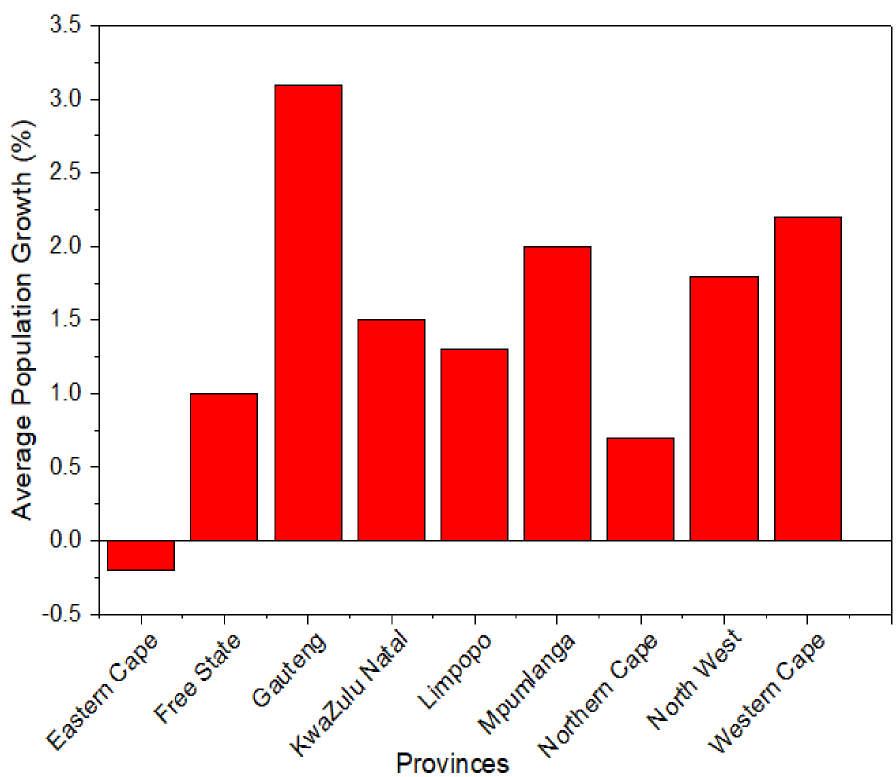

Figure 5 Provincial Population Growth rate

Table 2 presents South Africa's provincial data of socio-economic and demographic factors and waste generation in the year 2017. This reveals a direct correlation between the influencing factors and the waste quantity generated. The wealthier the population, the more consumption and consequently more waste are generated. The Gauteng Province has the highest population and contributes the highest share of about 34% to the Gross Domestic Product (GDP) of South Africa in 2017. Consequently, Gauteng province generated the highest quantity of waste in 2017, they, therefore, mount more pressure on the collection, disposal, and treatment facilities than any other province. The Northern Cape Province has the lowest population and contributed the lowest share of South Africa's GDP in 2017, the same trend is also observed in the quantity of waste generated.

Table 2 Provincial population, contribution to national GDP, and waste generated in 2017.

Province	Population (Million)	GDP (Trillion rands)	Waste generation rate (kg/capita/annum)	Waste generated (million tonnes per year)
Western Cape	6.510	0.651	625	10.98
Eastern Cape	6.499	0.372	113	2.21
Northern Cape	1.214	0.093	547	1.64
Free State	2.867	0.233	199	1.64
KwaZulu-Natal	11.075	0.744	158	4.98
North west	3.856	0.279	68	0.55
Gauteng	14.278	1.581	761	24.31
Mpumalanga	4.444	0.372	518	5.52

Limpopo	5.779	0.326	108	1.65
Total	56.522	4.650	-	54.18

There are generally two categories of Municipal solid waste. General waste and hazardous waste. About 54.2 million tonnes of general waste, 66.9 million tonnes of hazardous waste was generated in 2017 (DEA, 2018). Table 3 represents the amount and the percentage of each waste stream in the total general waste generated in 2017. The highest fraction of waste generated in South Africa consists of food waste, yard waste, kitchen waste, and other organic waste. The percentage of the organic waste stream is 56.3%, while tyres are the least generated waste, yet it is a significant waste that must be well managed. The waste stream tagged "others' comprises waste electronic products, furniture or bulky waste, diaper and sanitary product, roofing sheet, composite, carpet rug.

Table 3 Amount of General waste generated in 2017 (DEA 2018)

Waste Type	Amount (Millions tonnes)	Percentage of each waste type in the total General waste (%)
Municipal Waste	4.82	8.9
Commercial and Industrial Waste	3.55	6.6
Organic Waste	30.49	56.2
Construction and Demolition waste	4.51	8.3
Paper	2.24	4.1
Plastics	1.11	2.0
Glass	2.51	4.5
Metals	4.12	7.6

Tyres	0.24	0.4
Others	0.73	1.3
Total	54.18	100

Table 4 presents the average waste generation rate; food and domestic waste and different income levels in South Africa. The monthly income range in each income level presented in Table 4 is defined by NWDACE (2008). Noteworthy is the fact that quantification of waste generation was based on waste disposed at landfill sites which may not be a true representation of the actual waste generation figures. Waste from regions without formal collection system due to waste delivery backlogs and illegally disposed wastes are excluded in the estimation which questions the accuracy of the figures (City of Johannesburg, 2011)

Table 4 Waste Generation per income level category in South Africa

Income level	Monthly income range	Waste generated (kg/person/day) (Fiehn and Ball 2005)	Food waste (millions tonnes/annum) (Nahman et al. 2012)	Domestic waste millions tonnes/annum) (Nahman et al. 2012)
Low	R0 – R38600	0.41	1.01	5.60
Middle	R38601 – R153600	0.74	0.32	2.93
High	R153601 and above	1.29	0.10	1.09

4.2 Separation at Source

The mechanism of separating waste streams at sources of generation is vital in the diversion of an appreciable volume of waste from landfills and enhances materials recovery. However, due to Public apathy, there is a lot of failed attempts in separating the waste into the stream at sources in South Africa since the system of separation at the source is not formalized at the municipalities. Bags and cans or bins are supplied to each municipality by recycling Industries for sorting and collection of recyclable materials. There are also designated bins placed at schools, offices, businesses, institutions for separately collecting waste. Some material recycling facilities collect recyclables waste streams from mixed waste streams by mechanical sorting facilities. A general household survey on household source separation of waste in 2015 estimated that only about 10.8% of the total household in South Africa are actively involved in separating their waste at source (StatsSA, 2018). Between 2010 and 2015, an increase from 4% to 7.2% is experienced in the number of dedicated recycling activities in South Africa, source separation inclusive (UNEP, 2015). However, this is still very low and does not depict improvement in behavior and willingness of the municipalities to separate waste. A well-structured waste disposal tariff should be implemented and supported by the local, regional, district, provincial and national authorities in South Africa to reshape the mind-set of the municipalities, private and public sector on the need for minimizing waste that goes to landfill and the need to look into alternative waste treatments. Figure 6 represents the rate of household source separation of waste at different provinces

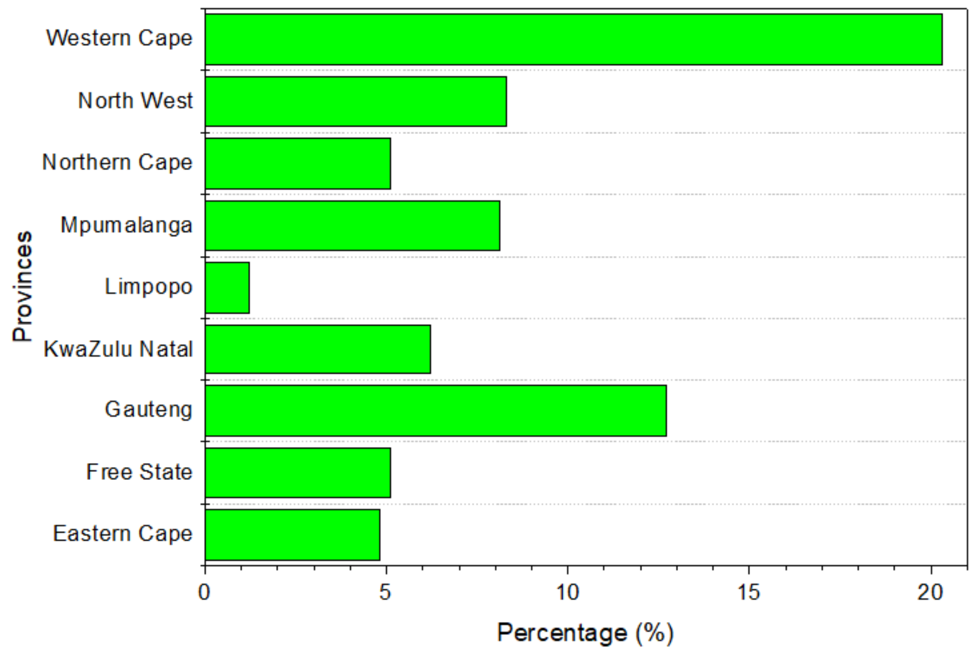

Figure 6 South Africa Provincial rate of household waste source separation (StatsSA 2018)

The numbers of informal collectors called scavengers have increased due to informality in the source separation systems. They pick papers, cardboards, scrap metals, plastics and cans, glass, and bottles from waste bins at households, streets, shops, and malls and sell to make a living. Oftentimes, because of the large quantities of these recyclables that end up at landfill sites, scavengers are found at the landfill sites to reclaim some of these materials. However, there are health and safety risks associated with the activities of these scavengers such as exposure to hazardous waste, consumption of unhealthy waste food. Other problems with informal salvaging are the reclaiming of inferior quality of recyclables from waste streams, uncontrolled access to landfill sites, and disruption of the operation of landfill workers, deficient statistics of scavenged waste (DEAT, 2005). These associated problems led to the intervention of authorities in controlling the condition of scavenging at landfill sites by registering, training, and offering Personal Protective Equipment (PPE), issuing identification documents to reclaimers (DEAT, 2005). However, informal scavenging cannot be 100% curtailed, few municipalities, therefore, allow recycling facilities at landfill sites to formalize the practice

4.3 Waste Collection and Disposal

Waste collection can be described as a set of actions that involve initial household storage of waste, loading, unloading, and transfer of waste and it's transportation till it lands at the point where it is treated, recycled, or disposed of (Manus and Adrian, 2010). A meticulous selection and adoption of efficient waste collection equipment is a fundamental solution to waste management problems. A basic parameter of the waste collection system is the frequency of collection. According to Manus and Adrian (2010), some of the important issues which influence the planning of the frequency of waste collection are as follows; (i) At a higher ambient temperature climate where more of certain foods are consumed and consequently biodegradable waste are generated, microbial actions in the waste are faster resulting into the faster occurrence of foul odor and disease-causing organisms. More frequent collections rates must be planned at such areas, say at least twice weekly, (ii) frequency of collection is also influenced by the cost of collection, this is because it costs more to collect a smaller volume of waste frequently, however such place, primary collection of waste with simple equipment's and low wages may reduce the cost of collection (iii) Generally, at developing countries, waste collection frequency must be higher than developed countries and must be acceptable by the municipality and reliable if not indiscriminate dumping along the road or illegal area is inevitable. A large quota of all the expenses in waste management and the budgets of the municipality are expended on the collections system because it involves a large workforce

This component of integrated waste management is very crucial. The deficiency in the collection and lack of convenient waste disposal sites has led to waste accumulations on the street, public places, and other illegal dumpsites. This is a threat to sustainable waste management because of the financial burden imposed by the repair and rehabilitation of illegal dumpsites. There are different collection systems namely: separate collection, combined collection, direct collection, and transfer. The separate system may be given considerations to collect recyclables separately using collection vehicles with separate compartments. However, this system might be expensive and unaffordable in developing countries, informal collection of recyclables may be a viable alternative. The direct collection moves the waste directly from the household collection points to its destination while a transfer collection is a tow stage collection where waste collected from collection points is taken and stored temporarily at transfer stations or moved from a smaller vehicle to a larger vehicle.

In South Africa, waste bags and bins are common means of household waste collection done on weekly basis by waste private contractors, communal dumpsites, or central collection points. Motorized collection vehicles with compactor vehicles are commonly used for collection, while the communal collection is common in areas without a formal refuse removal service. In rural areas, labour-intensive and non-motorized collections are common. According to schedule 5, part B, Act 108 of 1996 constitution of South Africa, the local municipality is accountable for the provision of waste collection (DEA, 2018). The municipality suffers backlogs in creating access to adequate waste services. Based on General Households Survey (2010), 57.8% of households had access to collection services in 2002, and it increased slightly to 59% in 2010 (StatsSA, 2011). According to the Community Survey, 2016 represented in Figure 7, a decrease was noted in the percentage of household removal rates from 2001 to 2016 in major metropolitan cities of South Africa owing to the increase in the population of informal settlements with limited access to collection services. Urban cities have more access, about 90% than the rural household which has about 47% access to waste services. About 59% of household waste is collected by the local authority, 34% disposed of in communal dumpsites while 2% are collected from central collection points (DEA, 2018).

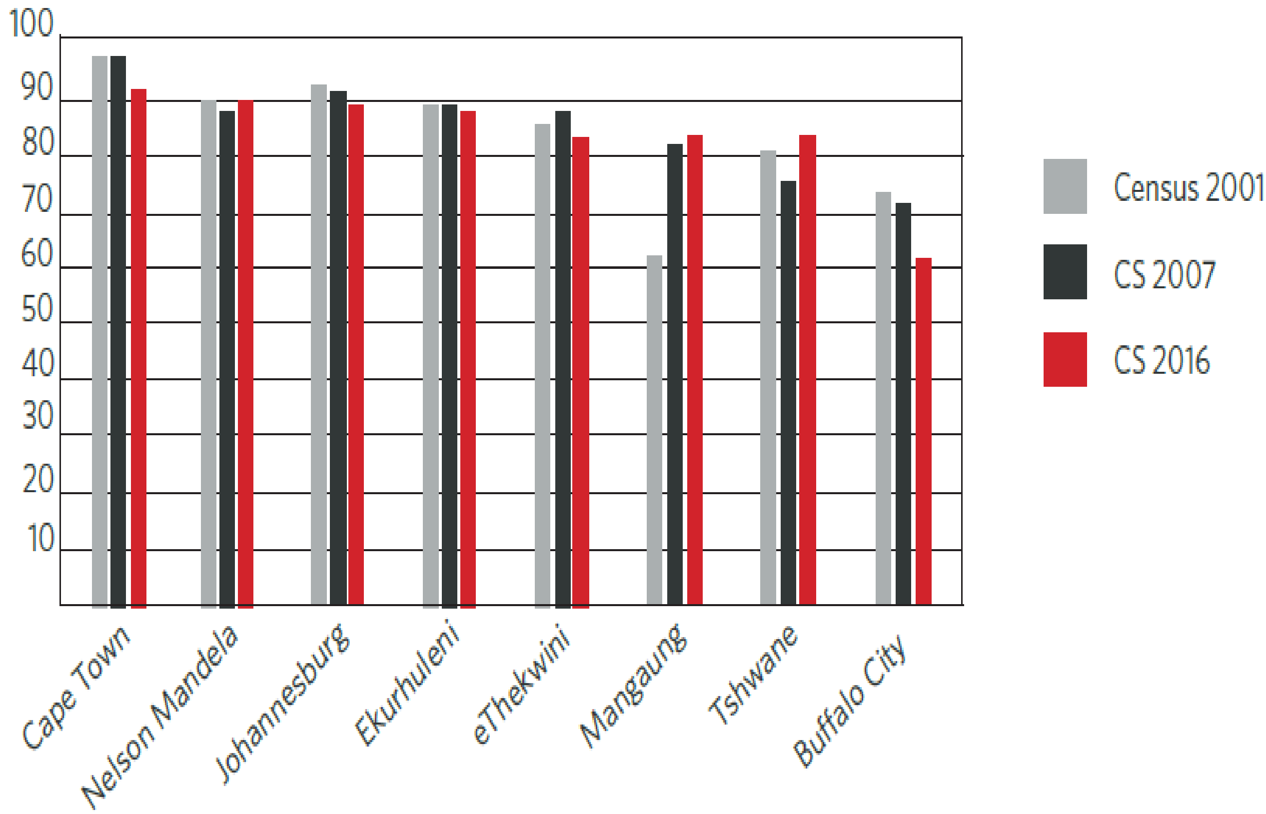

Figure 7 Household collection rate from 2001 to 2016 at eight metros in South Africa (StatsSA, 2016)

Landfill disposal is still a prevalent method of waste disposal in South Africa. This method is discouraged through landfill tax and thereby encourage alternative techniques of handling waste (Simelane and Sa, 2016). To prevent illegal dumping of some waste streams such as demolition and construction waste, garden waste, their gate fee is free (Godfrey and Oelofse, 2017). Table 5 presents the number of licensed and unlicensed landfill sites in South Africa. The poor performance of waste management might be attributed to the large number of unlicensed landfill sites which are poorly maintained and do not to the standard of operations. This requires urgent attention to mitigate the impact on the environment. The capacity of different landfill sites and their estimated service life varies significantly. Based on 2018 waste information (SAWIC, 2018), there are 370 waste storage facilities, 224 recycling facilities, 109 waste transfer stations, 20 incineration facilities, and 19 composting facilities in South Africa. Gauteng Province has the highest share of licensed facilities as revealed in Figure 8.

Table 5 Licensed and Unlicensed waste treatment facilities in South Africa (DEA 2018)

Type of facility	Number of facilities	Number of licensed facilities	Percentage of unlicensed facilities
General waste landfill site	990	432	56.4
Hazardous waste landfill site	161	86	46.8
Health care risk waste storage facility	25	0	100.0
Recycling facilities	198	44	77.8
Transfer stations	264	88	65.7
Total	1,548	675	56.4

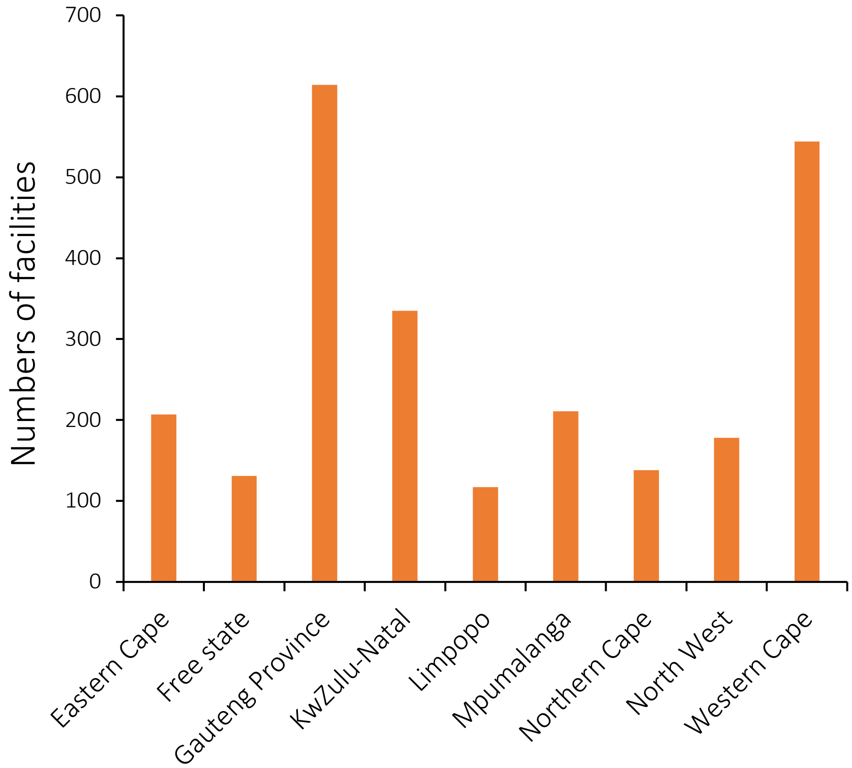

Figure 8 Number of facilities at each province (Adapted from SAWIC 2018)

4.4 Waste Recycling

There is a global transition from the traditional collection and disposal system that dominated waste management to minimization and recycling hierarchical systems which have attracted both local and global economy. Several regulations and policies enacted by most advanced countries have enhanced the shift to a point that landfill disposal systems have been brought to as low as 20% and recycling boosted to above 45%, and the final route is towards 100% recycling (SACN, 2014). South Africa has been noted as one of the five emerging waste markets with thrilling possibilities, including Brazil, China, India, and Russia (DST, 2014). As of 2012, the private and public formal waste sector in South Africa has a financial value of about

R15.3billion, representing 0.51% of the GDP and has the tendency to rise to 1% considering the trend in the local and global waste sector (DST, 2013).

Only about 10% of total waste generated in South Africa is recycled (DEA, 2012a), this is relatively low compared to other parts of the continent. For example, Belgium reached a higher level of success in recycling about 56% of their total generated waste (SDI, 2019), moved from 7% to 35% in Oregan, Portland and from 21% to 51% in Falmouth, Maine (Shawnee, 2009). About 38.6% of the total general waste in 2017 was recycled (DEA, 2018), showing an improvement in recycled waste from 2012 to 2017. This level is a good basis for improvement in South Africa's case and the priority of National Waste Management in South Africa is waste that can be recycled to save and recover resources and reduce the amount of waste that is landfilled. Noteworthy is the fact that waste recycling options may not be preferred especially when the cost involved in transporting recyclable waste is high to facilities in certain regions.

Figure 9 depicts the supply chain for recyclables. The largest source where recyclables can be procured is formal waste management companies that collect both bales and loose recyclables. Other links in the supply chain are the waste picker, buy-back, and drop off centers, and waste generators (Plastics SA, 2018). The informal sector in South Africa accounts for the collection of about 80%-90% of post-consumer recyclable paper and packaging for recycling and divert them away from landfills hence saving between R309.2-R748.8 million in landfill space in 2014 (Godfrey *et al.,* 2016). Plastic recycling is one of the fastest-growing waste recycling markets in South Africa. The recycling rate of plastic in South Africa is 43.7%, with about 334,727 tons of plastic recycled as raw materials in 2017 (Plastic SA). The percentage of each waste stream recycled and landfilled in 2017 is presented in Table 6.

Figure 9 Post-consumer recyclables Supply chain

Table 6 Waste streams landfilled and recycled in 2017 (DEA 2018)

Waste Category	Quantity Generated (Million tonnes)	Percentage landfilled (%)	Percentage recycled (%)
Municipal Waste	4.82	100	0
Commercial and Industrial Waste	3.55	90	10
Organic Waste	30.49	68.8	31.1
Construction and Demolition waste	4.51	10	90
Paper	2.24	42	58
Plastics	1.11	56.3	43.7

Glass	2.51	21.6	78.4
Metals	4.12	25	75
Tyres	0.24	0	100

4.4.1 Drivers and Pitfalls to recycling

The favorable outcome of recycling in most industrialized countries can be accounted for high demand for materials, low labor costs, a high rate of unemployment, and advanced recycling skills. About 25% of aluminum, 40% Copper, and 15% steel production in China use recycle material as raw (DST, 2014). Several drivers augment the transition of waste management priority to recycling in South Africa. Successful recycling programs in South Africa thrive through some funding sources, remarkably municipal projects, waste recycling inclusive. However, proper coordination of such funding such as Independent Development Trust (IDT), Poverty Relief Directorate, Municipal Infrastructure Grant, extended Public work Program by Department of Public works, is needed to improve public access to this fund for recycling Projects (DEAT, 2005). Generally in South Africa, recycling is economically driven compared to Europe where it is environmentally driven, the economic impact of recycling waste is twice burying it (Plastic SA, 2018). Recycling creates jobs in low-income regions. This could be encouraged by the Government by providing incentives and subsidies, tax reductions. Plastic recycling manufacturing in South Africa provides almost 52300 income opportunities for South Africans in 2017, out of which 5837 were formal jobs and the rest were informal, comprising people earning living by sourcing and reclaiming waste at landfills. (Plastic SA, 2018).

The creation of drop-off and buy-back centers where sorted and separated recyclable waste are sold by waste pickers are drivers to recycling. Waste picking and reclamation are survival strategies for those who cannot find a job elsewhere (Fiehn and Ball, 2005). The buy-back centers are a link between recycling activities and informal sector activities and can't be excluded from the recycling strategies. About 1.6% of households in South Africa earn living through selling recyclables (Stats SA, 2009). The significance of public awareness, education, and capacity building in promoting recycling services in South Africa cannot be overemphasized. To build capacity, there is a need to be involved in technical and entrepreneurial skill acquisition, and re-strategizing the mind-set of public and municipalities, education on municipal source separation.

Extended Producers Responsibility (EPR) is an idea that could promote recycling by the involvement of producers of the commodity in the buy-back centers. EPR is an environmental policy approach whereby a producer's role for its product is extended to the post-consumer stage of the life cycle of the product, its final disposal inclusive (Widmer *et. al*., 2005). EPR can be implemented in different ways either as a voluntary Industrial Initiatives or a mandatory regulation imposed by the Government to overcome some of the barriers to sustainable recycling Industries establishments (Widmer *et. al*., 2005). South African authorities have identified EPR as a helpful means to fund recycling, creation of a job, enterprise development in packaging, e-waste, paper, lightning, and tyre waste (Godfrey and Oelofse, 2017)

Some Provinces in South Africa have limited access to Recycling Companies, causing a major setback for recycling activities in such areas. The highest percentage of recycling facilities in South Africa is in Gauteng Province. Unstable prices of recyclables have resulted in unprocessed recyclables material backlogs, in such a way it still remains a waste. Other major setbacks for recycling activities in South Africa are; lack of competition, inappropriate use of levies and funds generated for waste management, improper coordination of recycling initiations, high transportation cost, limited access to funding, lack of skills, lack of incentives and support by Government (DEAT, 2005).

4.5 Energy potential and recovery

Utilization of energy from waste is a viable consideration in sustainable waste management to divert a considerable amount of waste from landfill sites and promote a clean, safe and healthy environment (Dlamini *et al.*, 2019)**.** About 64% of generated waste in South Africa can be diverted away from landfills through materials recycling and energy recovery (Stafford, 2020). A potential electricity capacity of 207 MW can be recovered from the organic waste of the six largest South African city municipalities (SACN, 2014). The composition of the waste determines the amount of energy that can be recovered from waste. The highest fraction of organic waste stream characterized by high moisture content can be found in waste generated in South Africa, Therefore, the most appropriate technological pathway to require energy is the biochemical conversion through anaerobic digestion, fermentation, and landfill gas recovery. According to Scarlat *et al.*, 2015, South Africa has the highest theoretical energy potential recoverable from waste. Considering the actual percentage of generated waste that is collected, energy recovery through incineration and landfill gas recovery processes have the potential of 104463 TJ/annum and 22710 TJ/annum with a methane potential of 2058×10^6 Nm^3.

However, South Africa do not have advanced waste-to-energy (WTE) facilities and system to operate to its full potential of utilizing energy from waste. Some of the factors which impede the growth of WTE industries making it operating below its full potential of energy recovery from waste are; cheap landfill tax, lack of roadmaps for WTE projects, abundant coal resources, lack of convincing academic research on WTE adoptable technologies in South Africa, little WTE infrastructure investment, insufficient technical skill and human capacity, cheap landfill tax, abundant coal resources lack reliability data to support decision making (Dlamini *et al.*, 2019; Baker and Letsoela, 2016; Mbav *et al.*, 2012; Dowling *et al.*, 2012; Couth and Trois, 2012). There are still very few commercial-scale WTE plants in South Africa. Table 7 presents a few selected small-scale WTE projects in South Africa.

Table 7 some selected existing and proposed energy recovery from waste projects In South Africa. (Adapted from Mutungwazi et al. 2018)

S/N	Location	Conversion technology	Substrate	Power Output
1	Bredasdorp	Anaerobic digestion	4 tonnes of abattoir waste per day	100KW
2	Cavalier	Anaerobic digestion	20 tonnes abattoir waste per day	500KW
3	Darling Uilenkraal	Anaerobic digestion	Bovine manure	600KW
4	Alice, Eastern Cape	Anaerobic digestion	4000 m^3 of dairy and piggery manure Athlone	Two 132 KVA Generator
5	Grabouw	Anaerobic digestion	Above 5 tonnes of fruit waste per day	500KW
6	Jan Kempdorp	Anaerobic digestion	5.5 tonnes of abattoir waste per day	135KW 150KW
7	Klipheuwel (Zandam)	Anaerobic digestion (biogas)	Above 5 tonnes of manure per day	600-700 KW
8	Stellenbosch Franschhoek	Anaerobic digestion	Sewage, silage, manure, agricultural waste	0.5 – 1 MW
9	Springs	Anaerobic digestion	Slaughter and organic waste	0.4 MW
10	Pretoria	Anaerobic digestion	Animal manure	4.6 MW

11	Riverdale	Anaerobic digestion	4 t abattoir waste per day	100 KW
12	Durban	Landfill Gas Recovery	3500–5000 tonnes refuse per day	6.5 MW
13	Durban	Landfill Gas Recovery	550–850 tonnes per day	1.5 MW
14	Johannesburg	Landfill Gas Recovery	Landfill waste	19 MW
15	Johannesburg	Wastewater treatment	Sewage sludge	1.2 MW
16	Mossel Bay	Wastewater treatment	Refinery wastewater	4,2 MW
17	Stellenbosch	Wastewater treatment	1000 m^3 wastewater per day	Not available
18	Klipheuwel	Composting	700 t organic waste per day	-
19	Kwazulu-Natal	Biofuels Production	Manure from cows, school organic and sewage waste	Cooking fuel for rural use
20	Kwazulu-Natal	Biofuels Production	Manure from cows, school organic and sewage waste	Cooking fuel for rural use
21	Eastern Cape Western Cape Kwazulu-Natal	Biofuels Production	Manure from cows, school organic and sewage waste	Cooking fuel for rural use

There are many available technologies for treating waste to recover energy, however, landfill gas recovery is a viable energy recovery pathway in South Africa thereby minimizing the chances of exploration of other treatment options such as incineration, gasification ad pyrolysis in South Africa. As of May 2012, about 7449 m^3/h of landfill gas which could have been emitted as harmful greenhouse gas (GHG) to the atmosphere at both Robinson Deep and Marie Louise landfill sites in Johannesburg has been recovered and flared (Baker and Letsoela 2016). Energy recovery pathway through landfill gas recovery and anaerobic digestion is valuable to South Africa to overcome waste management crisis, generate electricity, and contributes to GHG mitigation, however, South Africa has not captured the full benefit and operate to its full potentials (Baker and Letsoela 2016; Dlamini et al. 2019). An agreement was made by the city of Johannesburg with EnerG system Joburg to developed a landfill gas recovery system to generate electricity which operates for 20 years in the city of Johannesburg. This technology generated revenue through the sale of electricity and helped to realize the Kyoto protocol commitment of the nation through its clean development mechanism (CDM) (Baker and Letsoela 2016; Dlamini et al. 2019). Another emerging attractive recovery option from landfill sites is the generation of alternative fuel which can be used to power vehicles as a substitute for the compressed natural gas (CNG)

5. Challenges and future directions of Waste Management in South Africa

Records have shown some appreciable progress in South Africa waste management systems over the years, however, it is still being constantly faced with some challenges. The exhaustion of landfill airspace, limited resources, and an upsurge in population growth and economic development which consequently accelerated the quantity of waste generated has placed a serious burden on the waste management system in South Africa. The current waste management facilities and strategies are insufficient to combat the challenges faced by the waste management sector. According to Nahman and Godfrey (2010), some key issues in the waste management sector of South Africa were identified as follows; insufficient waste collection services, illegal and indiscriminate dumping, unlicensed waste management activities, permitted landfills limited airspace, deficient waste minimization, and recycling initiatives, scarce and unreliable waste data, weak regulation and legislation enactment. These challenges have retarded the growth of a cleaner and greener future for South Africa.

Limited access to funds has been identified as a major challenge of waste management (Godfrey and Scott, 2010). A measure to combat the challenge of insufficient funding in waste management by the National Waste Management Strategy (NWMS) is the impetration of the Polluter Pays Principle (PPP) involving all waste generators (Mosidi, 2011). This cost includes the direct cost of collection, treatment, and externalities such as health and environmental damages (DEAT 2005). The revenue from PPP accounted for 7% and 6.5% of the total municipality annual income in 2007 and 2008 respectively (StatsSA, 2009). In addition to this, there is a need to sustain, improve, and optimize capital investment into the waste management sector. Capital investment in the waste management sector is more focused on compactor trucks, maintaining existing landfill sites, creating new landfill sites (Goldblatt, 2009). Keys areas of investment in the order of preference and the significant difference in investment across municipalities must be identified in the sector to optimize the investment cost

Waste flow operations are affected by the following key economic incentives at different handling points; collection tariff, disposal or landfill tax, illegal dumping sanction, and materials recovery incentives (Eberhard, 2018). The success in waste management in some developed countries relies on the levy of high landfill tax which discourages landfill disposal and encourages materials recycling and energy recovery. A high-cost landfill tax was introduced by the EU, for instance in the UK, landfill tax rose from £7 to £80 per tonne between 1996 and 2014 (HMRC, 2015). Also, the 1999/31/EC landfill directive has minimized the number of recyclables and biodegradable waste disposed of in landfills (EEA, 2012). A well-structured waste disposal tariff should be implemented and supported by the local, regional, district, provincial and national authorities in South Africa to reshape the mind-set of the municipalities, private and public sector on the need for minimizing waste that goes to landfill and the need to look into alternative waste treatments. However, the issue of landfill tax is a complex issue in South Africa whose solution cannot be achieved by merely increasing or decreasing the disposal or collection tax imposed on waste generators.

The lesson learned from experience revealed that increasing landfill gate fees might increase the awareness and incentives to reduce the quantity of waste disposed of in a landfill, and at the same time result in more indiscriminate and open dumping of waste at unaccepted and unhygienic places. More so, clamping down disposal fees to discourage illegal dumping might place an extra financial burden on the waste management sector. For instance, the city of Cape Town in 2013 engaged in measures which discouraged illegal dumpings such as eliminating landfill disposal fee for general waste and clean construction waste, this cost the city R 183,000 per day (Eberhard, 2018). Therefore an optimal solution to this issue must incorporate consideration for engaging the waste generators in an educative and enlightenment program especially in the urban areas where more of the waste is generated. More reuseable and recyclables waste are generated in the urban area, an educative program should be seriously prioritized in urban cities on the need for waste reduction, re-use, and source separation of waste. A discriminated landfill tax policy can then be hopefully productive in that case, while waste generators in urban cities pay more

5.1 Application of Artificial Intelligence modeling in Waste management in South Africa

The National Waste Management Strategy Implementation (NWMSI) was established in 2000 to introduce the concept of Integrated Waste Management Planning (IWMP) aimed at upgrading the operations of solid waste management in South Africa. The Department of Environmental Affairs developed a guideline that conforms to the Integrated Waste Management Planning (IWMP). The guideline declares that an integrated waste management plan requires the collection of reliable and updated waste-related data. Some of the data which are vital to the IWMP guidelines are waste characteristics, composition, and quantity generated. Planning of sustainable waste management is contingent on the availability of accurate data on waste. The South Africa Waste Information Centre (SAWIC) was created as a national repository for the collection of waste data such as tonnage of waste generated, recycled, treated, exported, and landfilled in South Africa (DEAT, 2005). The sources of data for SAWIC are from municipalities report, landfill sites, and other treatment facilities, buy-back centers, public and private sectors.

Waste management decisions are data-driven decisions. The efficient and smart use of available historical waste-related data is a journey towards achieving sustainability in waste management. To further improve the quality, accuracy, and reliability of waste-related data in South Africa, this study recommends the intelligent data mining approach to this issue. As Figure 10 depicts, several techniques of data mining could be predictive or descriptive in functionality. Artificial intelligence application has been gaining traction globally in solid waste management systems as an alternative computational approach to conventional techniques. Owing to the complex nature of the waste management elements which involves several parameters such as socio-economic, demographic, environmental, legislative, and climatic parameters, a paradigm shift from the classical modeliing techniques to the artificial intelligence techniques has been necessitated.

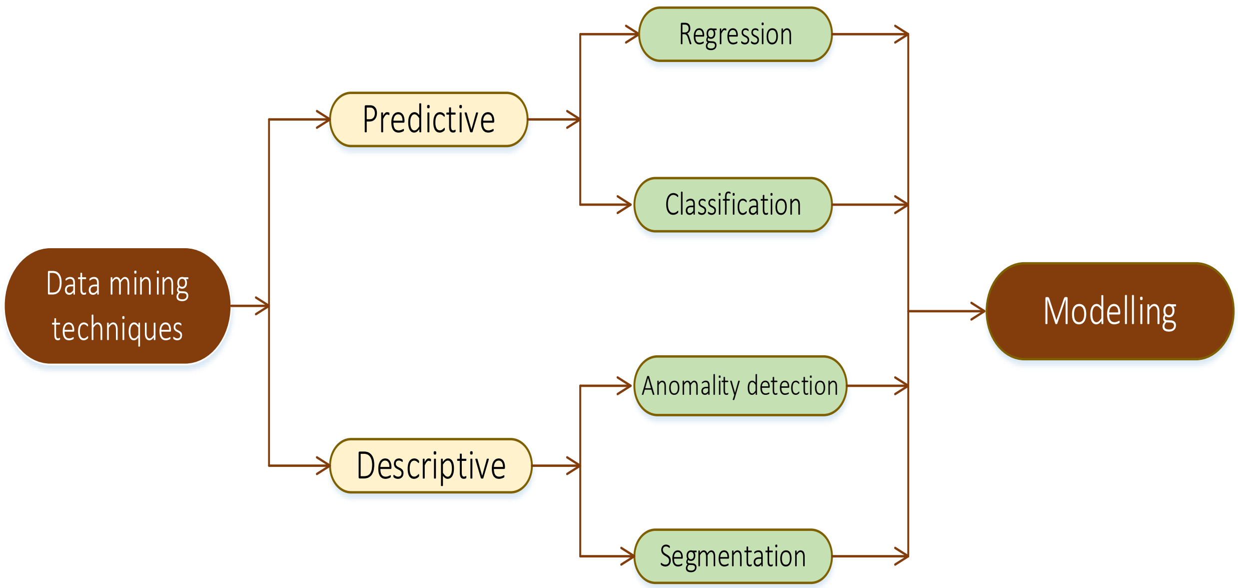

Figure 10 Category of data mining techniques by functionalities

The conventional computational method in waste management is characterized by incomplete, ill-defined, unreliable, and scarce waste-related data which has impeded the efficiency of sustainable waste management planning. According to Abdallah et al. (2020), artificial intelligence models can be applied to components of waste management such as waste characteristics (waste generation, physical and elemental composition), waste heating value estimation, process output prediction, optimization of waste collection routes, energy recovery estimation and utilization, waste bin-level monitoring. This is schematically represented in Figure 11. Waste management decisions, allocation of resources, formulation of policies, the promulgation of rules, and regulations relating to waste management all rely on accurate prediction of waste characteristics.

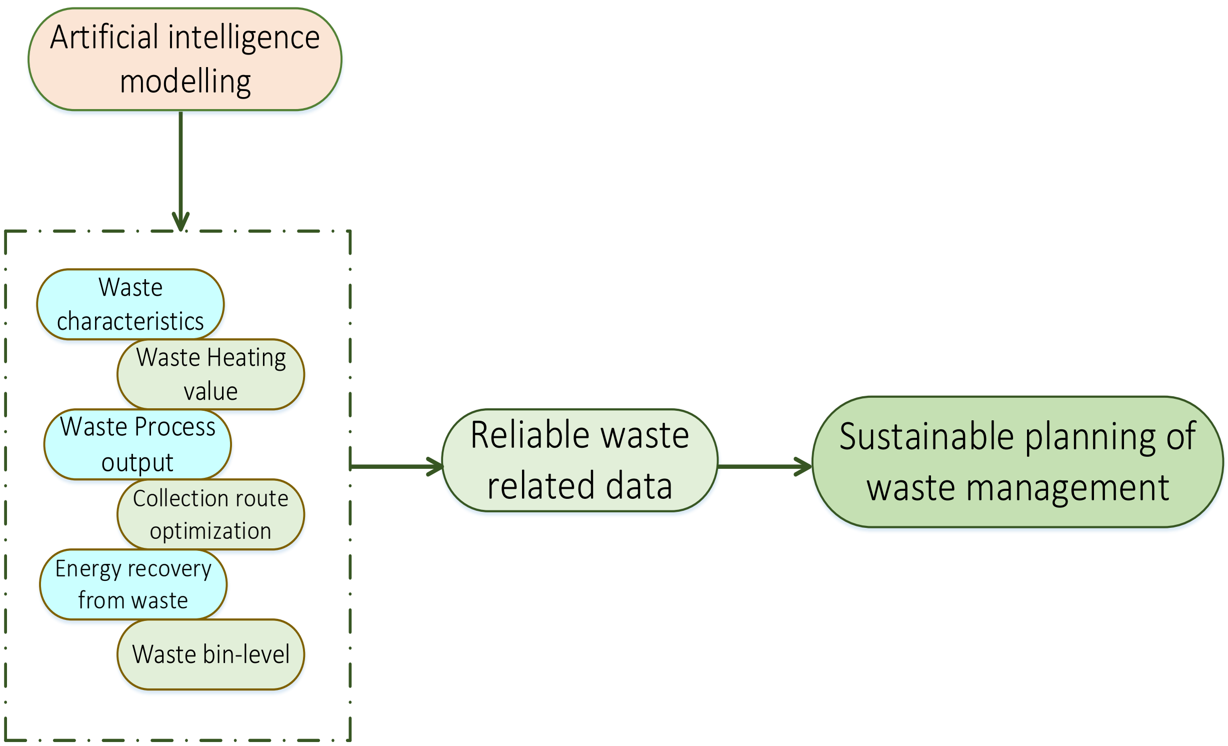

Figure 11 Application of artificial intelligence modelling towards sustainable waste management planning

It has been observed that some waste data especially real-time annual provincial waste generation data in South Africa are scarce, unreliable, and not updated. This is because the tonnage report of waste received at the treatment facilities at different provinces in South Africa which is published by SAWIC does not accurately represent the quantity of waste generated at each province annually, it rather represents the collected waste received at the treatment facilities in each province. This excludes illegally dumped waste, informal waste sectors do not report waste data and others. To overcome this, Adeleke *et al.* (2020), developed an artificial intelligence model to predict the quantity of waste generated in South Africa's provinces using socio-economic and demographic parameters. This model developed will be helpful for the national repository of waste generation data.

This study further recommends the application of artificial intelligence model to other components of waste management in South Africa such as the prediction of the extent of the influence of seasonal variation, income level, populations, and other demographic and socio-economic factors on the quantity of waste generated and its compositions at the municipality and provincial level. The quantity of separately collected waste can also be monitored intelligently and improved using this technique for considerations for materials and energy recovery from waste. These will form viable waste-related decision-making tools for concerned stakeholders

6. Conclusion

This study has presented a survey of the key elements of integrated municipal solid waste in South Africa. The information concerning state-of-the-art waste management practices in South Africa was highlighted. Important strides towards achieving sustainability in solid waste management in terms of policies and regulations have been made over the years. However, the current practices have not been able to sufficiently handle the quantity of waste generated in South Africa. The cost of managing waste is increasing, there is therefore a need to prioritize and optimize waste management investments to avoid overestimation and underestimation of resources. Limited availability and unreliability of waste data have resulted in deficient planning of management systems. Building an accurate national repository of waste data in South Africa is paramount for efficient planning.

The study identified that harnessing waste-related data using data-mining and intelligent prediction techniques are vital to achieving sustainability in waste management. Some of the drivers to the recovery of materials have been identified, it is paramount to emphasize more on extended producer responsibility. There are local peculiar factors that impede the considerations of the upper rank in the waste hierarchy to achieve sustainable development. The estimated airspace and capacity of most landfill sites are fast depleting, there is a need to divert a reasonable amount of waste from landfill by enhancing source separation of waste. As identified in this study, increasing or decreasing landfill tax or disposal cost is not a standalone solution to the issue of disposal. An integrated solution involves the engagement of municipalities in the educative and innovative program on the need for avoidance, reduction, and re-use of waste to reduce the quantity of waste that ends up in a landfill**.**

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The authors declare that there is no potential conflict of interest

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