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Research Articles

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Review Articles

This special issue was convened by and edited in partnership with the South African Research Chairs (SARChI) in the Community of Practice (CoP) 'Waste to Value: Transitioning South Africa towards a Waste-to-Resource Circular Economy':

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Cover caption

Waste as a resource:
South African perspectives on circularity.
Circularity, with a focus on waste management, influences social and economic resilience as well as planetary health. This special issue presents the current societal and environmental issues in waste, the technology available, and the sustainable practices within the waste sector to achieve a sustainable circular economy in South Africa.

Waste not, want not – Pathways towards a circular economy in South Africa

Waste is the end-product of any material transformation process, biogenic or anthropogenic, and refers to material flows that are of no further use to the process that generates them. Most waste in the biosphere is assimilated by entering other transformation processes that can utilise them as feed material. Thus, the material flow becomes circular.

Human activity started to break this circularity. As soon as we introduced tools that were not exclusively derived from the biosphere, the discarded materials at the end of their useful life left a lasting impact. Neolithic arrowheads that give us valuable clues about our origins are an early form of anthropogenic waste that has persisted for thousands of years. The archaeological and anthropological study of material culture through waste defines human legacy.

This legacy is in and of itself not problematic. Strictly speaking, all materials are subject to geological circularity which eventually turns over all materials on earth's surface, albeit over a period of millions of years. The problem with waste arises when its persistence interferes with the functioning of the biosphere or disrupts the circularity of other processes.

Historically, poor waste management was felt at a local level. Nuisances and health concerns such as the breeding of vermin and spreading of disease were the main concerns. However, as humans moved into a technological age, more and more non-biogenic waste was created. The exponential rise of non-biogenic waste presents new impacts to interfere with the biosphere or the environment at an increasingly global scale. Toxic chemicals released from certain industrial waste and acid run-off from many mining waste deposits enter ground and surface waters, damaging life-sustaining systems. Dispersion of lightweight plastics, especially as litter, causes increasing pollution of land and the oceans. Gaseous emissions of CO_2 and other greenhouse gases through anthropogenic activities is increasingly affecting global climate, thus affecting all processes in the biosphere.

The existential threat of climate change has inspired considerable mitigation and adaption measures focused on reducing, and eventually eliminating, all anthropogenic greenhouse gas emissions. When it comes to solid waste management, however, the focus often remains limited to pollution control. Nonetheless, the global debate is beginning to re-discover circularity and applying it to non-biogenic wastes such as municipal solid waste, light industrial waste, construction and demolition waste, waste electrical and electronic equipment (e-waste) and mining wastes. Returning these fractions to some form of use – or converting that which cannot be returned in this fashion into some form of societally acceptable end-form – recognises that waste is an integral part of economic activity within the societal context. Waste management needs to move from being some form of last rite consigning waste to its final resting place towards being a regular economic activity within a given broader local, national, and eventually global, socio-economic framework.

South Africa combines many characteristics of the economies of a developed and developing nation. This dual nature is reflected in the waste management interventions where well-managed landfill sites co-exist with waste pickers reclaiming materials that can be gainfully recycled. A reasonable legislative waste management framework is in place, which recognises the need and opportunity for circularity, yet the existing systems make economic activity in this space cumbersome, forcing activities to the legal and economic margins.

The Community of Practice (CoP) 'Waste to Value: Transitioning South Africa towards a Waste-to-Resource Circular Economy' has brought together an interdisciplinary collective of experts to explore the nexus between existing waste management practice, legislation, and the socio-economic realities in South Africa. A key realisation of the CoP is that addressing the status quo will require local solutions to the global problem, recognising that turning waste materials back into economic commodities needs to fit within the local socio-economic context, and there is no global one-size-fits-all solution.

Circularity in context

This Special Issue of the *South African Journal of Science,* entitled 'Waste as a resource: South African perspectives on circularity', presents 12 articles that reflect on perceptions of waste, investigate municipal solid waste management practice, explore the socio-economic realities of waste pickers, and study the legal framework that governs our relationship with an increasingly complex material legacy in South Africa. Transition to a sustainable circular economy will need to focus on establishing a material transformation process more akin to biogenic circular flows. Reduction strategies, re-design, and a focus on end-of-life management in the South African socio-economic context is at the heart of the CoP. The thinking that guides the formulation of potential pathways towards this transition is reflected in the articles.

In this spirit, the articles begin with classic studies of qualifying and quantifying waste streams including household solid waste, construction and demolition waste and plastic waste. Further articles explore the perception of littering and illegal dumping within low-income communities as well as the ownership of waste and concepts of positive and negative value that are critical when exploring circular activities compared to conventional disposal. The informal sector is a critical consideration when creating circular economic activity and is investigated considering the sustainable livelihood potential for waste pickers. A further article recognises that waste pickers in the context of e-waste are at the bottom end of a complex value chain that ultimately sees the economic value of their activity being realised outside the country due to a lack of the relevant processing capacity locally. Other articles explore technology for the valorisation of waste streams to produce energy and value chemicals. Lastly, two articles survey the transition towards a circular economy in South African and southern African contexts. It is particularly striking that the concept, despite its widespread use, is ill-defined and in practice often excludes the South African socio-economic context.

The integrated approach aims at a socially just transition to a waste economy that facilitates the re-entry of materials into the economic cycles within the local context as far as is possible and with an as broad as possible economic incentive for its participants. In going forward, the CoP intends to formulate a meaningful strategy by which material flows in the South African economy thus far considered as waste are evaluated for their potential to be returned into the local economic cycle in the most sustainable fashion. To achieve this, a continued multidisciplinary approach is needed that draws on the expertise of sociologists, economists, legal experts and – perhaps critically – technologists, jointly cognisant of the local and national socio-economic realities and aspirations.

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Waste characterisation in Stellenbosch Local Municipality, South Africa

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This article demonstrates how household solid waste (HSW) generation patterns differ in neighbourhoods of the same town by determining the composition of the residual portion of the HSW stream in 2017 in Stellenbosch. HSW was collected from 10 pre-identified suburbs out of a total of 48. These chosen suburbs and their 17 830 households were representative of all the HSW from all households in the catchment area of the Devon Valley Landfill Site. A separation at source programme was in place in nine of the suburbs. The confidence level and level of precision were set at 95% and ±8%, respectively. A total of 1543 bags of HSW were collected with a total mass of 5748.01 kg and an uncompacted volume of 84.87 m^3. The samples were sorted into 7 main and 18 final fractions. The main contributor to the total waste stream was organic waste by weight (35%) and plastic wrap and packaging by uncompacted volume (32%). The average HSW generation was 0.68 kg/capita/day. Households with access to a separation at source programme tended to have lower levels of highly recyclable materials in their samples. Roll-out of a separation programme is recommended for all 48 suburbs in the study area to save landfill airspace. Correlation analysis showed that household size influenced three of the seven main waste fractions, and household income five of the seven. No statistically significant results were obtained relating to household density and waste generation. Statistically significant results were obtained through an analysis of variance for all waste fractions, excluding organics, when considering household income, indicating that both household size and income could be explanatory socio-economic factors for variations seen. Other variables, such as human behaviour, could potentially also contribute to the differences and should be further explored.

Significance:

- The availability of reliable waste composition data is not only a contribution to the solid waste management field, but also to any related fields interested in beneficiating or recovering waste. These data are often unavailable, but form the basis for decision-making processes when addressing solid waste (and related) challenges.

Introduction

Solid waste management is a significant concern globally.[1] In particular, local municipalities need to account for increasing volumes of municipal solid waste annually, which is typically sent to landfill.[2] In many countries, substantial deficiencies exist in waste collection and disposal systems which are often coupled with inappropriate locations for processing and disposal facilities.[3] In the South African context, waste can be defined as any substance that the generator has no further use of and is thus considered surplus, rejected, discarded, and abandoned or disposed of.[4] Waste is continuously generated by a wide range of activities and the rate of waste generation is largely related to population dynamics, income, education and urbanisation.[3] As a result, many municipalities are faced with mounting pressure to deal with an ever-increasing municipal solid waste stream and a lack of space to dispose of this waste. In Stellenbosch, South Africa, for instance, the municipal landfill ran out of space in 2009, which resulted in the construction of a third cell at the landfill site so as to extend the lifespan of the facility.[5] However, by 2019, this third cell had also run out of space and diversion plans commenced whereby all municipal solid waste is transported to a landfill site located 40 km from Stellenbosch, within another municipality (De Wet J, Manager: Environmental Sustainability at Stellenbosch University Facilities Management, personal communication, 13 June 2021).

Detailed knowledge of the composition of the waste entering landfills can assist in the determination of priority waste and the identification of appropriate interventions to assist in diversions from landfill sites. However, one of the major stumbling blocks for waste managers is often the lack of reliable data on the composition of various waste streams.[6-8] Waste characterisation studies enable relevant data pertaining to this composition to be gathered to assist decision-makers to identify the constraints on and opportunities for managing their streams.[9] Dependable waste characterisation data are crucial to decision-making processes[10], which can be hamstrung when these data are lacking[11]. Optimal methods of collecting and freighting household solid waste (HSW), recovering materials and appropriate 'end-of-life' methods rely heavily on the characteristics of particular waste streams.[12] Thus, many HSW characterisation studies have been done in diverse geographical, environmental, political and climatic settings throughout the world.[13-16] Notably, there have been relatively few waste characterisation studies conducted in South African municipalities.[17] For instance, in 2012, only 17 of South Africa's 284 municipalities had conducted waste characterisation studies.[17] Of these studies, several issues arise, such as the lack of standardised methodologies and sample sizes, differing waste characterisation categories and the low number of samples.[17] Furthermore, these studies mostly exist within the 'grey' literature and typically focus on municipal-level analysis where different income groups are often not considered.[17] As HSW generation and composition are affected by geography, income and access to separation at source programmes, suburb-level analysis is crucial to evaluate the efficacy of certain inteventions (such as separation at source) and differences in waste composition between areas. Published research regarding waste characterisation in the South African context includes food waste[18-20], quantification of informally disposed waste[21], waste characterisation methodologies[17], management of mechanical biological waste[22,23], characterisation of waste at higher education institutions[24,25], and the difference in waste generation and composition between formal and informal areas[26]. Few studies have focused on sub-municipal level and the composition of HSW at a suburb level as well as understanding the socio-economic factors that influence HSW composition.

This paper presents the results of a waste characterisation study undertaken in 2017 in the Stellenbosch Local Municipality, Western Cape Province, South Africa (Figure 1). Although several investigations have identified the need for effective waste management in the Stellenbosch context[27-30], to date none has focused solely on waste characterisation of the HSW stream. The purpose of this study was to demonstrate how HSW generation and composition (destined for landfill) differ among suburban areas (suburbs) and to investigate the possible socio-economic explanatory variables for any differences in waste characteristics. The findings of a 2017 study are presented but, notably, the investigation concentrated on the contents of HSW destined for landfill and excluded all HSW already separated at source for further beneficiation.

Waste characterisation

A review of several waste characterisation studies reveals that the single factor most influencing the nature of waste characterisation studies and their findings, is the methodological framework of the study. To date, no single or specific research method nor set of research methods have been accorded the status of an internationally standardised approach to conducting HSW characterisations.[31] Thus, an array of generally accepted methods are found in the literature. Each method has been developed and applied in the absence of a single recognised approach and each has been employed in endeavours to remedy the same obstacle, namely the lack of data concerning the composition of HSW.[8,10,11,32,33]

Investigations by Edjabou et al.[11], Ozcan et al.[12], Emery et al.[13], Al-Khatib et al.[31] and Monavari et al.[34] have identified two sets of factors that potentially influence waste characterisation, namely seasonal effects and socio-economic factors (particularly household size and income). Thus, seasons can have pronounced effects on the composition of waste and the rates of disposal.[12,13] In particular the organic waste fraction is often influenced most by seasonal dynamics.[12] Additionally, seasonal variations can significantly affect the moisture content of waste streams (dry and rainy seasons), which in turn affects the weight of these streams.[11]

Regarding economic factors, strong correlations often exist between income level and the consumption of goods and services. There is also ample evidence from extant research confirming that the rates at which waste is generated in city environments are generally higher than those in rural areas, as a consequence of both higher living standards and higher levels of economic activity in cities.[31]

Not only do the volumes of waste generated differ among income groups in particular settings, but the relative contributions of the different waste fractions to overall waste streams also vary significantly. Relatively little organic waste is typically generated by the low-income segments of communities in comparison to their medium- and high-income counterparts.[11,12] Owing to economic circumstances, members of low-income households are likely to consume most of the organic materials they either grow or purchase for consumption and thus discard relatively little. Other fractions, such as waste in the form of paper and cardboard, are also generated at considerably higher rates in high- and medium-income areas than in low-income areas as a consequence of the formers' greater purchasing power, higher levels of consumption of pre-packaged foods and other products as well as their significantly higher levels of participation in activities which entail the use and consumption of paper. However, some studies have found no significant correlation or relationship between waste quantities and household income.[34] These findings point to income not being the only determinant of levels of daily consumption and that higher incomes may be invested or spent in ways that do not influence the rates at which waste is generated. Typically, waste characterisation studies are conducted in four phases – (1) sample size and method determination, (2) sample collection, (3) sorting and (4) analysis.

Determination of sample size and methods phase

The sampling phase of a HSW characterisation study has two distinct steps: first, the sample size is determined and, second, the sampling methods to be used are identified.[14,35] Studies typically adopt different sampling protocols and use different sample sizes. For instance, Monavari et al.[34] sampled one bag for every 563 households and Gomez et al.[14] sampled one bag in every 347 households. In contrast, Dangi et al.[15] sampled one bag in 84 households while Ezeudu et al.[16] sampled one bag for every 64 households in the population. A review of 18 waste characterisation methodologies based on physical sampling revealed that there is not a singular method appropriate for the determination of appropriate sample size and number of samples.[36] The range of recommendations clearly shows the differences in sampling employed by various researchers. These differences are because characterisation studies are often constrained by time and financial resources, with data collection and sorting often being prohibitively expensive, especially in developing countries.

Sample collection phase

The collection of samples in HSW characterisation studies is crucial to the success of a study and it can significantly influence the reliability of the findings produced.[32,35,37] The ways in which HSW is transported in developing countries ranges widely from rickshaws, animal-drawn carts, wheelbarrows and hand trolleys to motorcycles, tractors, trucks and compactors.[38] Relevant collection-related factors to be considered are whether samples are compacted or uncompacted during collection, how regularly collections are done and the methods used to select households.[39]

Sorting phase

The waste materials in each sample are then physically separated into predetermined fractions.[40] The number of fractions chosen is primarily determined by time, budget and human resources available to the researcher. Equally influential is the objective of each study.[12] Various sorting categories were reported in 19 HSW characterisation studies conducted between 2001 and 2019 (Table 1). The numbers range from five named fractions used by Ezeudu et al.[16] to the 167 main and sub-fractions sorted by Gu et al.[41] The 12 most frequently used waste fractions were: plastics, metals, paper, organic waste, glass, other, textiles, garden waste, household hazardous waste, cardboard, electronic waste, and sanitary waste. This again clearly denotes the vast difference in methods employed for waste characterisation studies.

Data analysis phase

The crucial issue in conducting waste characterisation studies is to determine the overall composition of waste samples. The usual solution is simple interpolation of the data from an individual waste fraction over the entire population.[11] Correlation and regression analyses are standard techniques for further examining the data, particularly to uncover causal relationships between waste generation and causal variables such as household income, size and density.[9,34,37,41] Another statistical technique used in waste characterisation studies is analysis of variance (ANOVA) applied to determine whether deviations about the mean distributions of compositions of waste can be attributed to the geographical origins of particular samples.[31]

Study area

The Stellenbosch Local Municipality (WC024) is one of five local municipalities which fall within the boundaries of the Cape Winelands District Municipality (CWDM) of the Western Cape Province of South Africa. Stellenbosch Local Municipality has jurisdiction over an area of only 831 km^2, with a total population of 155 728 people who reside in 43 420 households.[42,43] It houses 19.78% of the total population of the Cape Winelands District Municipalityon only 3.87% of the total area under its jurisdiction. From these statistics, it is evident that the area which falls under the Stellenbosch Local Municipality is the most densely populated in the overall district (186.40 people/km^2). In 2018, income inequality levels were the highest in Stellenbosch when compared to neighbouring municipalities within the Cape Winelands District Municipality as well as within the greater Western Cape, with a Gini coefficient of 0.60.[44] The Stellenbosch Local Municipality provides a weekly refuse removal service to 87% of the population – the highest collection rate in the district.[42]

Table 1: Frequency of including various sorting fractions of household solid waste in several waste characterisation studies

Reference	Total number of fractions	Fractions included (✓) or not included (×)											
		Pl	M	Pa	OW	G	O	T	GW	HHHW	CB	EW	SW
Ezeudu et al.[16]	5	✓	✓	✓	✓	×	✓	×	×	×	×	×	×
Aziz et al.[56]	6	✓	✓	✓	✓	✓	×	✓	×	×	×	×	×
Kumar and Goel[57]	7	✓	✓	✓	✓	✓	×	×	×	×	×	×	×
Al-Khatib et al.[31]	8	✓	✓	✓	✓	✓	✓	✓	×	×	×	×	×
Edjabou et al.[11]	9	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×	×
Dangi et al.[15]	10	✓	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×
Monavari et al.[34]	10	✓	✓	✓	✓	✓	✓	✓	✓	×	×	×	×
Doležalová et al.[58]	10	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Parizeau et al.[40]	12	✓	✓	✓	✓	✓	×	✓	✓	×	×	×	✓
Gomez et al.[14]	15	✓	✓	✓	✓	✓	✓	×	×	✓	✓	×	×
Yenice et al.[9]	17	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×
Ozcan et al.[12]	17	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	×
Miezah et al.[8]	23	✓	✓	✓	✓	✓	✓	✓	✓	×	✓	×	×
Emery et al.[13]	30	✓	✓	✓	✓	✓	✓	✓	✓	×	×	✓	✓
Ojeda-Benítez et al.[59]	37	✓	✓	✓	✓	✓	×	✓	✓	×	✓	×	✓
Bernache-Pérez et al.[32]	53	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Edjabou et al.[60]	56	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Thanh et al.[37]	83	✓	✓	✓	✓	✓	×	✓	✓	×	×	×	×
Gu et al.[41]	167	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Proportion of studies in which fraction is included		100%	100%	100%	100%	95%	74%	74%	68%	47%	47%	37%	37%

Pl, plastics; M, metals; Pa, paper; OW, organic waste; G, glass; O, other; T, textiles; GW, garden waste; HHHW; household hazardous waste; CB, cardboard; EW, e-waste (electronic waste); SW, sanitary waste

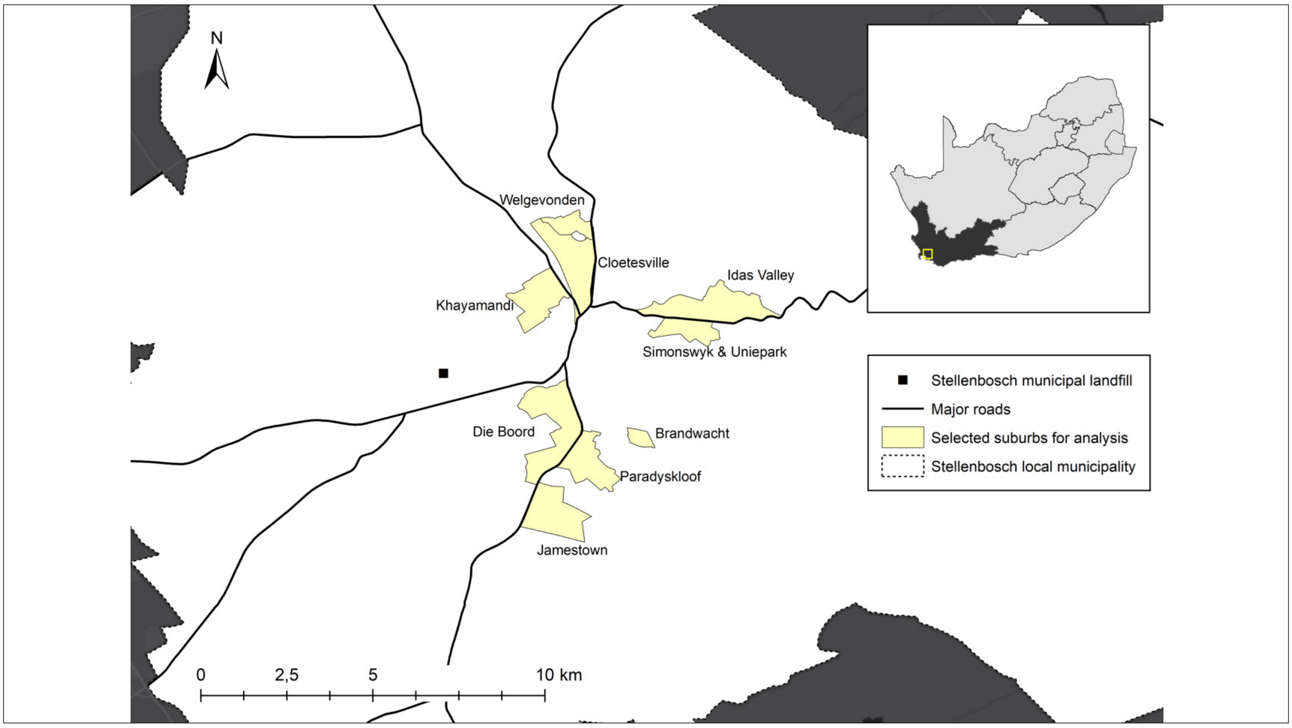

Figure 1: Map of the study area.

HSW produced in the study area is collected by refuse compactor vehicles. The vehicles are operated by a driver and five crew members. Houses in all formal areas are required to place their 240-litre municipal-issued wheelie bins on the pavement outside their homes on refuse collection days. HSW is collected once a week, from Monday to Friday.[45] Housing complexes may also request refuse collection three times a week (Mondays, Wednesdays and Fridays), which is offered by the municipality at an increased tariff.[46] A separation at source initiative, which is implemented in specific areas within the municipal area, enables residents to place recyclable waste in clear bags next to their wheelie bins on collection days. A different vehicle collects and transports recyclables to a small materials recovery facility located adjacent to the landfill site, where the recyclables are sorted manually before being baled and transported to recyclers.

HSW is collected from informal areas by removing 6-m^3 skips up to five times a week. The use of skips is preferred by the municipality in these areas because access to homes is often hindered by low-hanging electrical cabling and a lack of formal roads (Heckrath N, Foreman: Disposal, Stellenbosch Municipality, personal communication, 18 January 2018). Consequently, the locations of skips are usually determined by the ease with which refuse removal vehicles are able to reach them and not necessarily by other equally significant factors such as the distances between the skips and residents (Hendricks C, Principal Technician: Collections, Stellenbosch Municipality, personal communication, 5 February 2018).

The study area map (Figure 1) shows the location of Stellenbosch within South Africa, as well as the selected suburbs in this study.

Garden, industrial, construction, demolition and household solid wastes are all accepted at the local landfill site and each load is individually recorded on the weighbridge's software system prior to disposal in terms of type of waste and weight. The municipality chips garden waste on-site whereafter it is removed for further beneficiation. Construction and demolition waste is crushed and screened on-site to predetermined specifications in accordance with tender requirements and made available for resale. Industrial waste is transported to the facility by private contractors and accepted if it can be classified as 'general solid waste'. This classification implies that it may not be classifiable as a sludge or liquid waste and may not contain any hazardous material. Households in areas where the separation at source programme is not implemented, generate waste destined for landfill only. The waste consists of a mixture of recyclable, non-recyclable and organic waste, which is disposed of in black bags. Households which participate in the programme also generate 'black bag' waste consisting of non-recyclables and organic waste destined for landfill. This waste destined for landfill is referred to as the 'residual waste' portion. All recyclable waste is placed in clear bags and the separation at source programme provides the municipality with a monthly breakdown of the types and quantities of recyclable materials separated by households from residual waste in participating suburbs. Accordingly, the contents and composition of the 'clear bags' are known. Consequently, the composition of the waste stream which enters the municipal landfill of which the Stellenbosch Municipality is most uncertain, is the residual portion of the HSW stream, which is why this study focuses on the characterisation thereof.

Materials and methods

A waste characterisation study was conducted for the Stellenbosch Municipality and involved the application and implementation of the four phases of such studies as outlined above. These phases are discussed further here. Ten suburbs within Stellenbosch were selected because they reflect different socio-economic areas within the municipality and are also serviced by municipal refuse compactor vehicles, i.e. the HSW collected in these suburbs is destined for landfill.

Determination of sample size

In March 2017, the Department of Environmental Affairs and Development Planning (DEA&DP) of the Western Cape, South Africa, published guidelines on waste characterisation[47] to ensure the standardisation of waste characterisation studies conducted in the Province, in the interest of obtaining reliable and comparable results. Because the Stellenbosch Local Municipality is a local authority under the provincial jurisdiction of the DEA&DP, the guidelines were assessed to ensure standardisation of the sampling procedures and compliance with the prescriptions. The guidelines essentially are grey literature and the robustness of the sampling process has not been tested. The need for integrating these guidelines with those extracted from a broader literature was thus identified. The minimum requirements of the guidelines were complied with, but lessons learnt from other waste characterisation studies highlighted above were also incorporated into the study design.

The sample size for the study was determined by combining Cochran's formula (Equation 1) and the DEA&DP's sampling guidelines.[47,48] This combination was necessary because the DEA&DP guidelines were intended for waste characterisation studies in poorly resourced municipalities, whereas a substantial budget and more human resources were available to conduct a wider, more in-depth study. Cochran's formula, which was further developed by Bartlett et al.[35], has been successfully used in a number of studies to calculate sample sizes for waste characterisation[8,49]. The formula is appropriate for studies of large populations with unknown degrees of statistical variance. The formula is:

$$n_o = \frac{z^2pq}{e^2} \qquad \text{Equation 1}$$

where n_o is the sample size;

z is the selected critical value of the desired confidence level;

p is the estimated proportion of an attribute which is present in the population;

q is $1-p$; and

e is the desired level of precision.

According to the United Nations Environment Programme[50], confidence levels for data collected for the characterisation of solid waste are usually set at 80% to 90%. However, a survey of relevant studies revealed that confidence levels and precision vary substantially, with confidence levels ranging from 90% to 99% and precision between ±5% and ±10%.[8,12,14] The confidence level for this study was set at 95% with precision of ±8%. Table 2 provides details about each suburb studied and the number of samples required as calculated using Equation 1.

Table 2: Particulars of the 10 suburbs selected for study in Stellenbosch

Suburb	Number of households[43]	Number of samples collected	Separation at source programme
Cloetesville	3327	113	Yes
Jamestown	601	207	Yes
Uniepark	138	190	Yes
Kayamandi	8564	384	No
Idas Valley	2128	166	Yes
Die Boord	1089	80	Yes
Welgevonden	1070	62	Yes
Paradyskloof	593	122	Yes
Brandwacht	182	119	Yes
Simonswyk	138	100	Yes
Total	17 830	1543	

Stratified random sampling was conducted to identify the 10 suburbs selected in this study. A second round of spatially stratified random sampling was done in each suburb to ensure that the sampled households were evenly distributed spatially in each suburb. The study was undertaken with the permission of the Stellenbosch Local Municipality, but without the knowledge of household members so as to minimise any changes in their waste-related behaviour. Sample bags were, in no way, traceable back to individual houses.

Sample collection

The collection of samples started with the identification of the suburb from which samples were collected each day. Each pre-identified suburb was assigned a unique coloured sticker for the day. The appropriate sticker was attached to the bags collected in a specific suburb on a particular day. This enabled the crews of the special collection vehicles, sponsored by the municipality, to collect samples from more than one suburb per collection round before offloading the samples. By not requiring crews to separate the bags from the different suburbs, potential sampling errors were minimised and crews were not overburdened with excessively complex instructions.

Samples were collected on the same day as the scheduled municipal refuse removal day for a suburb. The municipality's solid waste management department, which is responsible for the collection of HSW, ensured that the crews collecting samples were given a head start over the department's scheduled compactor vehicles. Because HSW is collected once a week from homes in the suburbs, it was assumed that the samples represented 7 days' worth of waste per household.

Uncompacted samples were collected as this best suited the time and budget available for the study. The samples were collected by the crews consisting of two to four workers on two vehicles driven by appropriately licensed drivers. Each crew member was issued with suitable personal protective equipment. In total, 1543 samples (10.2% of the households) of a planned 1821 were collected. The samples weighed a combined total of 5748 kg and had an uncompacted volume of 84.9 m^3.

Sample sorting

Each unopened bag was weighed and its mass captured by trained supervisors. The suburban origin of each bag was noted by the supervisors. The sorting team of unemployed individuals selected by the municipality and trained by the researchers opened the bags under supervision. Extreme caution was exercised when opening the bags, because the unknown contents could have contained sharp objects or hazardous substances. The use of reusable black bags minimised the creation of additional and unnecessary plastic waste.

The sorting process was supervised to ensure correctness. Seven major waste fractions were considered during the sorting phase, namely (1) hard plastics, (2) plastic wrap and packaging, (3) metals, (4) glass, (5) paper and cardboard, (6) organic waste and (7) other. Organic waste and other fractions were further divided into subfractions, a procedure that promoted a deeper understanding of the various waste fractions. Organic waste was subdivided into food waste, garden waste and leachate. Other waste was subdivided into Tetra Pak® cartons, household hazardous waste, expanded polystyrene, tissues, ash, electronic waste, small furniture items, maize meal bags, textiles and 'residual other'.

Once the entire contents of a bag had been sorted into relevant fractions, the platform scale was zeroed to account for the weight of the 20-litre buckets into which the fractions had been placed and each fraction was individually weighed and the readings captured by a supervisor. The uncompacted volume of each fraction was determined by estimating its volume in the 20-litre bucket into which the fraction had been emptied. Waste fractions that exceeded the capacity of one 20-litre bucket required the use of additional buckets. Consequently, the volume of some waste streams exceeded 100% (one bucket).

Data analysis

Two software packages were used to analyse the waste characterisation data: Microsoft Excel 2016 for a basic analysis and R for the statistical analysis.

Basic analysis

The mass (kg) of each waste fraction did not require any further conversion. The estimated volumes captured as percentages of a 20-litre container were converted to cubic metres. This was crucial because the volumes give an indication of the physical space which the uncompacted materials would occupy on a landfill site. The results were used to develop waste profiles for each suburb as well as waste profiles for each fraction in the overall waste stream, namely hard plastics, plastic wrap and packaging, metal, glass, paper and cardboard, organic waste and 'other'. The volume of waste landfilled per annum was projected. Potential seasonal fluctuations were not taken into account during this study on the basis of the findings of a study conducted by the Stellenbosch Local Municipality. The study, conducted in 2012, was to determine whether seasons influenced the overall compositions of waste streams. The findings revealed that although the size of the garden waste fraction was most affected by seasonal changes, the generation and disposal of other waste fractions were mainly unchanged, with a few exceptions, such as those which occurred as a consequence of spikes in waste generation at times such as public holidays.[51]

Statistical analysis

The data captured during the waste characterisation process were analysed statistically using R. In the absence of household-level demographic and socio-economic information, an ANOVA[52] was performed to determine any significant differences in the waste fractions of HSW among waste generation rates and the explanatory variables household income and household size. Information available in the public domain, such as census data regarding average household size and income per suburb, was also used.

Results and discussion

Results concerning the characterisation of waste in Stellenbosch are presented here, followed by an exploration of variables which may explain these results.

Composition of residual HSW

The overall composition of the characterised waste, expressed as mass and volume, is summarised in Table 3. Data from the municipal landfill weighbridge revealed that the average quantity of HSW sent to landfill over the previous 4 years (the period for which data were reported by the municipality) was 3236.2 tons per month or 38 833.8 tons per year generated by a total of 155 728 residents – an average of 0.68 kg/capita/day. In contrast, a review of 19 published HSW characterisation studies conducted (Table 1) showed average waste generation rates of between 0.26 kg/capita/day and 0.98 kg/capita per day with an average of 0.54 kg/capita/day. These figures place this study's waste generation rate at the higher end of the spectrum.

All the densities in Table 3 were calculated for uncompacted materials. Information about uncompacted waste materials is crucial in determining the amount of space required at diversion facilities for storing unprocessed materials. The overall waste stream can also be linked to certain causal variables discussed below.

Relationship between waste composition and household socio-economic factors

As mentioned previously, socio-economic factors are strongly linked to waste generation rates as well as the types of waste produced by households. An ANOVA was performed to determine the statistical differences between waste generation rates in each suburb and the influence that household income and household size were found to have on these rates. Table 4 summarises the economic parameters for each area surveyed.

Table 5 presents the results of a one-way ANOVA of the relationships between the various suburbs studied and select waste fractions. The results of the ANOVA suggest that a statistically significant ($p<0.05$) difference exists between the mean mass of the different waste fractions across all the suburbs considered. Plastic wrap and packaging (Figure 2), paper and cardboard (Figure 3) and glass (Figure 4) waste fractions showed the greatest variance in means between suburbs.

Table 3: Proportions and quantities of waste fractions landfilled in Stellenbosch in 2017

Waste fraction	%Contribution to waste stream by mass	%Contribution to waste stream by volume	Average uncompacted density (kg/m^3)	Tons/a landfilled	m^3/a landfilled (uncompacted)
1. Hard plastics	8	15	36.02	3244.59	90 077.46
2. Plastic wrap and packaging	12	32	*26.91*	4699.07	174 621.70
3. Metal	2	2	91.3	920.75	10 084.88
4. Glass	11	2	293.13	4261.71	14 538.63
5. Paper and cardboard	16	26	40.77	6015.19	147 539.61
6. Organic waste	35	10	251.07	13 440.42	57 933.28
6.1 Food waste	27.30	7.30	251.07	10 552.07	42 028.40
6.2 Garden waste	7.35	2.70	179.12	2803.67	15 652.47
6.3 Leachate	0.35	0.00	335.44	84.67	252.41
7. Other	16%	13%	173.2	6252.02	91 307.94
7.1 Tetra Pak® cartons	1.12	1.56	44.35	463.27	10 445.77
7.2 Household hazardous waste	0.16	0.00	167.57	30.47	181.83
7.3 Expanded polystyrene	1.28	4.16	16.72	489.4	29 270.33
7.4 Tissues	3.84	3.64	58.74	1 501.16	25 556.01
7.5 Ash	2.08	1.17	104.39	802.79	8792.88
7.6 Electronic waste	1.12	0.26	208.05	432.4	2078.35
7.7 Small furniture items	0.16	0.00	183.15	43.78	239.04
7.8 Maize meal bags	0.16	0.13	164.64	71	431.24
7.9 Textile waste	0.00	0.13	50.47	25.17	498.71
7.10 Residual other	6.08	1.95	173.2	2392.54	13 813.74
Total	**100.00%**	**100.00%**	**N/A**	**38 833.75**	**526 491.96**

Table 4: Economic parameters for each area surveyed

Area	Average annual household income (ZAR)[43]	Income category[a]	Average household size[43]	Household density[b]	Separation at source programme
Cloetesville	103 694.18	Medium	5	1814	Yes
Jamestown	237 215.13	Medium	5	371	Yes
Uniepark	264 707.95	High	3	336	Yes
Kayamandi	42 607.51	Low	3	6082	No
Idas Valley	144 302.30	Medium	4	1014	Yes
Die Boord	435 138.35	High	3	480	Yes
Welgevonden	398 359.20	High	2	1949	Yes
Paradyskloof	519 016.71	High	3	462	Yes
Brandwacht	592 431.93	High	3	265	Yes
Simonswyk	264 707.95	High	3	276	Yes

[a]There is no official generic definition for high-, medium- and low-income groups in South Africa. However, based on the housing market and existing state-subidised housing programmes, three distinct income categories can be identified: (1) Fully subsidised housing for households earning less than ZAR3500 per month (low income), (2) 'gap' housing market qualifying for Social Housing and the Finance Linked Subsidy Programme for households earning between ZAR3501 and ZAR22 000 per month (medium income) and (3) bonded housing market for households earning >ZAR22 000 per month (high income)[53]

[b]Number of households per square kilometre

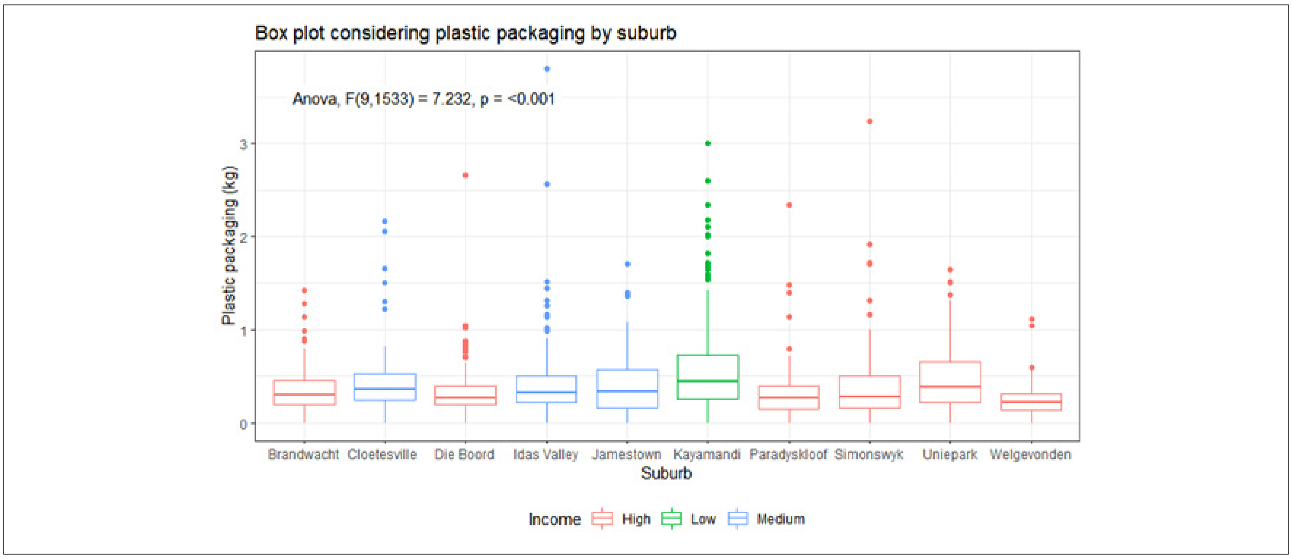

Figure 2: Box plot depicting differences in means of plastic packaging waste fractions among suburbs in Stellenbosch.

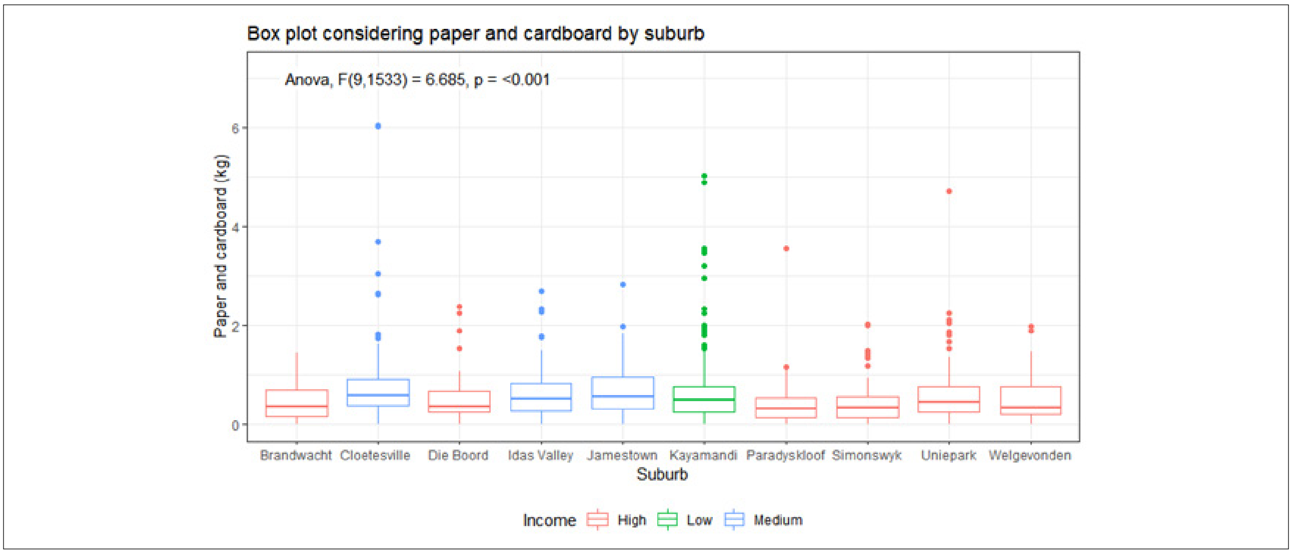

Figure 3: Box plot showing the differences in sample means for the paper and cardboard waste fraction among suburbs in Stellenbosch.

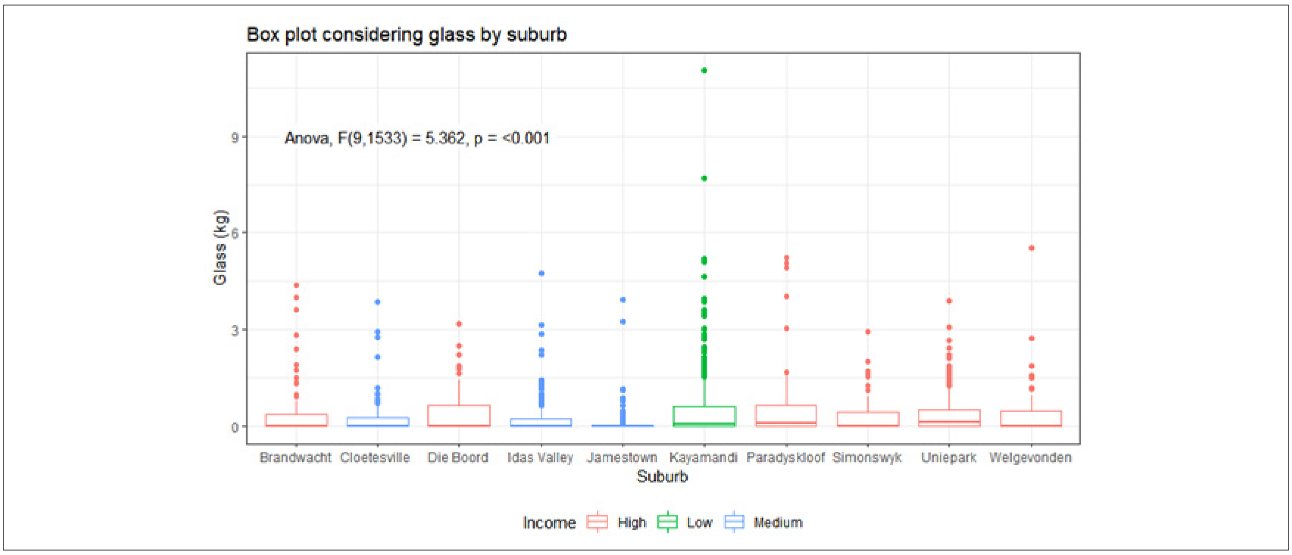

Figure 4: Box plot considering differences in mean glass composition of household solid waste among suburbs in Stellenbosch.

Table 5: ANOVA comparing differences in means across suburbs for different waste fractions

Waste fraction	One-way ANOVA by suburb	
	F (9, 1533)	*p*-value
Glass	5.362	<0.001
Hard plastics	2.179	0.02
Metals	3.403	<0.001
Organics	3.501	<0.001
Other	3.206	<0.001
Paper and cardboard	6.685	<0.001
Plastic wrap and packaging	7.232	<0.001

In relation to the prevalence of plastic packaging in the HSW stream between different suburbs, there is a statistically significant difference between sample means across the suburbs analysed (Table 5, Figure 2). Kayamandi has, on average, the highest amount of plastic wrapping and packaging by weight (0.5464 kg per bin) in the HSW stream destined for landfill. This is followed by Uniepark (0.4614 kg per bin) and Idas Valley (0.4418 kg per bin). Notably, Kayamandi, Jamestown, Idas Valley and Cloetesville are classified as low–medium-income areas and all show higher levels of paper and cardboard in the HSW stream when compared to higher-income suburbs (with the exception of Uniepark).

Paper and cardboard disposal between the different suburbs also differs significantly (Figure 3). The highest mean is for Cloetesville (0.8339 kg per bin), followed by Jamestown (0.6574 kg per bin), Idas Valley (0.6323 kg per bin) and Kayamandi (0.6008 kg per bin). Again, the four suburbs with the highest disposal are in medium- and low-income groups.

There is a significant difference between the means of each suburb for glass (Figure 4). Perhaps most noticeable is the high number of outliers collected from Kayamandi, while Jamestown has very limited variance. Kayamandi, Idas Valley, Jamestown and Cloetesville are often near the top in relation to the amount of recyclable materials placed in the HSW stream, particularly plastic packaging, paper and cardboard, and glass (Figures 2–4), even though three of these suburbs (Idas Valley, Cloetesville and Jamestown) have access to a separation at source programme. Strydom[54,55] argues that only a minor percentage of South African households actively engage in recycling programmes (7.2% in 2015). Household recycling is often inhibited by several factors, including: limited space, time constraints, inadequate recycling knowledge and the inconvenience of recycling.[54] In particular, non-recyclers indicate that a lack of time and knowledge influences household recycling activity, while those in highly dense urban areas suggest that an absence of recycling knowledge is an important variable explaining the lack of recycling in these areas.[54] Given these results, it is possible that recycling behaviour is influenced by income level, which affects factors like space limitations, housing density and the inconvenience of recycling.

Table 6 presents the results of a one-way ANOVA of the relationships between the various income groups and select waste fractions. The results of the ANOVA indicate that a statistically significant difference exists between the mean mass of the different waste fractions across all income groups considered, with the exception of the organics category. This finding is surprising as the literature often points to low-income areas producing less organic waste than higher income suburbs.[11,12] Plastic wrap and packaging (Figure 5) and paper and cardboard (Figure 6) waste fractions showed the greatest variance in means between income groups. The low-income group had the highest amount of plastic wrapping and packaging on average by weight (0.5464 kg per bin) in the HSW stream destined for landfill, followed by the medium-income group (0.4248 kg per bin) and the high-income group (0.3811 kg per bin). These results corroborate the observations made in Figure 2.

Table 6: ANOVA comparing differences in means across income groups for different waste fractions

Waste fraction	One-way ANOVA by income group	
	F (2, 1540)	*p*-value
Glass	19.74	<0.001
Hard plastics	7.455	<0.001
Metals	8.368	<0.001
Organics	2.302	0.1
Other	9.919	<0.001
Paper and cardboard	22.16	<0.001
Plastic wrap and packaging	23.37	<0.001

Paper and cardboard disposal between the different income groups also differs significantly (Figure 6). Here the highest mean is for the medium income group (0.6899 kg per bin), followed by the low income group (0.6008 kg per bin) and the high income group (0.4624 kg per bin). Income level clearly affects the amount of paper and cardboard in the HSW stream in Stellenbosch.

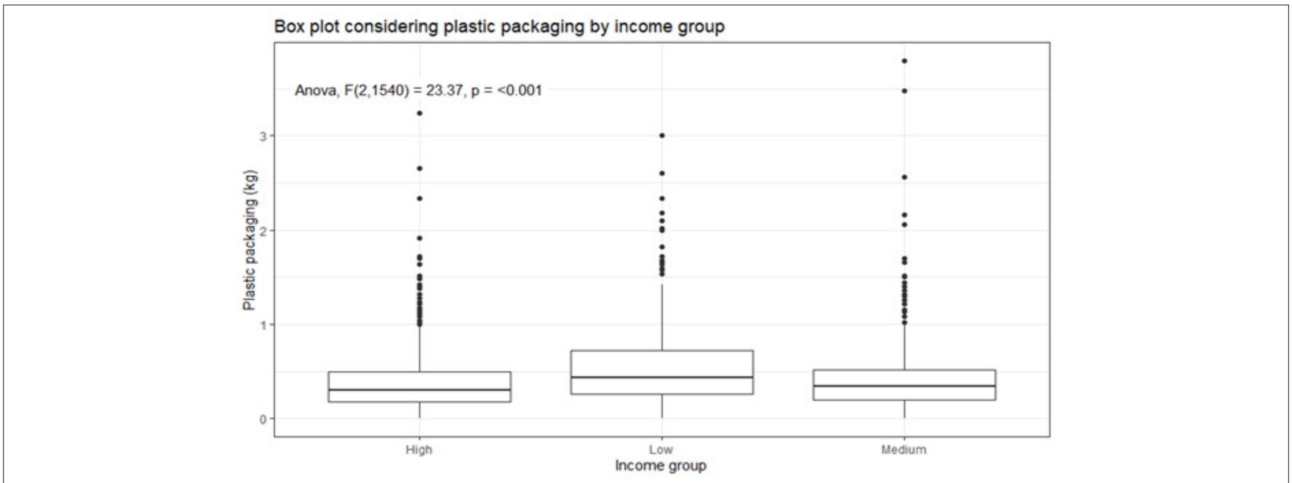

Figure 5: Box plot depicting differences in means of the plastic packaging waste fraction between different income groups in Stellenbosch.

Table 7 presents the results of a one-way ANOVA of the relationship between household size and select waste fractions. The results show that the low-income group has the highest means of the following waste fractions in comparison to other income groups: hard plastics, plastic wrapping and glass. The low-income group is made up of only one suburb, Kayamandi, and is also the only suburb sampled which did not have access to the separation at source programme in Stellenbosch. Thus lack of access to a separation at source programme might be an explanatory variable relating to the higher quantities of recyclables found in Kayamandi where one would expect large quantities of recyclable waste to be disposed of in municipal skips and bins.

However, the findings also suggest that the medium-income areas (with access to a separation at source programme) tend to have higher levels of recyclable materials in the HSW stream than higher-income areas, indicating that other factors, such as recycling attitudes[17] and types of waste generated in households, are important too. So while separation at source is an effective way of keeping the hard plastics, plastic wrapping and glass fractions out of the landfill, more can be done to ensure a greater use of this facility.

Increasing household size is typically associated with greater levels of waste generation, although the effect of household size on different waste fractions is not always clear. Table 7 shows that the results of the ANOVA indicate that a statistically significant difference exists between the mean mass of the different waste fractions across all household sizes considered, except for the hard plastics category. Glass (Figure 7) and paper and cardboard (Figure 8) waste fractions showed the greatest variance in means between household sizes.

Glass disposal varied significantly depending on household size (Figure 7). Households with three members were found to dispose of the most glass on average (0.4458 kg per bin), followed by two-member households (0.4182 kg per bin), four-member households (0.2586 kg per bin) and, lastly, households with five members (0.1686 kg per bin). In accordance with the ANOVA results when considering suburbs and income groups, when considering household size, the paper and cardboard waste fraction was again amongst the top two fractions showing the most variance (Table 7, Figure 8).

Table 7: ANOVA comparing differences in means across household size for different waste fractions

Waste fraction	One-way ANOVA by mean household size per suburb	
	F (3, 1539)	***p*-value**
Glass	11.29	<0.001
Hard plastics	1.419	0.235
Metals	6.08	<0.001
Organics	7.115	<0.001
Other	4.944	0.002
Paper and cardboard	10.94	<0.001
Plastic wrap and packaging	5.115	0.002

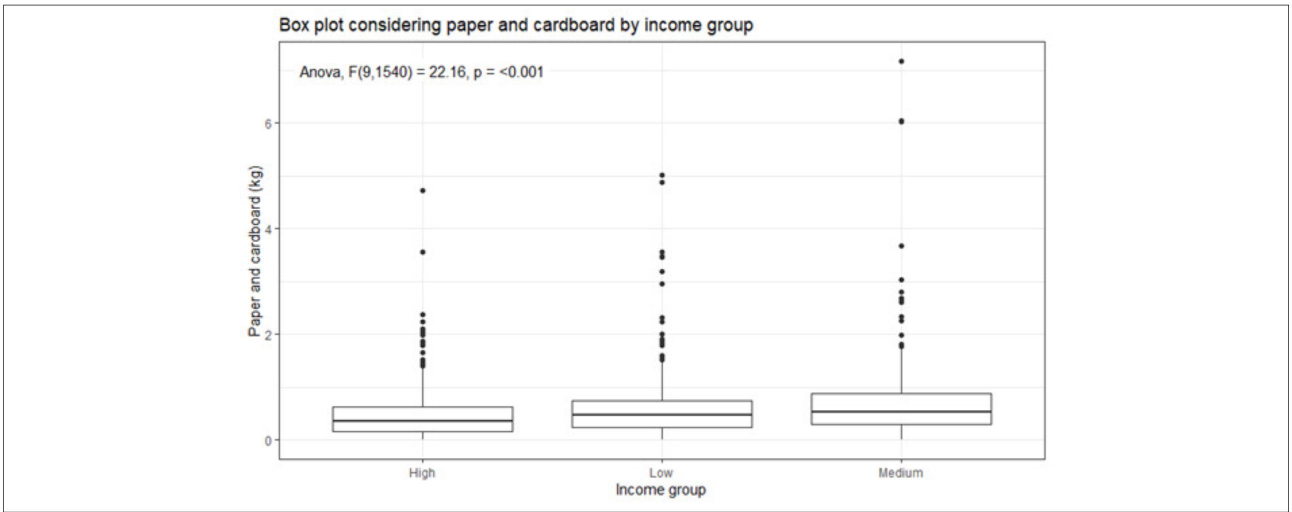

Figure 6: Box plot depicting differences in means of the paper and cardboard waste fraction between different income groups in Stellenbosch.

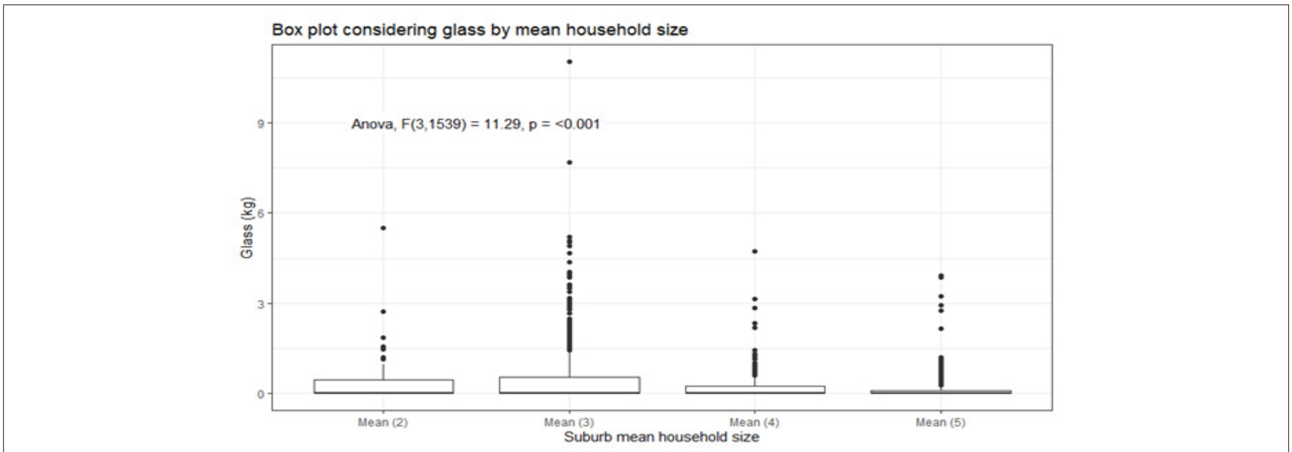

Figure 7: Box plot depicting differences in means of the glass waste fraction between different household sizes in Stellenbosch.

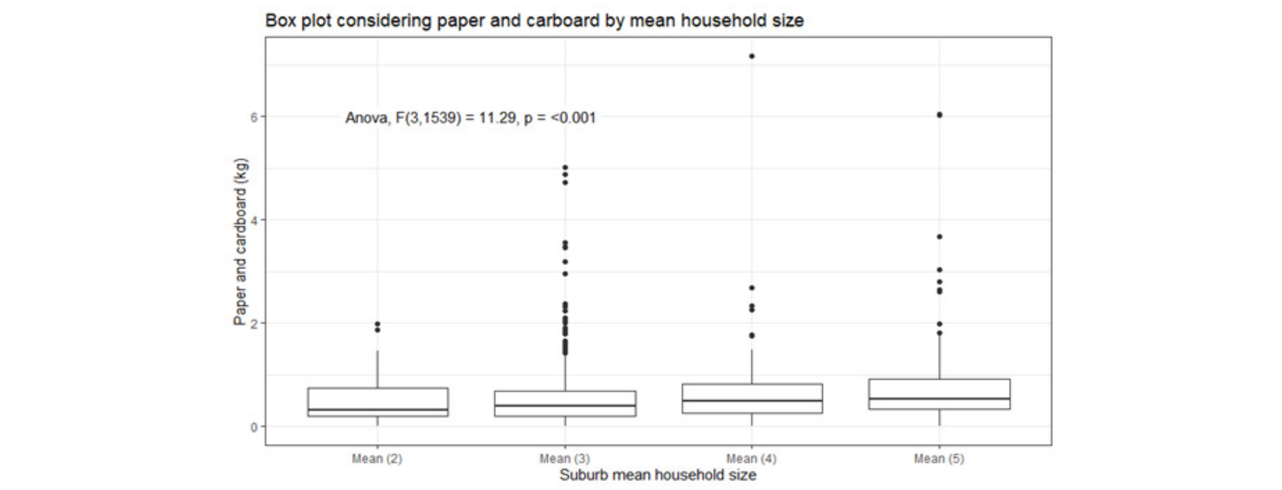

Figure 8: Box plot depicting differences in means of the paper and cardboard waste fraction between different household sizes in Stellenbosch.

Figure 8 shows that, as household size decreases, so does the amount of paper and cardboard disposed of. Households with five members disposed of 0.7197 kg paper and cardboard per bin, followed by four-member households (0.6323 kg per bin), three-member households (0.5136 kg per bin) and two-members (0.4977 kg per bin).

These results show that there are significant differences in the HSW streams of suburbs in the Stellenbosch Municipality. Mean household income and mean household size for these suburbs can be considered explanatory variables for these differences, with plastic packaging, paper and cardboard, and glass being the waste fractions that show the greatest difference in means. Lack of access to a separation at source programme may influence the high levels of recyclable materials in Kayamandi, but other (medium-income) suburbs with access to these programmes display similar levels of recyclable waste fractions in their HSW, suggesting that waste behaviour and types of waste used in households are more pertinent.

Conclusion

Few published HSW characterisation studies are conducted at sub-municipal level. The composition of HSW as well as the socio-economic factors that influence HSW composition are reported here for 10 suburbs in the Stellenbosch Municipality. Organic waste made the greatest contribution to the waste stream by mass (35%), although its contribution by volume was proportionally lower. The chief contributor to the waste stream by volume was plastics (47%), followed by paper and cardboard (26%). The mean waste generation rate (0.68 kg/capita/day) in these Stellenbosch suburbs was found to be slightly higher than the average rate reported in similar studies worldwide. During this study it was found that household size and income can be used as explanatory variables for waste generation and composition for the 10 suburbs characterised. Plastic packaging, paper and cardboard, and glass waste fractions were the most affected by household income. Typically, low- and medium-income suburbs had higher levels of these waste fractions in their HSW than did high-income areas. In future, the completion of a questionnaire, per household sampled, is recommended to obtain basic demographic and socio-economic information. This information would allow for a more nuanced analysis and correlation of individual household size and income with waste composition. Other variables, such as human behaviour, could potentially contribute to the differences and further studies to explore these are also recommended. Given the influence of separation at source programmes on waste characterisation data, it is recommended that the materials processed by these programmes are sampled in addition to the residual portion of the waste streams of areas. Such sampling would aid a more accurate understanding of the waste streams of areas and enable implementation of targeted interventions. Despite this, it is difficult to draw comparisons with other international studies, thus demonstrating the need for greater detail in reporting of such information. Further roll-out of a separation at source programme in Stellenbosch is recommended to include all suburbs in order to save landfill airspace.

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Competing interests

We have no competing interests to declare.

Authors' contributions

C.M.N.:Conceptualisation; methodology; data collection; sample analysis; data analysis; writing – the initial draft. C.S.: Conceptualisation; writing – revisions; funding acquisition. J.d.W.: Conceptualisation; writing – revisions; student supervision; project leadership.

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An estimate of construction and demolition waste quantities and composition expected in South Africa

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Construction and demolition (C&D) waste is generated from the construction, renovation, repair and demolition of the built environment. It is one of the largest waste streams and is generally not well documented or understood. Various methods for estimating C&D waste are reviewed, and the development of two methods for estimating C&D waste quantities and composition generated in South Africa is discussed. The lifetime method is based on current production quantities of key construction materials and their typical stock life. This is contrasted with the scale-up of a pocket of reasonably good statistics for Cape Town's C&D waste on a per-capita basis to determine totals for South Africa. The lifetime method yielded a result of 20.2 Mt of potential C&D waste generated in South Africa in 2017, while the per-capita method suggests that 10.8 Mt of C&D waste reached disposal sites. These quantities are much higher than the 4.48 Mt reported in official national statistics for 2017. It is important to understand and accurately quantify C&D waste in South Africa so that effective waste management can be implemented. Specifically, the reuse of C&D waste needs to be understood, as this takes precedence over recycling or downcycling according to circular economy principles. Overall, this research highlights that C&D waste quantities in South Africa appear to be considerably underreported, undermining attempts to introduce more sustainable waste management practices.

Significance:

- The results of both methods used in this study were significantly higher than reported in official South African statistics, indicating considerable underreporting in national databases as in most waste statistics worldwide.
- The informal sector is plausibly an intensive reuser of discarded building materials and demolition products from the formal sector. The omission of these informal waste management practices is a likely contributor to the difference between the official statistics and both estimates.
- It is important to accurately quantify this waste stream as this can contribute to increasing materials circularity in South Africa and lower environmental impact through the achievement of circular economy goals.

Introduction

Construction and demolition (C&D) waste is generated from the construction, renovation, repair and demolition of structures such as houses and roads. Construction waste consists of unused materials or other waste generated during construction activity and is a small but variable fraction of the total material used.[1] Demolition waste is generated during the demolition phase and includes almost all the material used in the original construction phase.[2]

The built environment consists of infrastructure, buildings and homes, and it is a major component of society's in-use stocks due to its long lifespan. It enables the flow of water, materials, energy and people, and it provides services such as shelter, transport and sanitation. In order to achieve the aims of a circular economy in the built environment, the careful selection of materials used in buildings and infrastructure needs attention. The long life of the built environment also needs to be considered, as well as end-of-life resource recovery for recycling. The built environment needs to be resource-efficient in terms of maintenance and repairability.

According to the South African State of Waste Report[3], the official national statistic for C&D waste generated in South Africa in 2017 is 4.48 Mt (megatons). Information in the SAWIS (South African Waste Information System) database is largely incomplete since many local municipalities are not reporting the numbers accurately. Strikingly, the integrated waste management plan (IWMP) for Cape Town[4] reports the annual C&D waste generated in Cape Town as 1.09 Mt, which would represent an implausible quarter of the national total.

There is a C&D waste data problem in South Africa, as these quantities appear to be underestimated. C&D waste is generally not well documented or understood in South Africa. It is speculated that this is due to the omission of informal waste management practices from official statistics as well as underreporting from formal recycling activities. It is important to quantify this waste stream so that effective waste management can be implemented. The purpose of this paper is to present methods for quantifying a more accurate estimate of C&D waste generated in South Africa. This estimate will be for the year 2017 so that the result can be compared to official national statistics.

Review and classification of C&D waste estimation methods

A study by Wu et al.[5] analysed 57 different papers on methods for quantifying C&D waste. These methods were classified based on the waste generation activity covered, estimation level and quantification method. The waste generation activity can be divided into three different areas, namely construction of new buildings, demolition of old buildings, and civil and infrastructural works. The estimation level refers to whether the study is at a project level or a regional level. Finally, the quantification approach can be described according to one of the following different methods, namely the site visit method (which can be direct or indirect measurement), the generation rate calculation method (which can be a per-capita multiplier, financial value extrapolation or area-based calculation), the lifetime analysis method (which can be building or material lifetime analysis), the classification system accumulation method, the variables modelling method or other methods. There is no single method that is better than others, and the choice of method is dependent on the data available and the circumstances of the study to be conducted. Wu et al.[5] summarise the analysed methods into a relevance tree so that the appropriate method can be selected (Figure 1).

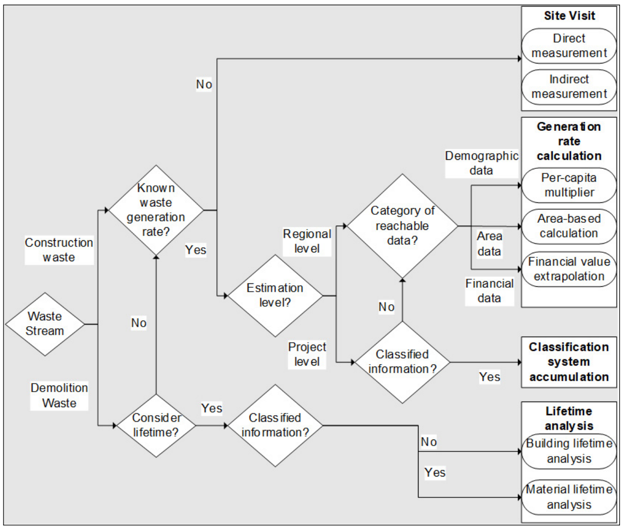

Figure 1: Relevance tree for methodology selection (from Wu et al.[5]).

An example of the material lifetime analysis method is described by Cochran and Townsend[6], who used materials flow analysis (MFA) to estimate C&D waste generated in the USA. To calculate the construction waste, the quantity of construction materials used in the USA each year was extrapolated from data from industry associations. This was done for each material. Typical waste factors are estimated from construction guides. These waste factors are used to determine the fraction of new materials discarded during the construction phase. Demolition waste consists of almost all the materials used in the original construction phase. In this study, the average lifespan of each material was used to determine the demolition waste, by estimating the quantity of material used one lifetime ago, and therefore the amount of material used to construct a project that would be demolished today. This was based on historical consumption data. It was found that the quantity of C&D waste generated in the USA in 2002 was between 610 and 780 Mt, and the majority of this was Portland cement concrete.

A version of the per-capita multiplier method is described by McBean and Fortin[7], who used the waste generation rate per person per year as well as population data to calculate the total domestic and industrial waste quantity per year. Waste generation coefficients, measured according to mass per person per year, were obtained for different dwellings and business sectors from surveys conducted in Ontario, Canada. These coefficients varied for each material type. A regression analysis was done on historical data, and this was used to forecast C&D waste data to a certain degree of confidence.

Methods

In order to develop a more accurate estimate of C&D waste generated in South Africa in 2017, two complementary methods are presented. The first is a lifetime analysis method based on estimated construction material volumes and the likely service lives of in-use stocks. Based on the review of potential C&D waste estimation methods, it was found that the material lifetime analysis method was the most suitable method for this study. This method is useful for estimating demolition waste quantities, especially when there is limited information available.

Since there are a number of uncertainties involved and assumptions used, a second method was used to attempt an additional independent estimate, namely the generation rate calculation method, which and uses a scale-up from a local municipal data source that is deemed to trustworthy, to the full population. Other estimation methods could be attempted, but this would require additional information such as area or financial data. Site visit methods were not considered for this study due to their labour and time intensity, and the results not necessarily being generalisable.

Method one: Material lifetime analysis

The first method used to estimate C&D waste in South Africa involves a material lifetime analysis based on the current production quantities of key construction materials and their typical stock life. The research described by Cochran and Townsend[6] was adapted to produce this estimate.

The first step for this method is to estimate the quantity of new construction material produced in 2017 for each of the key materials. Eight different materials were investigated including timber, glass, metal, concrete, masonry, plastic, gypsum and asphalt.

Timber includes wood products and offcuts. It is assumed that 70% of sawn wood produced in South Africa is used in construction.[8] The total production of sawn timber is estimated to be 4.74 Mt.[9] For glass, only flat glass was considered to be used for construction purposes. It was assumed that 50% of the flat glass produced is used in construction, while the rest is used in the automotive sector. The total production quantity is estimated to be 0.36 Mt.[3,10]

Next, it is assumed that the main metals used in the construction sector are steel, aluminium and copper. These metals are used for frames and furnishings and account for 99% of the metals used. The quantity of steel used in construction is estimated to be 2.10 Mt.[11] For this analysis, it is assumed that half this amount is used for metal frames and furnishings, while the other half is used in reinforced concrete. Aluminium is used in the automotive sector, for cans and in construction. It is estimated that 24% of the aluminium produced is used for construction purposes.[12] The total quantity of aluminium is estimated to be 0.72 Mt.[13] Approximately 15% of the copper produced in South Africa is used for construction purposes, mainly for plumbing.[14] The total quantity of copper produced is assumed to be 0.066 Mt.[15]

Reinforced concrete generally consists of cement, sand and gravel in a ratio of 1:2:4[16], as well as steel. As mentioned already, half of the steel used in construction is used in concrete. For this analysis, it is assumed that half of the total cement production of 14.7 Mt[17] is used in concrete, while the other half is used in bricks, plaster and mortar. The cement-to-sand-to-gravel ratio is used to calculate the other components.

The next category, masonry, includes clay bricks and tiles, concrete blocks, mortar and plaster, and paving. The production of clay bricks and tiles was reported to be 7.4 Mt.[18] The remaining cement is split between cement bricks and mortar, and it is assumed that 25% is used in bricks and 75% in mortar and plaster. The cement-to-sand ratio of bricks is 1:8. Mortar and plaster is assumed to have a cement-to-sand ratio of 1:3.

Plastics include pipes, frames and furnishings. This is assumed to be 50% of the 0.81 Mt of plastics used durably in 2017.[19] For gypsum, approximately 96% is used in construction activities[20], and the total production quantity is 0.41 Mt.[21] Asphalt includes bitumen and aggregate, and usage is reported to be 3.5 Mt.[22] Finally, miscellaneous and other materials were assumed to comprise 5% of the total construction materials. These new production estimates are summarised in Table 1, yielding a total estimated material use of 114 Mt in South Africa's construction industry in 2017.

After the new production quantities have been estimated, the next step is to estimate the fraction of new construction materials that go directly to waste. This waste fraction is usually between 1% and 10% of new materials[1], and varies per material type based on various literature sources.[23-25] Table 1 lists the portions of new construction materials that are scrapped during the construction project.

The average of the other eight key materials was taken as the waste factor for miscellaneous and other materials.

Next, the amount of demolition waste needs to be determined. This is calculated from the material service life and average annual growth of the construction industry. The growth rate is based on the construction

GDP for South Africa and was estimated as an average 2.68% per annum[26] over the last 60 years, which is the oldest available data.

The stock life also varied per material type based on the literature.[6,27-29] Table 1 summarises the typical lifetime of each material. A sensitivity analysis on the lifetimes for concrete and bricks was done, as these materials make up the majority of the total waste, and their lifetimes have the biggest effect on the final result.

The amount of material used one lifetime ago is then calculated using an exponential growth formula shown in Equation 1 below, where Q_0 is the material used for construction one lifetime ago, Q is the new material used for construction today, r is the construction industry growth rate, and t is the material service life. This result translates to the amount of demolition waste produced today.

$$Q_0 = \frac{Q}{e^{rt}}$$

Equation 1

Table 1: Summary of input variables for the material lifetime analysis

Material category	New construction materials in 2017 (Mt)	Construction waste factor (%)	Material service life (years)
Timber	3.32[8,9]	5[23,24]	50[27-29]
Glass	0.180[3,10]	1[25]	20[27,29]
Metal	1.23[11-15]	0[23-25]	75[28,29]
Concrete	52.7[11,16,17]	3[23-25]	75[28,29]
Masonry	46.1[17,18]	4[23,24]	75[28]
Plastic	0.405[19]	1[25]	50[29]
Gypsum	0.394[20,21]	10[23,24]	75[29]
Asphalt	3.50[22]	5[23,24]	20[27,29]
Other	5.82	4	–
Total	**114**	**100**	–

Method two: Per-capita multiplier

The second method is based on a scale-up of a pocket of reasonably good statistics for Cape Town's C&D waste, on a per-capita basis, while also considering likely differences in construction intensity between urban and rural populations, to determine totals for South Africa. This analysis is based on research done by McBean and Fortin[7]. For this method, only a final result for the total C&D waste quantity is obtained, and not the composition.

Radzilani[30] evaluated the quality of the IWMPs for the major metropolitan municipalities in South Africa. The study included 10 key categories as well as a number of important sub-categories. It was found that in terms of reporting, monitoring and review of waste and waste management practices, the City of Cape Town had the best-quality IWMP out of the eight that were analysed.

C&D waste generation in Cape Town is reported as 1.09 Mt.[4] In order to scale this figure up to the national level, the populations of Cape Town and South Africa need to be taken into account. The population of Cape Town in 2017 was estimated as 4.01 million, while the population of South Africa was estimated to be 55.6 million.[31] These figures can be used to determine the ratio of waste to population.

The per-capita ratio for Cape Town and other South African urban populations is assumed to be the same, but the fraction of urban and rural populations needs to be taken into account. It is estimated that 35.7% of the South African population lives in rural areas and 64.3% in urban areas.[32] In order to include the impact of both urban and rural populations, five times lower generation intensity of C&D waste is assumed for the rural population than the consumption reported for Cape Town. Therefore, the average citizen's annual building waste relative to Cape Town's is 71.4%. The total C&D waste generation can then be determined. A sensitivity analysis was done on the waste generation intensity of rural populations in relation to Cape Town.

Results and discussion

From the methods described, the final estimate of potential C&D waste generation in South Africa is 20.2 Mt for the material lifetime analysis method, while the final result for the per-capita multiplier method is 10.8 Mt. The first method allowed for the estimation of the composition of the waste, which is shown in Table 2. These results are much higher than the quantity of 4.48 Mt reported in official statistics.

Table 2: Summary of results for the material lifetime analysis

Material category	Construction waste estimate (Mt)	Demolition waste estimate (Mt)	Construction and demolition potential waste estimate (Mt)	Composition (%)
Timber	0.166	0.793	0.959	4.74.
Glass	0.00180	0.102	0.103	0.511
Metal	0	0.144	0.144	0.711
Concrete	1.58	6.16	7.74	38.2
Masonry	1.85	5.39	7.24	35.8
Plastic	0.00405	0.0968	0.101	0.498
Gypsum	0.0394	0.0460	0.0854	0.422
Asphalt	0.175	1.97	2.15	10.6
Other	0.211	1.51	1.72	8.49
Total	**4.02**	**16.2**	**20.2**	**100**

For the lifetime method, the final result was most influenced by the assumed service life of concrete and masonry. A sensitivity analysis was done in which the lifetimes of both were varied from 50 to 100 years, as this was the most common range given in the literature. The result of this uncertainty analysis can be seen in Figure 2, which shows that the higher the lifetime of both materials, the lower the quantity of C&D waste. The minimum value here is 14.3 Mt when both lifetimes are set at 100. The maximum value when both lifetimes are set at 50 years is 32.5 Mt.

In terms of the composition of C&D waste, the dominance of concrete (38%) and masonry (36%) items is consistent with the findings of Cochran and Townsend.[6] They also compared the total C&D waste estimate using long, typical and short service lives for the various materials. It was found that the total estimate increased with shorter service lives, and the short service life estimate was approximately double the estimate for long service lives. This is consistent with the findings in the sensitivity analysis shown in Figure 2.

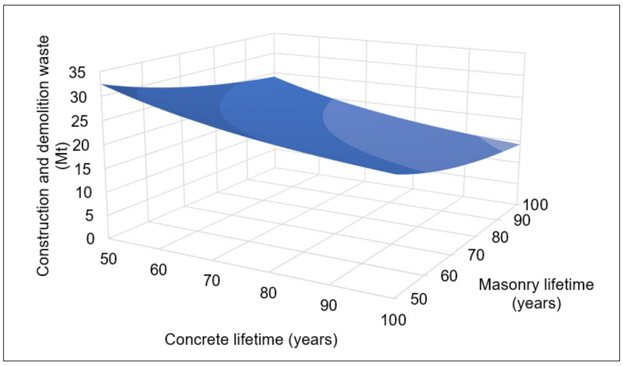

Figure 2: Sensitivity of the material lifetime analysis result to concrete and masonry lifetimes.

For the per-capita method, the C&D waste generation intensity of the rural population was varied from 0% to 50% of that of urban dwellers. The upper limit of 50% was chosen due to there being more commercial and office space in the cities, so there would be much less C&D waste arising in rural areas. It can be seen from Figure 3 that there is a linear relationship between rural waste generation intensity and C&D waste. This estimate for C&D waste generation in South Africa thus ranges from 9.74 Mt to 12.4 Mt.

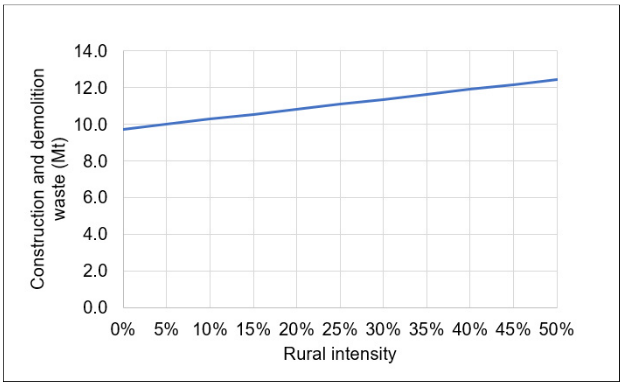

Figure 3: Sensitivity of the per-capita multiplier result to rural waste generation intensity.

The large gap between the results of both methods needs to be addressed. For the lifetime method, it is likely that this is an overestimate of actual C&D waste due to the potential hibernation of some end-of-life stocks. It is a common observation that there are remaining 'ghost stocks', or structures that have reached the end of their life but are not demolished. For the per-capita method, since this is a scale-up of official statistics, there is still the possibility of underreporting. This also excludes some informal waste management practices as well as some formal recycling. This can be better understood from the C&D waste value chain shown in Figure 4. The lifetime method gives an estimate of all the C&D waste leaving the construction or demolition site and includes a number of fates such as formal recycling, informal dumping, informal reuse and disposal to a landfill site. The quantities in the per-capita method are scaled-up from what was reportedly measured at the gates of Cape Town's disposal sites and what actually goes over the weighbridge, so a lower estimate is expected. This estimate would include the portion of informally dumped C&D waste that is collected by the city. The results of the two methods are thus not incompatible and indicate that of the 20 Mt per annum of total potential C&D waste, approximately 10 Mt per annum has fates including hibernation, formal and informal reuse, recycling or downcycling, while the other 10 Mt is likely disposed or used as cover material in landfill sites.

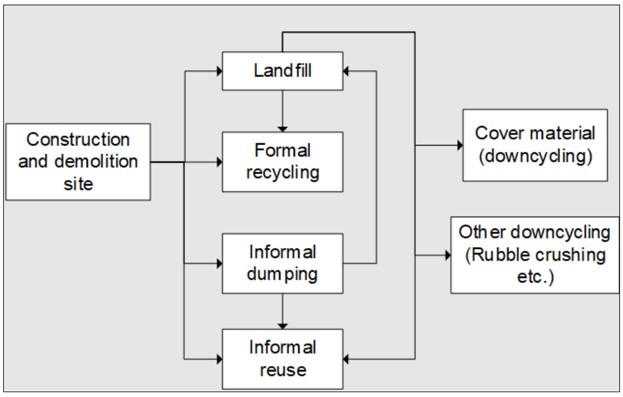

Figure 4: Construction and demolition waste value chain.

Conclusions

Two methods were used to estimate the quantity of C&D waste arising in South Africa. The first method involved a material lifetime analysis. New production quantities, waste factors and material service lives for key construction materials were used to estimate the total C&D waste generated in South Africa in 2017. The second method used a per-capita multiplier based on Cape Town's waste statistics and applied population data to scale up to a national estimate. The result for the first method was 20.2 Mt, but could range between 14.3 Mt and 32.5 Mt. The second method had a final result of 10.8 Mt with a potential range between 9.74 Mt and 12.4 Mt. The first result could be an overestimate due to the possibility of hibernation of end-of-life construction materials. The second method represents the portion likely to enter waste management facilities and could be an underestimate due to the omission of informal waste management practices from official statistics as well as the exclusion of some formal recycling practices that bypass municipal disposal. The results of both methods are significantly higher than the official national estimate of 4.48 Mt.

It is important to understand and accurately quantify C&D waste so that effective waste management can be implemented. Specifically, the reuse of C&D waste needs to be understood, as this takes precedence over recycling according to circular economy principles. Overall, this research highlights that C&D waste quantities in South Africa appear to be strongly underreported, undermining attempts to introduce more sustainable waste management practices.

In order to improve the accuracy of these results, further research into construction waste factors and material service life or other input parameters could be done in the South African context. The results could also be further validated by conducting site visits and utilising a direct measurement method. Other methods such as financial value extrapolation could also be used to validate the results.

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Competing interests

We have no competing interests to declare.

Authors' contributions

S.B.: Conceptualisation; methodology; data collection; data analysis; and writing. H.v.B.: Conceptualisation; methodology; writing – revisions; student supervision.

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What material flow analysis and life cycle assessment reveal about plastic polymer production and recycling in South Africa

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Global production and consumption of plastics have increased significantly in recent years. The environmental impacts associated with this trend have received growing attention internationally with single-use plastic packaging responsible for most plastic pollution. Locally, the SA Plastics Pact, the Industry Master Plan, and the National Waste Management Strategy all aim to transform the current linear sector model into a circular system by setting targets for increased collection and recycling rates and recycled content. However, the associated impacts of implementing such circular interventions have not yet been assessed across the plastics life cycle. Industrial ecology tools, material flow analysis and life cycle assessment, are used to generate mass-based indicators as well as indicators of climate damage in the form of the global warming potential. The carbon footprint of the South African plastics value chain from cradle to grave was estimated at 17.9 Mt CO_2eq emissions in 2018, with 52% of these due to the local coal-based monomer production process. The end-of-life stage lacks proper waste collection for a third of the population, but contributes only 2% to the total greenhouse gas emissions, with recycling having a minimal environmental impact. Future projections of plastics production, use, disposal, and recycling for 2025 show that increasing mechanical recycling rates to achieve stated targets would start to have a significant effect on virgin polymer demand (in the order of several billion rands of sales annually) but would also reduce waste disposal by 28% relative to baseline growth and 18% below values calculated for 2018.

Significance:

- Despite increased attention, the flows and resulting life cycle-based carbon footprint of the plastics sector have not been evaluated on a local scale.
- The carbon footprint of the South African plastics industry is sizeable at almost 18 Mt CO_2eq per annum with emissions strongly associated with the linear rather than the circular stages of the value chain.
- The impacts of a key circular economy intervention, namely increased recycling rates to achieve set targets include demand reduction for virgin polymer to the tune of several billion rands.

Introduction

Plastics play a crucial role in modern-day existence due to their unique properties of chemical resistance, durability, and low cost. As a result, plastic production globally has increased rapidly by 4% between 2010 and 2015.[1] However, historical and current levels of consumption and disposal have led to several environmental concerns. Approximately 4-8% of the world's oil and gas production is used as fossil fuel feedstock for plastics production, contributing to global greenhouse gas emissions.[2] Additionally, poor waste management of short-lived plastics, which are typically discarded or disposed of in landfills within a year of manufacture, has contributed to plastic pollution in the natural environment.

There have been various solutions proposed to tackle the issues associated with the plastics life cycle. The circular economy concept is described as 'an industrial economy that is restorative or regenerative by intention and design' which aims to replace the 'end-of-life' concept with restoration for the elimination of waste.[3] Aligned to the principles of the circular economy is the 'New Plastics Economy' which aims to deliver improved environmental and economic systems by dissociating from fossil-based input materials, reducing plastic leakage into the ecosphere, and creating an effective after-use plastics economy.[4] In line with this vision, The SA Plastics Pact has undertaken to transform the country's packaging sector by 2025, setting targets centred around the concepts of material reuse, recycling, and recovery.[5] The recently published extended producer responsibility (EPR) regulations also seek to set reuse, collection, and recycling targets as well as a mandatory percentage of recyclate content for various plastic products.[6] The aim of these two initiatives is to foster more closed-loop ad-hoc recycling applications which will translate into better recyclate quality to substitute virgin material.

Literature

The plastics industry in South Africa

The South African plastics industry is responsible for the conversion of over 1.8 million tons annually of both locally produced and imported polymer as well as recyclate.[7] In terms of end-of-life management, there is a large disparity in the provision of formal waste management services with just under 32% of South African households lacking access to basic refuse removal services.[8] Although recent plastic recycling surveys report high input recycling rates of over 40% for all plastics[9], only a small fraction of recyclate is a suitable substitute for virgin polymer[9]. The majority of recyclate currently produced is used in open-loop recycling, i.e. it is employed in lower value markets (bottles to pipes, bags, etc.) as opposed to closed-loop recycling (bottle-to-bottle). This is highlighted by the fact that there is only a single bottle-to-bottle recycling company operating in South Africa.[10] Furthermore, a fragmented waste management system leads to the disposal of a large proportion of post-consumer material into illegal dumps and unlicensed landfill sites which increases the potential of plastic leakage into the environment.

As the 32nd highest producer of plastics globally[11], the South African plastics industry forms one of the key segments of the local chemicals manufacturing sector. The production of monomers, namely ethylene and propylene, are by-products of the coal-to-liquids process employed by Sasol.[12] This process is recognised as a major emitter of carbon dioxide and plans are being developed to address this concern. In particular, the company's latest climate change report indicates their target of a 30% reduction of scope 1 and 2 emissions by 2030 with a view to achieving net-zero greenhouse gas (GHG) emissions by 2050.[13]

Industrial ecology tools

As waste management strategies evolve from disposal to recovery and reuse, indicators based on suitable tools are required to measure and monitor progress. Material flow analysis (MFA) – a tool used in resource and waste management – is defined as a systematic assessment of the flows and stocks of material within a system defined in space and time.[14] As a material accounting tool, it is used to compare inputs, accumulation, and outputs of a process on various levels. On the other hand, life cycle assessment (LCA) is an analytical assessment tool used to determine the potential environmental impact of a product or process through its life cycle.[15] The guidelines dictate that the assessment consists of four phases: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. Both methods of assessment can be combined in systems analysis as MFA can be considered a technique to obtain data required for the life cycle inventory.

There have been numerous MFAs conducted for plastics, on local and national scales, for countries in Asia and Europe. In Austria, consumption increased by 15% within a 10-year period[16] while the growth in India was projected to increase by a factor of six between 2000 and 2030[17]. Recently, Babayemi et al.[18] presented the first continental analysis of mass importation and consumption of polymers and plastics products in Africa, with the assessment highlighting a strong link between GDP and plastic consumption. In the case of South Africa, plastic MFAs have been commissioned by the Department of Environmental Affairs to determine issues plaguing the plastics sector as well as to provide guidance regarding policies to support sound end-of-life management.[19] Another joint research project has been published in which a local inventory of plastic flows was used to identify plastic pollution and leakage hotspots.[20] In both cases, the scope of the investigation differs, which results in a variation in the estimated quantities of waste generated and disposed of. The former included indirect plastic imports in their input flows which required knowledge of the plastic content of the product and the associated weight of primary and secondary plastic packaging. In terms of scope, the latter considered the use and leakage of plastics in sectors such as textiles, automotive, and electrical and electronics. Both studies highlighted the fact that there was a degree of uncertainty with respect to the estimation of certain flows due to data availability.

To minimise environmental impacts caused by plastic waste, LCAs have been conducted for national waste management systems. Results of Spanish and Austrian case studies indicate that mechanical recycling was the most favourable waste management option compared to disposal in landfills and incineration.[21,22] On a global scale, Zheng and Suh[23] evaluated projected life cycle GHG emissions for conventional and bio-based plastics. It was found that a combination of strategies (introducing renewable energy, increasing recycling, and curbing demand) could reduce future emissions. In Africa, LCA-based research is limited, with few studies focusing on the quantification of plastic-related impacts. In their ranking of waste management processes for municipalities in Africa, Friedrich and Trois[24] found the greatest GHG savings were achieved through recycling while the highest emissions were recorded for waste disposed of in landfills. Studies have also been conducted for carrier bags by Sevitz et al.[25] with updated research conducted by the Council for Scientific and Industrial Research (CSIR) incorporating additional impacts such as (materials) persistence, employment, and affordability[26]. Significant findings show that reusable fossil fuel-based plastic bags have lower environmental impacts than single-use carrier bags in all categories other than the persistence of plastics in the environment.

In this study, we aimed to firstly establish a baseline model to describe the status quo of the South African plastics sector in terms of material flows and their subsequent environmental impacts, and thereafter to explore the impacts of implementing a mitigation strategy, namely an increased mechanical recycling rate, to satisfy the aims of the SA Plastics Pact.

Methods

Material flow analysis

A mass balance was compiled that incorporated major process activities such as conversion, use, disposal, recycling, and trading for 2018. Figure 1 portrays the model showing relevant input and output flows.

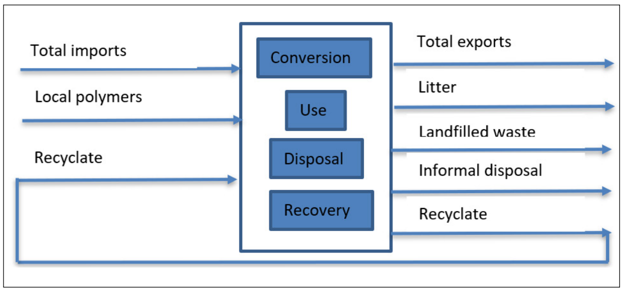

Figure 1: Inputs and output flows of the material flow analysis.

Information regarding total plastics production (local conversion of polymer into plastic products) was obtained from the annual recycling survey published by Plastics SA.[9] Imported polymers, products, and packaging as well as exported goods were included with data sourced from the South African Revenue Services (SARS) under tariff code 39. This refers to direct plastic imports and excludes products that contain plastic or are packaged in plastic and fall under another code, e.g. cosmetics or electronics. Imported recyclate was also considered under total imports. In terms of recovery, figures for recyclate were obtained from the annual South African plastics recycling survey with 2.2% of plastics recovered from the waste stream exported to be recycled internationally.[9] Informal disposal of waste represents the portion of plastic waste that remains uncollected and untreated via formal management processes and is typically discarded in open dumps with an estimated 60% burned.[27] Unlike other regions, South Africa does not implement waste incineration on a commercial scale. Landfill disposal is the standard employed, but not always to regulated standards. As a result, an estimated half of the formally disposed of waste ends up in what is termed 'deficient landfills'.

Life cycle assessment

Disaggregation of the total plastic flows obtained in the MFA was necessary to obtain individual polymer flows. The polymers considered include the six major polymers consumed in South Africa – low-density polyethylene, high-density polyethylene, polypropylene, polyethylene terephthalate, polyvinyl chloride, and polystyrene – as well as an additional category to represent other plastics. For import and export flows, data were sub-divided according to the description of SARS sub-tariff codes. Use, both short-lived and long-term, was divided according to a breakdown of domestic virgin polymer consumption provided in the Master Plan for Growth. Waste was disaggregated according to a municipal waste management plan which included a plastic characterisation study.[28]

SimaPro was utilised as the modelling software with most datasets sourced from the ecoinvent database. Where local data were unavailable, international datasets were modified with the inclusion of the local electricity mix. To accurately portray local polymer production, the South African dataset representing the Fischer–Tropsch synthesis process was incorporated into the model. Similarly, the end-of-life management scenario depicted in the MFA was modelled by constructing a disposal scenario to reflect accurate proportions of waste flows. The informal disposal term was described using a combination of disposal of plastic waste to an open dump as well as uncontrolled, open burning using a 40:60 split.[27] As there is no dataset which describes the presence of plastic litter, the discarding of waste in an open dump was used as a proxy dataset. The impact analysis was undertaken based on the single indicator of global warming potential with the impact assessment method selected as IPCC 2013.

Model of future flows

Flows depicted in the baseline model were projected to estimate future material flows. Based on the projected annual global demand growth rate of 4%/year, plastic flows were calculated for the year 2025. An additional scenario, using a 2%/year growth rate, was modelled to take into account the decrease in local plastic production from 2018 to 2019.[29] Thereafter, a mitigation strategy was modelled, and the changes analysed. In particular, the rate of mechanical recycling was increased to satisfy two of the objectives set by the SA Plastics Pact. This revolved around achieving a higher recycled content at 30% and an increased input recycling rate of 70%. To construct an initial future model, it was assumed that the production of local polymer would be constrained and would reach a maximum threshold based on nameplate capacities. This assumption is because there is a current shortage of ethylene monomer which limits the polymerisation of polyethylene and polypropylene copolymers.[7] The potential decline in liquid fuel use in the transport sector would also impact monomer supply resulting in reduced local polymer production.[30] This would entail that the balance of feedstock supply would be satisfied by importing polymers. Although the increased recycling rate would ensure higher collection of material for recycling, there would still be a significant quantity of waste for disposal. Due to the ongoing initiatives by Producer Responsibility Organisations, it is anticipated that waste generated from non-serviced households would decrease. A small fraction of waste would still be transported to sanitary landfill sites with the remainder discarded under deficient landfill conditions.

Results and discussion

Baseline model

Material flow analysis for 2018

The results for the MFA on an annual basis are displayed in Figure 2. The Sankey diagram depicts major inputs, outputs and activities for 2018, with quantities expressed in kilotons. Circularity is shown in the diagram in the form of the recycling loop with accumulation built into the model to account for build-up of stock within the system.

The quantity of polymer produced locally, which was calculated via a mass balance, was 20% less than the quantity of imported polymers. After the conversion process, domestic consumption was sub-divided into short-lived products and durables, with 40% of plastics locally produced embedded in long-lived applications.[9] Post-use, the amount collected for recycling excluded the non-plastic 'obsolete' material that is extracted when plastics are recovered from the waste stream and typically forms part of the collected material.[29] Results indicate that most of the waste is discarded via self-help disposal – a practice common amongst rural households and urban informal settlements – as well as through compliant and deficient landfills. The MFA findings also show that the amount of direct litter generated is relatively small. To evaluate the performance of the recovery and recycling loops, several mass-based indicators were calculated; the results are presented in Table 1. The input recycling rate, which is a commonly cited indicator and is defined as the percentage of collected plastic waste to short-lived waste, was calculated as 40.3%, which is comparable to the total EU plastic packaging recycling rate of 40.8% in 2016 (EU28 plus Norway and Switzerland).[31] The recycled content, which is an alternative circularity indicator and is calculated as the fraction of recyclate in total polymer converted into products, is 17.7%.

Table 1: Mass-based indicators based on material flow analysis for 2018

Indicator	Value (%)	Definitions
Collection rate	28.9	Collections / total waste
Input recycling rate	40.3	Collections / short-lived waste
Output recycling rate	30.9	Recyclate (local and exported) / short-lived waste
Recycled content	17.7	Used recyclate / total production

Life cycle assessment for 2018

The results for a life cycle-based carbon footprint are presented in Figure 3. The inner ring represents the total GHG emissions to produce plastic products consumed in South Africa, exported products, and imported products as well as end-of-life management of local plastic goods post-consumer use. The outer ring expands on the production process by showing the distribution of impacts between polymer production, conversion, and end-of-life impacts. The latter are partitioned to illustrate individual impacts for littering, recycling, and disposal.

The LCA revealed that the South African plastics industry was responsible for emitting 17.9 Mt CO_2eq over its life cycle. This amount is equivalent to 3.8% of the total emissions for South Africa in 2018 and is greater than the annual emission load for several entire country emissions, e.g. Kenya or Slovenia.[32] From the graph, it is evident that the production process (comprising both polymer production and conversion) is responsible for most of the burdens in comparison to the end-of-life management process. This is mainly due to the local production of monomers (propylene and ethylene) from coal which is responsible for 52% of the total climate impact. This result is validated by LCA studies[33] that verify the emission-intensive nature of coal-based monomer production pathways. Figure 3 also shows the significance

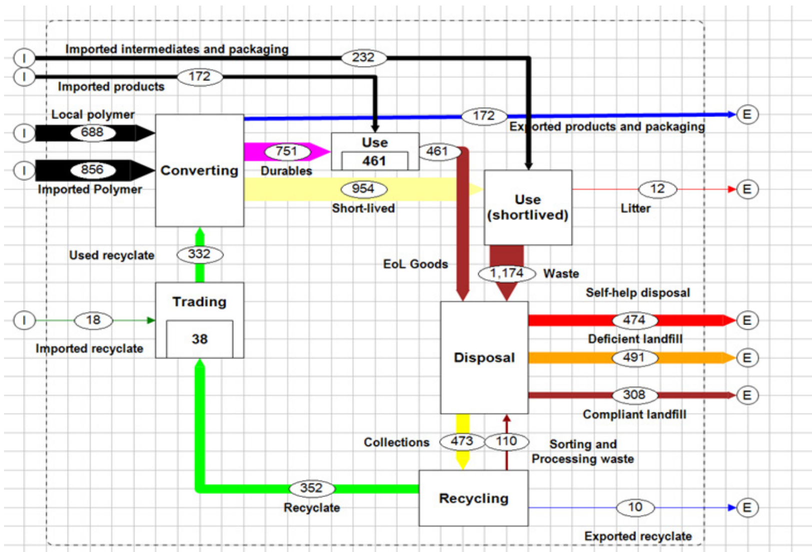

Figure 2: Sankey diagram depicting results of material flow analysis of plastics in South Africa for 2018.

of the local conversion process, contributing to 17% of the total climate impact with emissions attributed to electricity produced by the country's energy grid. The end-of-life stage makes a very small contribution, within which the disposal process accounts for the majority of climate impacts which is ascribed to the burning of plastic waste that generally occurs at some homes or at dump sites.

Model of future flows

Annual flows of plastics produced, consumed, disposed of and recycled were projected for 2025 for three scenarios. Table 2 shows the business-as-usual models with a 2% and 4% annual growth rate (Scenarios 1 and 2), as well as calculated flows for the case of increased mechanical recycling (achieving the targeted input recycling rate of 70% and recycled content of 30%) as a mitigation strategy (Scenario 3).

A comparison of Scenarios 1 and 3 indicates that increasing the recycling rate would increase the quantity of recyclate available by 241 kt, which would consequentially decrease the need for virgin polymer by the same amount. This is shown in Table 2 to be entirely at the expense of lower imports, but this reduced demand relative to a 'no recycling growth situation' might have a significant economic impact on both local polymer production and imports. An analysis of the custom's value of imported polymers in 2018 estimates that the potential reduction in the quantity of imports would result in a loss in the order of four to six billion rands. This highlights the fact that, at some stage, ambitious pursuits of circularity would inevitably impact business models built on linearity.

For 2018, the per capita plastic consumption of 36 kg/year is within the 34–52 kg/year range estimated in a previous MFA for 2015.[19] As anticipated, the quantity of plastics produced would increase from 1876 kt to 2155 kt and 2469 kt, respectively, under the two business-as-usual future models for 2025 with no intervention. This increase in production would lead to a projected increase in plastic consumption over the 7-year period to a maximum of 43 kg/capita/annum as per Scenario 2. Although this is significantly higher than the annual per capita consumption for Africa of 16 kg in 2015[18], it is still lower than the historical average plastics consumption in other regions such as China and Latin America[34]. Table 2 also shows that an increased consumption of plastics would cause the total waste generated to exceed 2000 kt in 2025 if production increased at an annual growth rate of 4% per annum. In addition to the increased availability of recyclate, a higher recycling rate (Scenario 3) would also significantly decrease waste directed to landfills, by 28% relative to the business-as-usual baseline model, and even to levels 18% below those modelled for 2018 despite a 2% increase in the annual production rate.

Conclusions and recommendations

To establish material flows and subsequent impacts arising from the plastic industry in South Africa, a combination of an MFA and an LCA

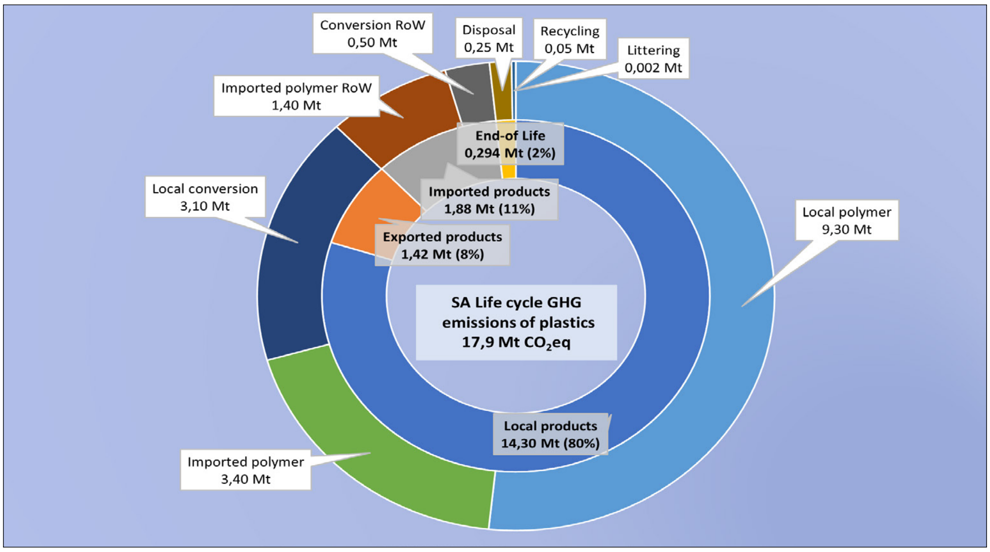

Figure 3: Estimate of the life cycle-based carbon footprint of plastics in South Africa for 2018.

Table 2: Projected flows in the South African plastics value chain for 2025

Indicators	Units	Baseline model 2018	Scenario 1 BAU (2%) 2025	Scenario 2 BAU (4%) 2025	Scenario 3 Increased recycling (2%) 2025
Production					
Local polymer	kt	688	928	994	928
Imported polymer	kt	856	821	1010	580
Recyclate	kt	332	406	465	647
Total plastics produced	kt	1876	2155	2469	2155
Use					
Plastic consumption	kt	2108	2379	2726	2379
Plastic consumption	kg/capita/annum	36	38	43	38
Waste					
Waste generation	kt	1635	1846	2115	1846
Waste sent to landfill	kt	799	907	1039	658

BAU, business-as-usual

was utilised. Results indicate that, although recycling rates are higher than for other countries, a large quantity of waste is still disposed of via regulated and deficient landfills as well as self-help methods. The LCA revealed the total carbon footprint as 17.9 Mt CO_2eq with local monomer production and energy use in converting identified as the major contributing factors. A model of future flows indicates that mitigation strategies, such as an increased mechanical recycling rate, have the capacity to significantly reduce virgin polymer demand as well as waste directed to landfill. This is anticipated to have a positive environmental impact on the total emissions generated by the local plastics value chain, although economic implications would also need to be considered.

To avoid burden-shifting, it is recommended that the environmental analysis be expanded to include additional indicators related to ecotoxicity and acidification. Furthermore, other circular economy strategies – such as demand management and reuse, integration of bio-based plastics as well as decarbonisation of the energy system – would need to be evaluated to determine the optimum combination of strategies.

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Competing interests

We have no competing interests to declare.

Authors' contributions

T.G.: Conceptualisation; methodology; data collection and analysis; writing – initial draft. K.H.: Conceptualisation; student supervision. V.R.: Data analysis; student supervision. H.v.B.: Conceptualisation; student supervision.

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Reasons for littering: Social constructions from lower income communities in South Africa

Littering has been defined as the careless and improper disposal of small amounts of waste that results in unwanted and unnatural elements remaining in the environment. People tend to blame external factors for their own littering. A person seldom refers to themselves as being the litterer but will rather place the blame on insufficient infrastructure, such as lack of bins, or on other persons. When referring to other people, they identify problematic behaviour and personal traits such as ignorance, naivety, need for convenience, laziness and inattentiveness as causes of littering. This study addressed the gap in the literature on the socially constructed perceptions people hold about reasons for littering in the South African context, as subjectively perceived reasons for littering may correspond with actual causes and could point towards options for tackling the littering problem. Five lower socio-economic areas in South Africa – particularly those that experience major infrastructural challenges – were included in the study. Qualitative semi-structured interviews were held with 322 residents from the respective areas. The data were thematically analysed and the results from the areas compared with each other. The cross-case analysis confirmed that littering is contingent on contextual effects, and unique reasons for littering in the South African context were mentioned. The research reported on in this study highlights that we have only thematically 'identified' or named the socially constructed perceptions about the reasons for littering by the participants. The importance of creating platforms and processes for dialogues to deepen our understanding of people's socially constructed perceptions and subsequent behaviour, is of critical importance.

Significance:

- This study presents subjective or self-reported perceptions of people living in lower socio-economic areas on the reasons for littering and dumping.
- These perceptions about reasons for littering then provide directions for possible interventions to manage and curb littering in the South African context.

Introduction

In a recent study in South Africa, Ryan et al.[1] assessed the prevalence of litter during the 5-week COVID-19 hard lockdown period in 2020. Ryan et al.[1] highlighted the reduction of street litter in two of the cities as a result of less movement due to COVID-19 restrictions. This finding was to be expected, but the authors reiterate that it necessitates a focus on humans as the predominant cause of litter and consequently the need for strategies centred on human behaviour to curb littering.[1] As Ryan et al.[1] point out, the predominant cause of street litter is inappropriate waste disposal practices. Therefore, studies on litter need to not only address differences in the prevalence of litter between what Rutz et al.[2] term the 'anthropause' and periods of normal human activity, but also the root causes of this disposal practice. Rutz et al.[2(p.1156)], building on the common term 'Great Pause' used with reference to the lockdown period during the COVID-19 pandemic, suggested the term 'anthropause' 'to refer specifically to a considerable global slowing of modern human activities, notably travel'.

Littering has been defined as the careless and improper disposal of waste that results in unwanted and unnatural elements remaining in the environment.[3-5] Chaudhary et al.[6] accept the definition that litter is trash, discarded or scattered about in disorder over a socially inappropriate area. New forms of litter increasingly appear and have been linked to changing consumer patterns in terms of take-away food, the increase in unsolicited advertising materials[5] and the recent uptake of plastic personal protective equipment during the pandemic[7,8].

Van Doesum et al.[9] relate littering to either active or passive behaviour. Active littering behaviour is defined as the active placement of items in a space when departing, while passive behaviour refers to leaving items behind in a space either intentionally or unintentionally. Personal traits such as laziness, as well as lack of vigilance by municipal authorities, lack of infrastructure such as litter bins in streets, and imitation are given as the main reasons for littering.[3,10-12] Rodríguez-Rodríguez[12], investigating litter in protected areas of the Autonomous Region of Madrid[13-15], also mention deficient environmental consciousness and urban origin as further causal factors. The presence of litter can also increase littering.[3,16-18] This causal relationship is related to the influential 'broken windows' theory that provides disorder cues in neighbourhoods that trigger littering and antisocial behaviour.[19] However, Volker[19] indicated that the effect of these cues is not as pronounced as originally postulated and that neighbourhood and individual characteristics play a moderating role.

Al-Khatib et al.[5] emphasise a lack of social pressure in terms of litter prevention, the absence of 'realistic penalties or consistent enforcement, social rebellion, and lack of knowledge of the environmental effects of littering'. Poorly designed packaging of commercial products, the amount of litter at a particular location, the presence and wording of littering signs, and the number, placement and appearance of waste disposal bins also contribute to littering.[5]

In a systematic review by Chaudhary et al.[6] only 70 scientific peer-reviewed articles on research that sought to understand littering behaviour globally, could be sourced. Only a few factors that influence and are useful in reducing littering behaviour were identified. Chaudhary et al.[6] regard the results as 'equivocal'. They highlight that most (53) of the 70 articles included in their systematic review were from developed countries while only 13 research studies were published from eight developing countries.[6]African studies are almost non-existent. Chaudhary et al.[6] also emphasised the fact that no qualitative studies had been conducted in developing countries to determine reasons for littering. The research in developing countries is regarded as still in its exploratory phase.

Research has further shown that behaviour is based on perceptions of reality.[16,20] Therefore, the analysis of public perceptions of litter is important given the link between littering and individual behaviours[21], and understanding perceptions is one of the primary steps in developing comprehensive and sustainable anti-littering interventions[16,22]. As a starting point in the context of this study, it was therefore important to determine what residents perceive as, and how they construct the reasons for littering, before considering how perceptions and subsequent behaviour change can be facilitated.

In a study conducted in Switzerland by Hansmann and Steimer[10], it was found that people tend to blame external factors for their own littering. A person seldom refers to themselves as being the culprit but will rather place the blame on insufficient infrastructure such as lack of bins, or on other persons. Conversely, when referring to other people, they identify problematic behaviour and personal traits such as ignorance, naivety, need for convenience, laziness and inattentiveness as causes of littering.[10] Both Hansmann and Steimer[10] and Chaudhary et al.[6] point out that very few studies have been conducted to determine people's perceptions about reasons for littering. They regard this research gap as unfortunate 'because knowing more about the subjectively perceived reasons for littering seems crucial for understanding the cognitive and motivational processes to this problematic behaviour'[10]. They also propose that subjectively perceived and socially constructed reasons for littering may correspond with actual causes and could point to options for tackling the littering problem.

Building on Hansmann and Steimer[10] and Chaudhary et al.[6], the aim of this study was to explore the socially constructed reasons for littering in the South African context. Globally, very few studies have been conducted on understanding littering behaviour. The aim of these multiple case studies was to contribute to the literature on the correlation between littering and human activity. Our research focused specifically on lower socio-economic townships in South Africa that experience, amongst other issues, major infrastructural and service delivery challenges. This study delineates community-specific perceptions concerning the reasons for littering as a starting point for generating strategies to reduce its impact.

Theoretical framework

In their systematic review of 70 articles written on litter and littering behaviour, Chaudhary et al.[6] concluded that there is a lack of the use of theories when studying littering, in particular in the studies from developing countries. In this study, we used the theory of social constructionism. It is a theory of knowledge built on the premise that reality is constructed within a socio-economic, political and cultural context.[23-25] Social constructionism holds that no single objective perception of the world or reality is possible, but that social constructionism is how people make sense of the world. In 1967 the sociologists Berger and Luckman[26] introduced the concept of social constructionism. They argued that people, interacting with each other, over time create concepts or mental representations of each other's and their own actions.[23] In referring to these mental representations, the mathematician Alfred Korzybski commented that 'the map is not the territory'. We only have maps of the territory; we will never know the territory.[24] In summary: knowledge and people's perceptions/constructions and belief systems of what reality is, become embedded in the institutional fabric of society. Reality is not seen as objective truth waiting to be uncovered but as multiple realities and meanings continuously created in changing social contexts.[23]

The following premises are the foundation of social constructionism:

- How we understand the world is the product of historical, social, political and cultural sense making processes of interaction between people, which means that realities are constructed collectively – the map is not the territory but perceptions or constructions of the territory.
- The identity of the person or constructs of the self and emotions are formed in interaction with other people – they are not intrinsic to the person but produced in social discourses.[23,24,27]
- Language, an aspect that is fundamental to the process of knowledge production, is not used to describe and represent the world or reality. Instead, realities are constructed through language. Language gains its meaning from its use in context.[28]
- Furthermore, realities are created through language and meaning making.[24] Meaning is not a property of the objects and events themselves, but a social construction. Meaning is the product of the prevailing cultural frame of social, linguistic, discursive and symbolic practice.[28.]
- Social constructionism views research not as the production of knowledge that is fixed and universally valid, but holds that research can open up new perspectives, constructions and new possibilities.[23.]
- From a social constructionist perspective, change is seen as creating and co-creating new or different perceptions and meanings which will open up new possibilities through participatory processes and within non-hierarchical relationships.[24,25]

Study settings

Four townships (characterised by lower socio-economic status) and one rural village were included in the study. All selected areas were characterised by high unemployment and grant dependency. The townships were selected based on differences in waste management service delivery. Descriptions of the study areas and reasons for their inclusion are provided below:

- Drakenstein Municipality, where Paarl East and Mbekweni are situated, is a well-functioning municipality with regular consistent weekly waste management practices. Drakenstein Municipality was recognised as being the cleanest and greenest municipality in the Western Cape Province in 2019.[29]
- Calvinia, situated in the Northern Cape Province, has regular household waste removal but does not provide bins or bags to assist in household waste collection.
- Philippolis in the Free State Province used to have regular waste removal but, due to bad financial management, services are currently irregular and in some instances are managed by the community themselves. Waste removal depends on the availability of a functioning vehicle. No bins or bags are provided to the households to assist with waste removal.
- Matshelapata, under the City of Polokwane in Limpopo Province, does not have any form of waste removal service.

Paarl East and Mbekweni townships

Paarl East and Mbekweni are located in the Drakenstein Local Municipality, which is regarded as a secondary city and encompasses the towns of Gouda, Paarl, Saron and Wellington. Paarl and Wellington are the two major economic hubs in this municipal area.

The municipality has a population of 305 281, which includes 74 230 households and 41 informal settlements. The municipality governs a total of 33 wards. In terms of service delivery, 37 848 households (just over 50%) have access to refuse removal, 68 956 to sanitation, and 68 956 to piped water.[30]

Mbekweni Township has been demarcated as Ward 12 of Drakenstein Municipality. Mbekweni was initially developed as a black African residential township.[31] Subsequently, it provided a legal area of residence for black Africans when the Western Cape was classified as a coloured labour preference area in 1955 under the apartheid government.[31] Census data from 2011 still reflect a population that predominantly mirrors apartheid demographics, with 97% of the residents reported as black African.[31] A large part of the population are first-generation urban residents, migrants hailing from the Eastern Cape.[31] The township has high levels of unemployment, with limited economic opportunities and prevalent social problems.[31] Barry and Whittal[31] point out that conflict between state institutions and local residents of the area has a long history connected with resistance against apartheid. The conflict has continued and found expression in protests, for example in relation to housing.[31]

Paarl East

Paarl East is a predominantly coloured community and 82% of the residents live in formal Reconstruction and Development Programme houses with backyard dwellers. Only 41% are formally employed and 38.4% are grant dependent. Paarl East is also known for crime and gangster activities.[32]

Philippolis

Philippolis is the oldest town in the Free State Province in South Africa.[33] It forms part of the Kopanong Local Municipality, along with eight other small towns.[33] Kopanong Municipality ranks as the most sparsely populated municipal area in the province and has been a municipal area of dire governmental concern in terms of financial viability for the past two decades.[33]

With regard to municipal services, data from 2011 listed the percentage of flush toilets connected to sewerage at 82.1% for Kopanong Municipality and 80.5% for Philippolis; 46.7% for piped water inside dwellings in Kopanong Municipality and 74.5% for Philippolis; and weekly refuse removal at 76.5% for Kopanong Municipality and 99% for Philippolis. The current Integrated Development Plan for the greater Kopanong Municipality states that all households have '100% access to refuse removal'[34]. However, this statement is qualified with reference to waste removal challenges:

> [S]*ometimes the municipality could not adhere to weekly refuse removal schedules in some of its towns or wards due to ageing yellow fleet and its constant mechanical breakdowns – notwithstanding the fact that most of the yellow fleet is not appropriate for waste removal.*[34]

Recent media reports confirm that Philippolis, along with other Karoo towns, are challenged in terms of service delivery.[35] Consequently, local communities have attempted to deal with water provision, waste management and recycling issues themselves.[35] Residents from Philippolis have conducted waste dumpsite clean-ups and also cleaned the entrances of the town.[35] At the time of the study, due to Kopanong Municipality's non-payment of their water bill to Bloemwater (the major water provider), households only had access to water for a few hours per day.

Calvinia

Calvinia, which forms part of the Hantam Local Municipality, is about 400 km from the large urban centres of Cape Town, Springbok and Upington. The 2011 census recorded a population of 9680, and the town had 2509 households with an average household size of 4 members.[36] The percentage of formal dwellings was recorded at 97%. In terms of service delivery, 80.5% had flush toilets connected to sewerage, 65.2% had access to piped water inside dwellings, and 97.4% received weekly refuse removal.

The coloured township Calvinia-West formed part of the study.

Matshelapata

Matshelapata is a small village in Mentz located 70 km from Polokwane, the capital of Limpopo Province. The residents are black African and mostly Sepedi speaking. No waste management services are delivered to the village. Although the community has access to piped water, during our visit, water was delivered to the houses by a truck due to the drought in the area. In addition to the political ward councillor, the village is still under the traditional rule of an *Nduna* and a Chief.[37]

Table 1 provides a summary of waste management services rendered in the selected areas.

Table 1: Summary of the townships studied

Name of Category B Local Municipality	Focus areas	Level of waste management service rendered (2019–2021)
Drakenstein	Mbekweni and Paarl East	Weekly door-to-door waste collection by the municipality. Daily mini drop-off waste collection by the municipality.
Hantam	Calvinia West, Calvinia	Weekly door-to-door waste collection by the municipality.
Kopanong	Poding-tse-Rolo and Bergmanshoogte, Philippolis	Weekly door-to-door waste collection by municipal workers and trucks, if and when available, alternatively by local residents. Collection services funded by the Philippolis Concerned Citizens group as a result of bankrupt municipality.
Polokwane	Matshelapata	No waste collection services rendered by the municipality.

Methodology

Building on the theory of social constructionism, qualitative cross-sectional studies were completed in the aforementioned four townships and rural village (Matshelapata). The studies were part of the DSI/CSIR-funded Clean City/Town project which seeks to gain an understanding of how people make meaning of the reasons for littering in these towns. Multiple mixed methods were used to collect data. The research was approved by the Humanities and Social Sciences Research and Ethics Committee of the University of the Western Cape (HS19/5/5). In this article, we report on only one of the datasets collected.

In Drakenstein Municipality, data were collected in the townships Mbekweni and Paarl East. In Mbekweni, 40 semi-structured interviews were completed by students from the University of the Western Cape. In Paarl East, 91 interviews were completed by three members of the community. Community members were recruited as a result of concerns raised by the municipality about the safety of students due to high crime levels and gangster presence. The councillor of the area assisted in selecting three unemployed women from the area who had easy access to the community and who would be able to navigate the research process. The fieldwork also provided an income to the three fieldworkers, which created credibility and acceptance of the research process in the community.

In Calvinia, three unemployed community members were recruited with the assistance of the official responsible for the Extended Public Works Programme's (EPWP) database of unemployed individuals. Three men were recruited, and together they completed 73 interviews.

In Philippolis, eight young unemployed community members (seven women and one man) were recruited to conduct 70 interviews. The fieldworkers collectively covered Bergmanshoogte, consisting mostly of coloured Afrikaans-speaking residents, and Poding-Tse-Rolo, which is a predominantly black, Sesotho-speaking community. The fieldworkers were recruited through one of the teacher assistants in the local school who was in close contact with the unemployed youth.

In Matshelapata, students from the University of Limpopo, which is close to the community of interest, completed 48 interviews. These students can speak the local language, Sepedi.

The students and community members were well trained to approach participants, obtain consent and conduct the interviews. In an interactive workshop session, they were allowed to practise the semi-structured questionnaires with each other. The fieldworkers worked in pairs – one conducted the interview and the other captured the answers given by the participants on the questionnaires, using the words of the participant. We are aware that this way of capturing some answers might be selective and biased. Working in pairs attempted to curb these biases. The fact that the same themes appeared for all selected areas supports the validity of the results.

In total, 322 semi-structured interviews were conducted. Braun and Clarke's[38] six stage thematic analysis was used to analyse the data. The six stages consist of: familiarising of data; generating of the initial codes; searching for the themes; reviewing the themes; defining and naming the themes; and producing the report.

We captured the answers from the questionnaires in a single document. Each township and the village's answers were captured and analysed separately, and then compared with each other. Capturing the data from each area already allowed for familiarisation with the data. Then we colour coded the data and identified and named the themes. Some of the themes could immediately be linked to the literature and a few unique South African themes emerged, as will be described in the following section.

Findings

Themes on reasons for littering

Firstly, Table 2 presents a summary of the themes identified in each of the selected areas. Theme 1 (Value systems and personality traits), Theme 3 (Non-caring government), Theme 4 (Lack of infrastructure and resources), and Theme 6 (Lack of education/awareness) appeared in all five research areas. Theme 2 (No respect and care for self, others and the environment) was regarded as a reason for littering in all areas except for Paarl East. Theme 5 (Littering and dumping leads to job creation) emerged in four areas (Matshelapata, Philippolis, Calvinia and Mbekweni). Each theme will be briefly discussed.

Theme 1: Value systems and personality traits

Oguntayo et al.[39] define the personality of a person as individual differences and an enduring characteristic pattern of thinking, feeling and reasoning that leads to behaviour. The American psychologist Carl Rogers views behaviour as intentional and determined or constructed by a person's emotions, thoughts, experiences, perceptions and locus of control.[40] As indicated, social constructionism views the identity of the person as a construct of the self, formed in interaction with other people – it is not intrinsic to the person but produced in social interaction and discourses.

In all townships, littering was constructed as emanating from personality traits and as being part of the value and normative system of the person. The question asked was 'Why do people litter?', not 'Why do you litter?' It was therefore easy for the people to ascribe the personality traits to other people. Freije et al.[41] cautioned against asking participants whether they litter, as the majority of participants in Freije et al.'s study in Bahrain denied that they littered.

In the current study, participants identified constructs such as laziness ('because they are too lazy to use rubbish bins'; 'People are lazy and don't want to be clean'), ignorance ('… ignorance and not wanting to take responsibility for their waste'), naivety, ('nevermindedness') and habit ('… like at home that's how they act in other places too') as reasons for littering. Upbringing and 'It's a lifestyle' were mentioned. 'You eat chips and cooldrink not near a bin so you just throw in the streets. If you are not clean and tidy in your own house you will not be clean outside. I like cleanliness outside and inside.' In Paarl East and Mbekweni, blame for littering and dumping was attributed to 'those from the rural areas' (of the Eastern Cape and/or foreigners). 'People are lazy and don't want to be clean.' Given the previously described historical context of Mbekweni, the other townships are more homogeneous and the local people are less exposed to the influx of migrants and in-migrants.

Both Govender and Reddy[42] and Salvia et al.[43] confirm the constructions of similar value systems and personality traits of those who litter.[44-46] Chaudhary et al.[6] identified five stages of litter research in developed countries. The period from 2001 to 2010 is referred to as the time when the focus of the research was on factors associated with littering such as values, religion, culture and gender, with no conclusive results. However, Ojedokun and Balogun[4] emphasise traits such as altruism and locus of control as anti-litter personality traits. Locus of control refers to a psychological concept indicating how strongly people believe they can take control over the situations and experiences that affect their lives. From a behavioural theoretical perspective, Singh and Kaur[47] identified self-efficacy as an anti-litter trait. Self-efficacy refers to the belief in one's ability to succeed. The stronger the internal locus of control and experience of self-efficacy, the less likely the person will be to litter as they take responsibility for their own behaviour.

What is significant from the results of Ojedokun and Balogun[4] and Singh and Kaur[47] is that the socially constructed belief of a person in themself and their abilities will facilitate the person to take responsibility for their own behaviour and actions, including towards the environment.[46]

Theme 2: Those who litter have no respect and care for self, others and the environment

This theme confirms the results by Ojedokun and Balogun[4] and Singh and Kaur[47] (mentioned in the previous discussion) that people with a disregard for self, others and the environment will take less responsibility for their own environment – the responsibility will be assigned to other persons or institutions. In this study, participants highlighted the following traits as reasons for littering: 'They have no self-respect for themselves and other people'; 'They do not care about the environment'; 'They do not care about the community.'

The non-caring behaviour is also ascribed to '… being raised badly. Not raised properly at home. Neverminded attitude. It looks right to us but actually it's very wrong.' A participant confirmed that littering is due to '… no discipline. No respect. Because we don't think.' One participant

Table 2: Thematic analysis of reasons for littering, by area

Themes	Matshelapata	Mbekweni	Paarl East	Philippolis (Bergmanshoogte and Poding-Tse-Rolo)	Calvinia
Theme.1: Value systems and personality traits	X	X	X	X	X
Theme 2: No respect and care for self, others and the environment	X	X		X	X
Theme 3: Experiences of a non-caring government	X	X	X	X	X
Theme 4 Lack of infrastructure and resources	X	X	X	X	X
Theme 5: Littering and dumping leads to job creation	X	X		X	X
Theme 6: Lack of education and awareness	X	X	X	X	X

then also explained the notion of internal locus of control and self-efficacy in her own behaviour:

> *I have a rubbish bin at home so I keep everything in my pocket until I reach home. We have to keep our town clean. People have no discipline at their homes. Need to care.*

In addition, the lack of caring for self, others (the community) and the environment is also constructed as a result of experiences of a non-caring community or context: 'People litter simply because they see other people don't care; they just throw their litter in the streets.' This view links with the broken window theory: 'People litter sometimes because the area is already dirty and they just add on to the dirty place'; 'People don't respect [town's name]'; '… because they find the place already littered so they think that there is no need to bother looking for bins.'

The comments reflecting non-caring relate to the lack of social cohesiveness in the communities. Manca[48] defined social cohesion as connectedness and solidarity among groups in society. Socially cohesive communities provide a sense of belonging and caring to community members. The non-caring attitudes can also relate to socially disorganised communities due to structural poverty, vulnerability and the historical, political and economic landscape of South Africa.[48-50.]

In Philippolis and Calvinia, the absence of community collaboration and cohesion was constructed as a reason for littering: 'They litter because they don't encourage each other not to. They don't understand how important it is to keep the streets clean.' The importance of socially cohesive families and communities was confirmed by Cherng et al.[51] who found that communities that are not cohesive do not work together and encourage each other to take responsibility for their environment. Participants emphasised the urgency for cohesion in communities in order to create cleaner, dignified environments as a collective.

Theme 3: Experiences of a non-caring government

The non-caring constructed theme continues in the participants' reported experiences of a government (local and national) that lacks care for their residents: 'Honestly, I couldn't care less [about the litter]. The South African government doesn't take their citizens seriously'; 'Some people already decided that there is nothing good left for them because the municipality is corrupt and so they will keep on littering.' This attitude was explained as deliberate: 'They [residents] are spiteful ('aspris')'; 'At times they are spiteful – even if they stand next to the bin they will still throw it [the litter] on the ground.' It was explained that people litter '…because they can'; 'People litter because some of them just want to.'

'They [the municipality] don't have facilities. They don't care about the community'; 'All the bins are broken'; 'People litter because municipality don't collect waste'. This theme also emerged in the study with train and taxi commuters.[44,46] The failure of service delivery in South Africa is further evident, as Botes[52] explains, in the increase in service delivery protests. According to Botes[52], in 2018, two million people per year were taking to the streets to protest against the lack of service delivery, authoritarian governance and political decisions and non-responsive governance. In the 2020/2021 Auditor-General South Africa (AGSA) report on municipalities[53], only 16% of the municipalities received clean audits. Interestingly, by the time of the publication of the report from AGSA[53], the Kopanong Municipality (under which Philippolis, Bergmanshoogte and Poding Tse Rolo reside) had not even submitted their financial statements. Botes[52] is of the opinion that it is in fact the poor people who suffer the most as a result and that the protests are an attempt for freedom and human dignity. Some of the participants also argue that littering and dumping are part of the broader systemic issues in the communities such as overcrowding, crime, vandalism, unemployment and general unhappiness with service delivery: '… because so many people are living together on one stand and there are not enough bins'; 'Our people love to vandalise. They do get the needed facilities but then it is stolen'; 'Some people steal the dustbins'; 'People are unemployed'; 'The dustbins are stolen and burnt'; 'Governmental problems, unemployment problems'; '… because there are no jobs.'

Green[54] emphasises that competence, fairness and care are the three main elements for a government to be regarded as legitimate and be taken seriously. Political interference and corruption should be eliminated. The provision of appropriate infrastructure is a sign of engaged and caring service delivery. We support Kalina's[49] viewpoint that 'if we want to safeguard the environment and create cleaner communities, the poverty, unemployment and inequalities must take centre stage'. Kalina[49] further argues that waste management studies have yet to effectively acknowledge the systemic and structural inequality, crime, poverty and unemployment in South Africa. Only then will research on societal issues in waste be meaningful.[49]

The lack of service delivery and experiences of a non-caring government were therefore evident in the lack of provision of sufficient waste infrastructure and resources, as described next.

Theme 4: Absence of infrastructure, resources and waste removal

Sotamenou et al.[55] and Salvia et al.[43] found that people's waste behaviour in Cameroon and Kisumu, Kenya, respectively, was determined by the disposal resources and alternatives available to them. Similarly, the lack of sufficient and appropriate receptacles and resources or waste infrastructure was noted as a reason for littering in all five townships involved in the current study: 'There are no dustbins here at the shops'; 'I think it's the lack of proper facilities because street vendors even opt to use card-boxes as bins'; 'Lack of dustbins around. When there are no dustbins near, a person can litter because they want to get rid of the waste they're carrying especially when they have just finished eating.'

Also, a shortage of cleaning staff was construed as part of the problem: 'Because there aren't enough cleaners or facilities for waste disposal available.' This issue was confirmed by Philippolis participants who commented: 'They [the municipality] can't afford to buy facilities'; 'Not enough resources for waste. They don't have facilities at all.' At Philippolis, residents referred to stray animals causing litter in the streets. Due to the late or non-collection by the municipality and lack of appropriate facilities, dogs and pigs get to the bags first: 'The municipality don't collect waste. People don't have enough facilities and they use old maize meal bags and you find out dogs and pigs tear the bags.'

Theme 5: Littering and dumping leads to job creation

Littering was mentioned as a motivation for job creation in Calvinia, Mbekweni and Matshelapata: 'People litter because they think it is a way for them to create jobs for others.' The following comment by a resident from Matshelapata was interesting: 'We are black and a black child will always want to give another person a job.'

A participant in Matshelapata expressed the following view: 'I think that democratic rights has been well explained to people because people use this (to) act literally and they end up thinking that when they litter, many jobs would be opened because the municipality would see (the) need to hire more waste pickers.'

A slightly different perspective was raised in Philippolis (where the municipality is not functioning): 'The municipality should hire us to do the work as they [Kopanong Municipality] are not doing their work'; and 'The municipality should give our children the work as they don't do their work.'

Although the waste management system in Philippolis was not functioning, the municipality employs a number of EPWP workers to clean the streets. Similarly, in Calvinia, there were very active EPWP and community development worker programmes to keep the streets of Calvinia clean. Participants from these two communities believed that residents abdicate responsibility for a clean environment because someone will eventually clean up: 'The problem lies with the people that likes to live like this and expect the municipality to clean'; 'Spiteful, because they know there are people who clean after them and that they [the cleaners] get paid.'

Studies by Freije et al.[41] in Bahrain and by Salvia et al.[43] in Kisumu (Kenya) are the only studies that also refer to littering as an act of job and income creation. In the studies by Schenck et al.[44-46] among street vendors, train commuters, taxi drivers and taxi commuters in South Africa, the same theme of job creation came to light.

Theme 6: Lack of education and awareness

In their systematic review, Chaudhary et al.[6] identified one of the phases of littering research during the period 1991–2000 in the USA as the education and awareness phase to curb littering behaviour. They concluded that raising awareness and education are important, but that these aspects should be seen in the context of the real-life world of each community. It is one of the aspects that needs attention to address wicked waste problems.[43,45]

In all townships except Calvinia, littering was ascribed to the fact that people are not 'waste wise'[48] or not aware of the consequences of littering, or that they have not been educated and raised not to litter: 'Some people are negligent and others lack education and awareness about a clean environment'. Concerns were raised about the youth and children not being disciplined and taught by their parents: '[It is] children that are not taught to be respectful to throw litter in bins'; The parents do not teach their children not to litter'; 'You as parent have to teach the child. Neatness and cleanliness come from the parent.'

Suggestions for improvement

The participants also added suggestions for improvements to the current waste management practices. The thematic suggestions were clearly based on the reasons constructed in the previous section, as discussed below.

Suggestion 1: Ensure the provision of services and sufficient and appropriate facilities and waste infrastructure

To assist residents to manage waste and prevent littering, appropriate and accessible infrastructure is needed.[6,43] Participants requested regular refuse removal, and bags and bins for those areas that do not receive them. Although Mbekweni and Paarl East households receive bins and bags, backyard dwellers have to do without these amenities, therefore they requested that they be given the required receptacles. Comments included: 'Collect waste on time'; 'I think if backyard dwellers and informal settlements got their own reusable bins and more green projects in wards'; 'Collect the waste weekly'; 'Provide bins and bags'; 'Provide skips'; 'Waste managers must always make sure that bins get emptied on time.'

Diligent service delivery and the provision of services and infrastructure are seen as evidence that the authorities do in fact care and that participants are not left alone with managing their own waste[46] over and above all the other aspects of poverty such as lack of housing, proper roads, water, electricity and sanitation. This echoes a statement by a participant in the study by Salvia et al.[43] that 'waste management is not for the poor – but for the rich'.

Suggestion 2: Establish collaboration with and within the communities

Suggestions were made for collaboration between the municipality and the community towards a cleaner environment. Residents do not only see area cleaning as a municipal responsibility but an opportunity for community engagement: 'We as the residents of this place can help to keep this town clean'; 'Organise workshops to keep clean. Get people to talk about it. Schools teach children'; 'Appoint people to keep their own areas clean.' Residents from Calvinia commented: 'Community and municipality for service'; 'Train a team to monitor the cleanliness of the town', and 'Community groups must be made responsible for cleaning the town.'

The request for collaboration is an expression for the need for participation, for participants to have a voice which they seldom had in the past and currently have – a movement towards a stronger internal locus of control. Collaboration with each other and government can create a greater sense of social cohesion, respect and dignity and a sense of care from the authorities.

Suggestion 3: Create income in the community

One of the major suggestions made by the participants was to utilise the potential for income generation. This suggestion is clearly a socially constructed need in the context of high levels of local unemployment, insufficient waste management and the need for a cleaner environment. Ideas included: 'Create jobs in waste removal. If the community clean the areas themselves, they will not litter where they have cleaned'; 'Municipality can hire local people to clean the town each and every day'; 'They can put people in positions to work in certain areas. To work and people will benefit from it'; 'Projects for recycling of waste.'

Discussion and recommendations

In this study, we explored the perceptions of the residents in four townships and a village in South Africa on littering. The socially constructed themes that emerged and that coincide with the globally identified themes are the absence of bins and waste infrastructure; the lack of education and awareness, personal traits and value systems of individuals; and the broken windows theory (litter creates litter).[6,15]

Uniquely socially constructed themes, linked to the South African context, are that littering has the intention to create income opportunities due to the high levels of poverty and unemployment in South Africa; that littering is an indication of the lack of respect and care for each other, the community and the environment; that it highlights the perception that littering is due to the lack of socially cohesive and collaborating communities; and that it is seen as a response to and manifestation of the lack of service delivery and care from the corrupt and non-caring government.

Important are the suggestions constructed by the participants – which confirm reasons put forward in the international literature – that are related to requests for proper and appropriate infrastructure and collaboration within the community and with the municipality towards finding solutions, income opportunities, and education and awareness.[43] Both the reasons and the subsequent constructive suggestions reflect the deep structural, systemic inequalities and marginalisation that exist in the South African context, which is evident in the (lack of) past and current waste management in the townships. The lack of sufficient and appropriate waste management adds to the daily struggle in these lower-income communities.[52]

Nkwocha and Okeoma[56] are of the view that littering is 'a brutal expression of loss of hope among urban dwellers' whose behaviour may be a reaction against authorities. Also, Brennan and Portman[57], in their study on fisher's perceptions of marine litter, came to the conclusion that 'until the relationships between local people and various governing institutions are transformed, there is little hope for citizen cooperation to reduce (marine) litter'. Salvia et al.[43] and Schenck et al.[45] further highlight the complex wicked nature of waste management which needs systemic, complex and process orientated approaches. Kalina[49], Botes[52] and Du Toit[58] direct our engagement towards systemic socio-economic and socio-political conditions that created, and continue to create, our waste problems. At the local level, the proposals of Medina[59] and Gutberlet[60] link well with the participants' suggestions. Waste management in developing countries needs decentralised, low-cost, labour-intensive, collaborative solutions that provide income and reduce poverty and inequality.[59,60]

Both Salvia et al.[43] and Schultz et al.[61] suggest that littering needs to be studied within the unique setting, region and culture of the place where it occurs[61] and that such studies should include an understanding of the socially constructed drivers of littering[43] to devise measures tailored to particular circumstances. Brennan and Portman[57] developed a tick-box guide (Figure 1) to assist policymakers and practitioners when co-creating new possibilities with the relevant affected communities. Brennan and Portman[57] suggested these tick-box guidelines to ensure that all elements for sustainable interventions are co-designed.

The perceived reasons given by the township residents who were interviewed and their ensuing suggestions provide us with directions to initiate further research and start facilitating dialogues regarding how

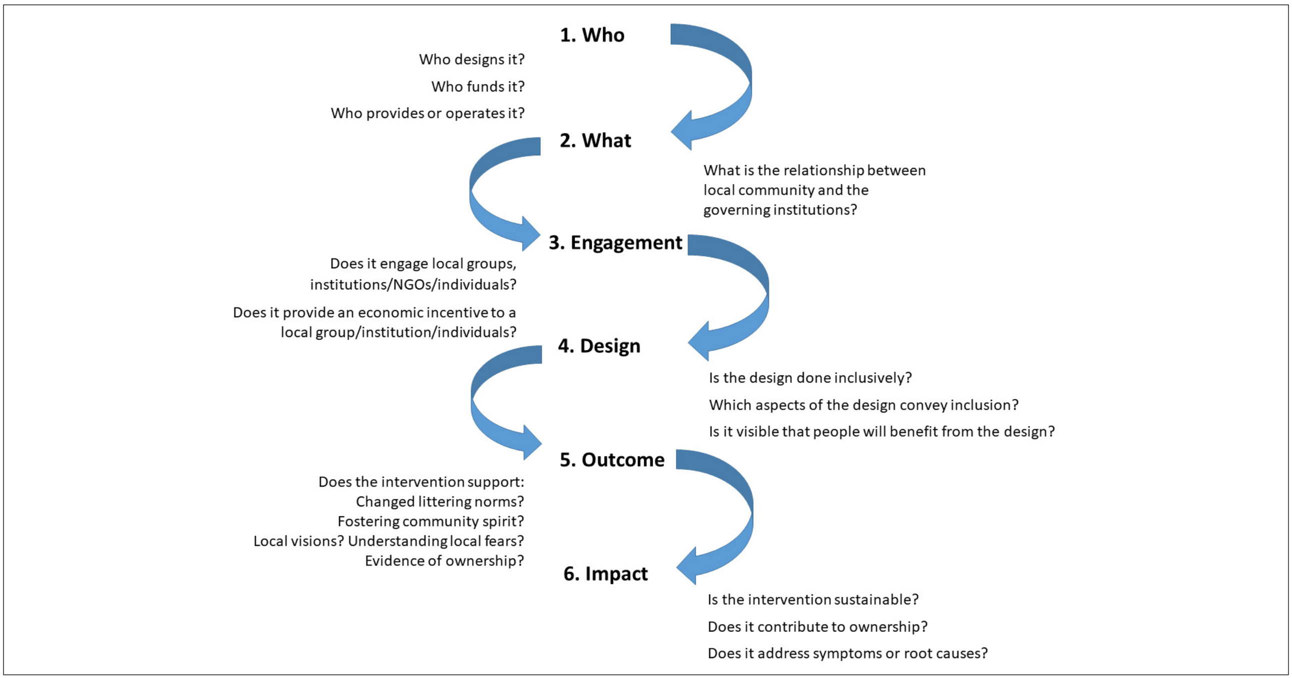

Figure 1: Brennan and Portman's six-stage checklist designed to assess the potential effectiveness of litter interventions in a local context.

waste and waste management can be socially co-constructed and co-managed to the benefit of residents, stakeholders and the environment.

The question that now remains is: how should we facilitate and co-create collaborative change to complex wicked problems? Change from a social constructionist perspective is seen as creating and co-creating unique new/different constructions and meanings through dialogue which will open up new possibilities through ongoing local participatory processes in non-hierarchical relationships[24,25] with all stakeholders involved, where the focus is on the potential of multiple local realities that can be co-constructed[62,63]. Dialogues provide a space for conversation that invites participants to bring in a multiplicity of voices and the co-creation of new realities, meanings and possibilities for action. These dialogues or linguistic events should focus on competencies and strengths, and instead of summaries and conclusions, they should focus on inclusive and rich descriptions and multiple possibilities.

Recommendations for further research from a social constructionist perspective will then include creating a series of participatory dialogical opportunities in the communities to:

- Facilitate the sharing of knowledge, stories, perceptions and meanings attached to waste and waste management in the community and their perceived reasons for littering. Critical reflection on or deconstruction of, for example, each socially constructed reason for littering – such as littering creates jobs or is a lack of education and awareness, or an act against a non-caring government – should be facilitated.
- Co-construct new meanings about waste, littering and waste management as well as opportunities towards collaboration, possible income generation and effective and appropriate service delivery, responsibility and accountability.
- Facilitate processes of what Biggs et al.[64] refer to as adaptive co-management where small co-created incremental changes are made, reflected on, and adapted if and where necessary. It develops and takes shape as experience is gained.[65]

Qualitative appreciative research methods such as participatory, creative, and visual activities can facilitate the dialogical co-construction, deconstruction and meaning-making processes through methods such as group discussions, co-design workshops, photo voice, videos, transect walks and mapping exercises.[65]

The research reported on in this study highlights that we have only thematically ‘identified’ or named the socially constructed perceptions about the reasons for littering by the participants. The importance of creating platforms and processes for dialogues to deepen our understanding of people's socially constructed perceptions and subsequent behaviour, is of critical importance.

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Competing interests

We have no competing interests to declare.

Authors' contributions

C.S.: Principal investigator; conceptualisation; main author; data collection. L.G.: Co-author; critical reader; data collection. D.B.: Critical reader; data collection. C.M.N.: Critical reader; data collection.

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Exploring community perceptions of illegal dumping in Fisantekraal using participatory action research

We present the results from two interactive methodologies (interview and focus groups) that were used as part of a participatory action research (PAR) project to identify the reasons for and solutions to illegal dumping in Fisantekraal, Cape Town, South Africa. Worldwide, PAR has been applied in the context of marginalised groups and in different fields to stimulate dialogue amongst research participants, with the ultimate goal of promoting social change. The opinions expressed by the research participants (community members, NGOs, municipal officials, academics) demonstrate that the voices of the community matter and illustrate the transformative potential of the PAR methodology to change the status of stakeholder engagement in decisionmaking regarding a pressing concern such as illegal dumping in community. The research discussed here led to some planning of initiatives and to planned change because the conversations/interviews/focus groups at least allowed people to come together to discuss possibilities. It helped the community and other stakeholders to come together and share their views of the problem and to plan together for what could work to curb illegal dumping. Community projects were subsequently initiated, and their impact will be evaluated in future research.

Significance:

- This study shows the potential of the PAR process to facilitate conversations about a particular issue between various stakeholders in a community where effective communication is challenging. The inclusivity of PAR allows for the voices of marginalised communities to be heard and allows people to take ownership of an issue in their community, such as illegal dumping.

Introduction

Indiscriminate or illegal dumping, called flytipping in the UK, is a vast challenge faced by cities and municipalities globally[1-3], particularly in developing countries[4-7]. Low percentages of waste collection imply high incidences of littering, illegal dumping and burning of waste.[6,8] Brandt[3], Lynch et al.[9], Siegmunt[10] and Crofts et al.[11] all cite social disorganisation status as one of the major reasons for illegal dumping[12,13].

The 2019 General Household Survey by Statistics South Africa[14] shows that refuse removal declined from 65.74% in 2016 to 58.8% in 2019. More people must now rely on their own mode of waste management. The failure to achieve waste management targets is caused by a lack of commitment by stakeholders such as municipalities[15], the misuse of financial resources[16] and the selection of inappropriate methods or technologies to deal with the problem[17-20].

Godfrey and Oelofse[21] state that South Africa is known for having sound waste management legislation and policies, although practical implementation of these policies remains an issue. In order to achieve most of the desired waste management goals, successful collaboration and common understanding between stakeholders will be necessary.[15] Niyobuhungiro and Schenck's[22] research clearly shows that single and topdown solutions to illegal dumping are not effective.

One possible response to the problem of illegal dumping lies in the application of participatory action research (PAR) as a form of generating practical knowledge and solutions through engagement with all stakeholders.[23] Here we describe the PAR process utilised in Fisantekraal (Ward 105 of Cape Town Municipality) in search of possible solutions to illegal dumping with the community members of Fisantekraal.

Background

PAR as a method for social mobilisation

Although many have contributed to different PAR approaches[23-26], PAR has two main origins. Firstly, it can be traced back to the work of Kurt Lewin, who is considered to be the founder of action research.[25] His philosophy was that people, particularly the marginalised in society, would be more motivated about their work if they were involved in the decision-making process about how their workplace was run. Lewin's original idea was summarised in a cycle of steps which includes observing, reflecting, acting, evaluating and modifying (Figure 1).

The second origin of PAR emerged in the 1970s from the work of Paulo Freire, a Brazilian adult educator. Freire viewed PAR as a tool to enable marginalised members of society to enact social change through the pedagogy of problem formulation, creation, self-awareness and critical reflection.[23,27] Hope and Timmel[28] state that 'it is not participation when people just listen to the commands of those in authority and submissively do the donkey work involved'.

PAR and waste management

Globally, PAR has been used to facilitate dialogue amongst members of marginalised groups with the central goal of promoting social change.[20,23,25,29-31] Some studies show that traditional environmental education methods were largely unsuccessful at engendering environmentally friendly and sustainable practices and institutions, until the year 2000 when environmental educators became more aware of PAR.[32,33] PAR has been used in the management of natural resources[34-36], as well as in sustainable development[37-40]. Gutberlet et al.[20] report on the successful use of

PAR in community composting in order to reduce municipal solid waste management. This success particularly relates to the promotion of anti-littering and illegal dumping practices when all the stakeholders are centrally involved in the participatory research process.[40,41]

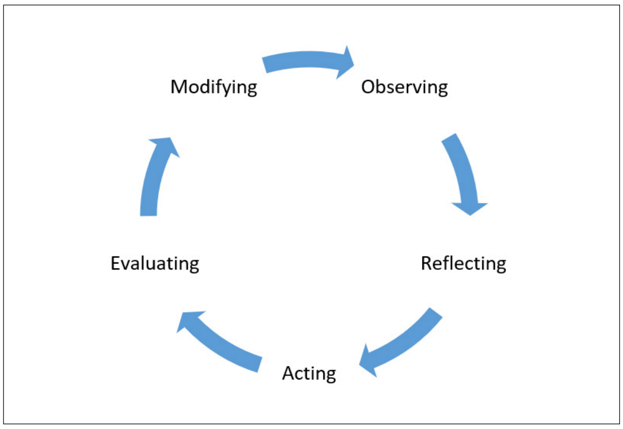

Figure 1: Lewin's cycle of participatory action research.[15]

This study builds on this literature by exploring the perceptions of both the community and the authorities with regard to illegal dumping, including the causes of and solutions to illegal dumping. To achieve the study objectives, we explored the opinions of the community, local government and other interested stakeholders. These opinions were gathered through interviews. This research was approved by the Humanities and Social Science Research Ethics Committee of the University of the Western Cape (reference number HS19/9/10).

The research was guided by the following questions:

- What are the main reasons for the illegal dumping of waste in Fisantekraal, Cape Town?
- What are the participants' perceptions with regard to the responsibility to prevent or clear illegal dumping in Fisantekraal, Cape Town?
- What are the best strategies to prevent illegal dumping in Fisantekraal, Cape Town?

Study setting

Fisantekraal is a suburb of the City of Cape Town that is surrounded by open space on one side and the Mosselbank River on the other. People regularly dump their waste in the area near the river, from where it gets blown by the wind into the river.

Fisantekraal is composed of three main areas (Figure 2):

- **Area A: Informal settlement/old Fisantekraal**

Area A is composed of two sides: one side consists of informal selfbuilt houses and the other side consists of lowcost social houses, the majority of which have at least three backyard dwellers on each plot.

- **Area B: Phase One**

Area B is also known as Phase One. The houses in Area B were constructed during the first phase of a low-cost housing scheme. In this area, the houses are formal and without backyard dwellers; the roads are paved and spacious.

- **Area C: Phase Two**

Area C is known as Phase Two. It has many of the same characteristics as Phase One, except that in this area there is still ongoing construction. The houses in this area are formal structures constructed as part of a low-cost housing scheme. The roads are wide and the municipality does weekly door-to-door waste collection.

Methodology

Nel et al.[31] explain that any systematic research process consists of five basic steps: deciding on the research question, designing the research method, collecting the data, analysing the data, and reporting the results. In participatory research, the members of the community participate as co-researchers in the five basic steps of the research process. Gaymans and Maskoen[42] assert that a study is more reliable when community members are coresearchers, as they have less difficulty establishing the needed relationships and are more likely to receive the full cooperation and trust of the people being surveyed.[23,42]

The study design was qualitative and included focus group discussions and interviews. The methodology consists of two main phases (Figure 3).The first phase comprised many steps, from entering the community to data sharing, and is discussed in detail below. The second phase is implementation, which is not reported on in the current article.

Phase 1: Exploring and describing the prevalence and dynamics of illegal dumping in Fisantekraal

The first phase consisted of exploring and describing the prevalence and dynamics of illegal dumping in Fisantekraal. This phase consists of three steps: (1) building relationships with the community, (2) data collection and analysis, (3) and results sharing (Figure 3).

Building relationships with the community and recruiting co-researchers

The first step in this phase is building relationships with the community and choosing the resident coresearchers.

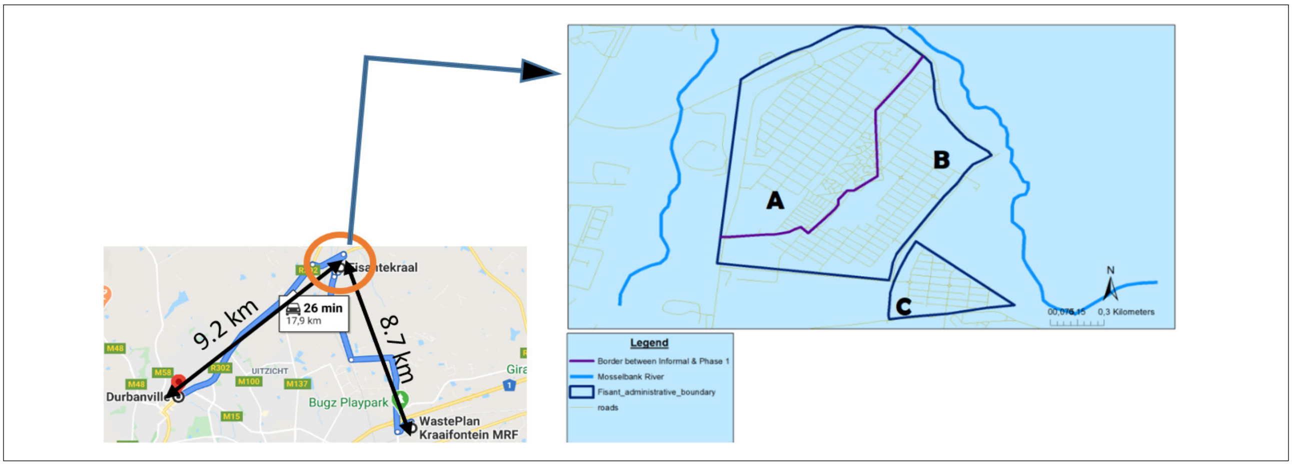

Figure 2: Fisantekraal boundaries.

According to Collins[43], before change can be enacted to alter a social situation, the situation must be well understood by all people involved. Relating to the current study, this suggests that the problem of illegal dumping must be well understood by all participants before possible solutions can be generated and implemented. A PAR network consisting of residents, researchers, local organisations and academic and government institutions was established by the first author. The purpose of the network was to design and carry out the study together.

The first author (R.N.) entered the Fisantekraal community to build relationships and networks by attending the monthly community meetings that took place on the first Friday of every month. The meetings were organised by the community development professional officer on behalf of the City of Cape Town. Permission to enter the community was negotiated at this meeting with the help of community members (the 'resident researchers' as referred to by Arcaya[30]). The researchers commenced data collection in May 2019 until the outbreak of COVID-19 in March 2020, when South Africa's national lockdown was implemented. Data collection resumed when COVID19 restrictions were eased and community visits were again allowed.

Seven resident researchers were recruited with the help of the community representatives who attended the monthly meetings. The resident researchers were well known in the community and had been or currently were community leaders, therefore they were familiar with most of the issues faced in the community, including illegal dumping. The recruitment was done by the first author (R.N.) in collaboration with NGOs, and local authorities.[30] The resident researchers were trained in conducting interviews prior to the commencement of interviews for data collection.

Data collection and analysis

The second step of the research consisted of data collection and analysis, which involves the identification and documentation of illegal dumpsites, individual interviews and focus groups. It subsequently involves planning and implementation of the changes and lessons learned in the first phase.

Before the interviews could commence, the first author (R.N.) toured the community with one of the resident researchers in order to identify possible illegal dumpsites.

The total number of research participants was 79 and included household members, community leaders, teachers and shop owners. Participants were interviewed on a voluntary basis after signing consent forms.[30] Participants also had to meet the following criteria: (1) be 18 years or older and (2) have lived in the area for at least 1 year.

Shamrova and Cummings[44] report that interviews and focus groups are the most common methodologies used in PAR studies. In this study, interviews and focus groups were both chosen due to their reported potential to validate each other.

To collect the data, semi-structured interview guides were developed. After testing the semi-structured interview guides with seven resident researchers, they were modified to include the suggestions from resident researchers. From 4 to 15 December 2019, the first author and resident researchers conducted the interviews in the three areas of Fisantekraal by going door to door. Observations and notetaking were also done during this process. Anonymity was respected and only pseudonyms were used.

On average, the interviews lasted 30 minutes each. All interviews were digitally recorded and later transcribed by a research assistant whose work was checked for consistency by the first author (R.N.).

In total, 79 individual interviews and two focus groups were conducted. The first focus group included six participants from the community while the second group had four participants: two from the local NGOs and two from the municipality. Although the size of the second focus group was small, which could be a limitation, the total number of interview participants in this study was substantial.

The focus group discussions commenced after the analysis of the individual interviews. Two separate groups were formed. The first group consisted of residents who were previously interviewed individually. The second group consisted of a group of informants such as members of NGOs and local authorities. The purpose of the focus groups was to explore possible information that was missed during individual interviews and to verify the individual interview responses.[28]

On 10 January 2020, the first group of nine residents from all the areas of Fisantekraal participated in the focus group. On 25 January 2020, the second group of four participants representing local NGOs, local authorities and academics participated in another focus group. With the consent of the participants, the focus groups were recorded, transcribed and analysed, as in the case of the individual interviews.

After the data were transcribed, they were exported into ATLAS.ti 8.1. for analysis. To aid this process, the results were shared with different audiences for review and interpretation in an iterative process that involved going back to the transcripts and recordings. Thereafter, data that shared common aspects were grouped together to form categories guided by the three main research questions. For each research question/category, a certain number of themes appeared and the link between them was also looked at. The categories are: reasons for illegal dumping, responsibility to clear illegal dumping, and strategies to prevent illegal dumping. Once all the data were categorised, they were then interpreted and triangulated with the findings from focus group discussions and interviews.

Triangulations helped in validating the qualitative data, together with the deep saturation of the responses from interviews as well as the focus group discussions. It is important to note that the data analysis and triangulations continued until after the data sharing because of the PAR process; as new information appears from stakeholders during feedback (validation), that information gets integrated into the existing data to improve the accuracy. This process (member checks) ensured the accuracy, validity and credibility of the data.

Results sharing

After analysing all the collected data, the results were shared with different stakeholders (community members, municipality officials and academics) for their feedback. Workshops were arranged for this purpose.

The first feedback session about the results from individual interviews was held on 21 January 2020 with academics from different disciplines to gather their input in order to shape the interpretation of the results. The feedback session had eight attendees. After incorporation of their feedback, the data collection, analysis and interpretation continued until it was time to share the results with the rest of the PAR participants.

The next feedback session was held on 10 March 2020. Two municipality officers attended this session. A meeting with the academics and the community was planned for April 2020. However, the national COVID19 lockdown was implemented before the meeting could occur. On 19 May 2020, a meeting with the ward officials was held in order to share the results of the study with them and to hear their opinions and guidance on the way forward in Fisantekraal. An online webinar for academics and other stakeholders was held on 22 May 2020; 42 people attended this webinar. The idea was to conclude with workshops in the community to communicate the findings of the research after incorporating the different stakeholders' feedback. When following a PAR approach, any change in policy or practice must be decided with the community before it can be implemented.[28,29] After the results were shared with stakeholders, the implementation phase followed.

Before any concrete steps were taken, they were discussed with the community in order to allow them to take the lead. The implementation phase took into consideration the recommendations from various meetings with stakeholders. It included community cleanups and establishment of a vegetable garden in order to curb illegal dumping by beautifying the area. A summary of the methodology is shown in Figure 3.

Results and discussion

The results and integrated discussion are structured according to the four main themes that emerged from the research questions: reasons for illegal dumping, responsibility to clear illegal dumping, solutions for illegal dumping, and strategies to sustainable solutions.

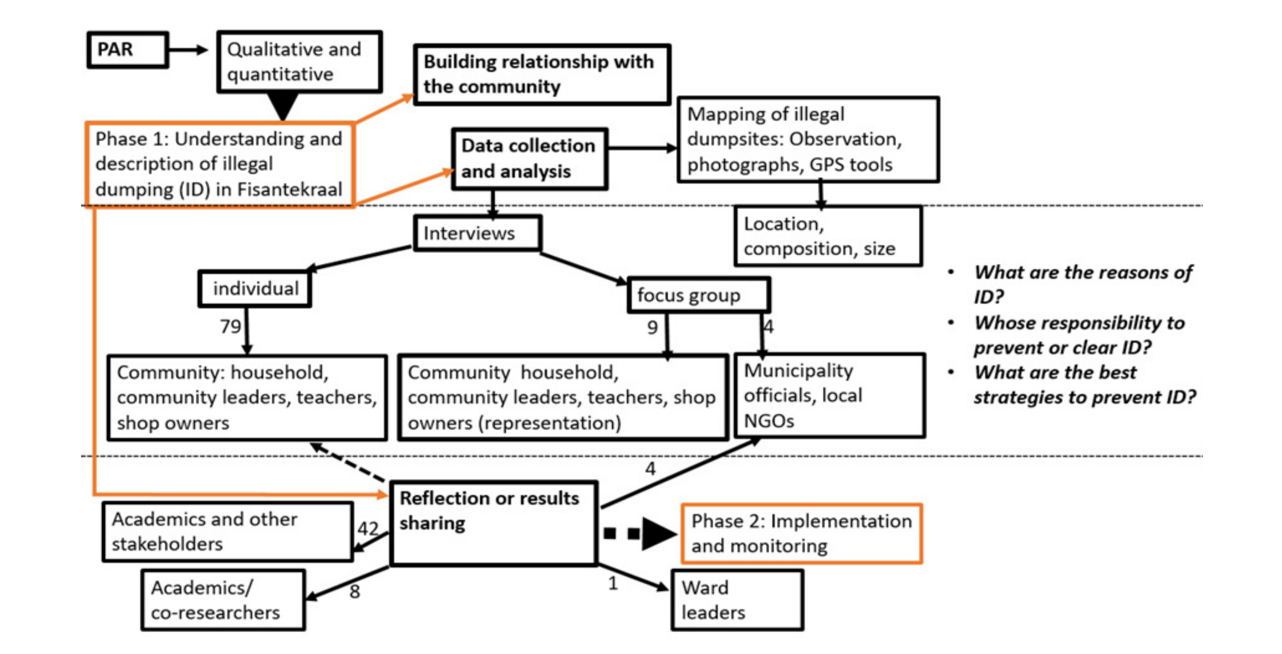

Figure 3: Schematic representation of the participatory action research (PAR) methodology.

The findings also reveal the potential connection and engagement among all the stakeholders as a result of PAR processes.

Reasons for illegal dumping

In both developed and developing countries, a lack of adequate waste facilities is one of the main reasons for illegal dumping.[5,17] In Fisantekraal, 32% of participants confirmed that a lack of containers (2 m x 3 m rectangular facility used for shared waste collection) caused people to dump their waste illegally, while 19% of the participants said this was due to the lack of bins (150-L black bins). 'The containers we have it's only people work for the municipality use it and lock it so we always find it locked then we throw the rubbish outside the container.' The statement above informs that the container is not for everyone, which implies that people in the community are not treated equally. As alluded to above (Study setting), due to the high density and poor road infrastructure of Area A in Fisantekraal, it is almost impossible to reach and provide services in this area, as in other areas (B and C). Another reason is the sharing of a bin between the backyard and the homeowner. This is seen by the community as a weakness on the part of the municipality; however, the municipality provides for the homeowner and not for the backyard dwellers. In the case of a container, the municipality appoints a volunteer in the community to look after it, i.e. locking and opening it. This means there are certain times that the container will remain closed as the people in charge often have other commitments. Those who come to dispose of waste when the container is closed have the impression that they are not allowed to use the container, which makes them look for an alternative, easy way to get rid of their waste, and hence dump it illegally.

Another participant from Area A said: 'There is so many people in this area and they share one bin.' This statement highlights the overpopulation reported in Area A. It further brings to light that the issue of illegal dumping cannot only be blamed on the lack of bins but may also be a result of the overcrowded living conditions in the area.

Not knowing what to do with certain waste streams was also cited as contributing to the practice of illegal dumping.[16,45] Some responses expressed that the plastic bags provided by the municipality do not accommodate heavy and bulky waste, for instance, which is why certain waste streams are dumped illegally. 'If we clean our yards then what do we do with the waste?' This comment refers to the fact that people did not know what to do with the garden waste from their yards as it cannot be put in black bags, so it gets dumped.

The community also cited unemployment as one of the reasons for illegal dumping. Unemployment is associated with an apathetic attitude, as described by Tunnell[46]. Unemployment leads to poverty and contributes to a feeling of apathy and futility among residents. Negative manifestations of apathy include a lack of will to ensure that neighbourhoods are not rendered unsightly by the dumping of waste. One participant said: 'We don't have places to stay, no jobs and also those employed to clean don't do their job.'

The inadequate and inappropriate waste collection was another reason given for illegal dumping. Although this is often blamed on local municipalities using trucks in areas where the roads are not passable[4], in Fisantekraal, it was blamed on residents who fail to put their bins out on the collection day. 'I think because some of the people are at work so they don't put bins out so that the truck can come and collect it, if they do so the bins get stolen.'

The focus groups with both the community and the municipal officials verified the information provided during the individual interviews[43], namely that there is a lack of bins in the area, but it was also added that bins are used for purposes other than waste storage. 'Bins are not used properly (sometimes no wheels), they are used for other things, beer, wood, toys…' Statements like this one alerted municipality officials to various reasons behind illegal dumping that they were not aware of. For instance, they began to learn that people in Fisantekraal felt treated unfairly or that black bags issued to residents are not sufficient for certain types of waste.

The responsibility to clear illegal dumping

Abel[47] is of the opinion that waste dumped on private land must be taken care of by the owner of the land, and waste dumped on public land is the responsibility of the municipality. However, as pointed out by Crofts et al.[11,48], this is also a question of environmental citizenship, where the community must be responsible for their actions and the consequences thereof regarding care of their environment.

In our study, 45% of research participants believed that it is the municipality's responsibility to clear illegal dumping, while 33% agreed that both the municipality and the community have a responsibility to clear illegal dumping. 'Municipal city of Cape Town, they must employ as many people as they can, to help out.'

Many participants were also of the opinion that illegal dumping creates jobs for others: 'People dump waste for street cleaners to get what to do.'

Other perceptions show that illegal dumping is an expression of dissatisfaction that the municipality employs people from other communities and not residents of Fisantekraal: 'Municipality is the one who give jobs to the people (who) don't stay in our community.'

The focus groups with officials and community members confirmed that the responsibility for illegal dumping is shared between the municipality and the community. This again implies some level of continued engagement between the two sides. This is evidenced in the following statements from both the officials and community, respectively: 'Since many services are free in the informal settlement, to change people's behaviour, perceptions some sort of ownership is necessary.' 'The City must employ us.' The above shows that the City needs to engage and monitor what happens in the community while the community also should be open to receiving requests from the municipality. This engagement can only be achieved through conversations in which real pressing issues are discussed and their respective solutions developed by both sides.

When the results were shared with different stakeholders, they also confirmed that engagement from both sides is crucial in allocating responsibilities.

Solutions to illegal dumping

Van den Bergh[49] and Whitmarsh et al.[45] confirm that there is no single solution to illegal dumping but rather multiple complementary solutions. Several solutions were suggested for Fisantekraal:

- **The provision of containers and bins**

Research participants stated: 'To put at all three areas the big containers for the different stuff e.g. plastics, gardening, household, etc.' Another stated: 'Set up a dumping area in the community or have more bins in each household. Have separate bins for recycled waste.' And: 'The container must be open at all times and [there] must be someone who is supervising that people throw their rubbish inside the container.'

These quotes show that there is a need for a common and bigger facility for, particularly, bulky waste and that the facility should be surveilled. In other words, someone should be employed to look after the facility.

In the focus groups, it was confirmed that bulky waste is one of the major waste problems which the communities cannot deal with and that the facility provided should be in the form of a skip that can accommodate bulky waste and which should be difficult to move for criminals, in order not to be stolen.

- **Issuing of fines**

Some research participants suggested introducing fines to prevent illegal dumping. However, if fines are lower than the cost of legal dumping, this solution will not be effective. 'I dump I get fined with R2 500, and it cost me R10 000 to formally dump, which one do I choose?'

Both individual and focus group interviews confirmed that if law enforcement is effective and fines are higher than the cost of a disposal fee, this solution would likely curb illegal dumping.

- **Education**

Education was also suggested as a possible solution to illegal dumping. Awareness campaigns should happen consistently and with the support of municipal officials and will aid the community to learn positive waste management practices through praxis.[25,27,29] For example, one participant asked, 'If we clean our yards then what do we do with the waste?' This statement suggests that the community is not yet educated about waste management practices and can still learn about reuse and recycling practices, as well as about income-generating opportunities, such as garden waste being turned into compost. The compost can then be sold or used in gardening.

Strategies to sustainable solutions

The participants differentiated solutions from strategies, arguing that strategies used to curb illegal dumping can sometimes become or translate into sustainable solutions. To attain a certain level of sustainability, the strategy should have the potential to change people's long-term behaviour with regard to illegal dumping. Figure 4 outlines the frequencies of suggested solutions to the issue of illegal dumping. It shows that the majority of participants proposed providing facilities (bins and containers) as solutions to illegal dumping (Figure 4a). The majority of participants also argued that education (Figure 4b) is not only a simple solution but a sustainable one as it will change people's perceptions in terms of recycling, reuse, etc.

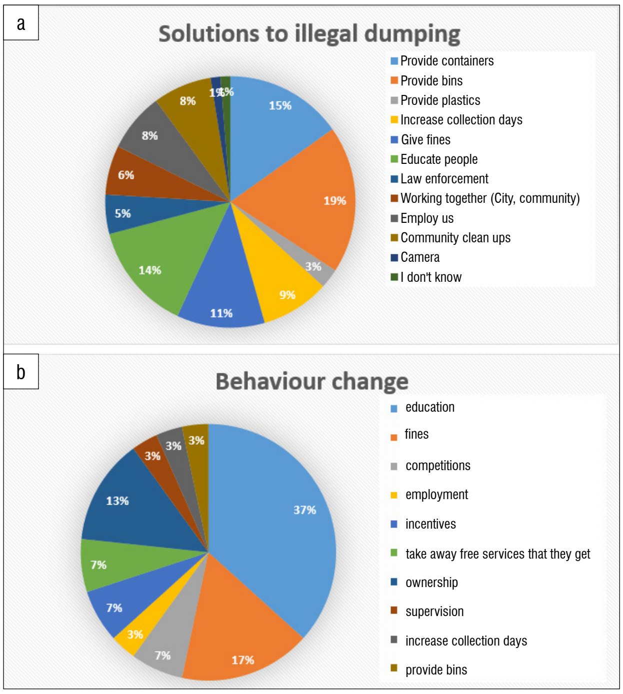

Figure 4: Comparative responses in regard to (a) solutions to illegal dumping and (b) strategies for behavioural change.

It is important that any solutions are arrived at through a knowledge-generation process by the community itself, as this will aid communities' self-awareness in defining which strategies and solutions can work best for them.[25,27]

It is important to note that the community's statements made the municipality realise that solutions have to be implemented with careful consideration of the community's expectations. It is therefore clear that the voices of the community, through the medium of participatory interviews, have the potential to influence important decisions if policymakers engage with the community.

Input and impact from results sharing

It is important to note that, although most of the suggestions given by the community have been reported to work in a few parts of the world as referenced, in Fisantekraal, this account can only be confirmed after the implementation stage (subsequent article).

In the meeting with the ward leaders on 19 May 2019 , it was confirmed that the community needs consistent reminders from law enforcement not to illegally dump their waste as well as surveillance of illegal dumping hotspots. They agreed that venues would be provided for meetings and workshops in order to teach the community about illegal dumping, as door-to-door campaigns are not effective.

During the feedback session on 21 January 2020, it was advised that it is important to determine not only the quantity of the waste but also the size of the dumpsites. A visit to the study area was then arranged to measure the size of the illegal dumps. This new information helped the community and other audiences to understand the extent of the land damage caused by illegal dumping.

The municipality officials learned, at the meeting held with them on 10 March 2020, that if people do not have bins, issuing them bins will not automatically solve the problem. Many participants stated that they do not put their bins out in fear of them getting stolen.

The municipality officers confirmed at this meeting that 'engagement' with the community could potentially lead to solutions to illegal dumping.

The fact that many community members had stated that they needed more bins and skips to accommodate bulky waste was also discussed at this meeting. It was suggested that the community should help to figure out how this would be implemented. A skip cannot just be put there. They must advise, for instance, who will look after the skips and for how many hours that person should work. This will create a spirit of ownership within the community and allow them to take responsibility for the cleanliness of their own space.

During the webinar with academics and other stakeholders held on 22 May 2020, the question was raised about why people assume they should be paid to keep their living space clean.

It was further suggested that the research team expand their data collection when sharing the results with the community. The expansion will include conducting in-depth interviews with a subset of participants, which will help the research move to a broadly descriptive theory based on descriptive answers.

This process would involve questioning research participants again and attempting to gain a deeper understanding of their answers. For instance, what exactly is meant by 'a lack of awareness'? Awareness of what? How much is this lack of awareness linked to dissatisfaction with government services? Could there be a wilful or performative element to this 'ignorance' that is in fact an expression of their dissatisfaction with government services?

After communicating all the feedback to them, the community displayed motivation to find solutions to their problems with or without the intervention and support of the authorities. This demonstrates the importance of this research project, because it has inspired the community to take ownership of their environment.

The first concrete action the community decided on was to start a vegetable garden in order to curb illegal dumping by beautifying the area and making the area functional. The vegetable garden was launched on 26 March 2021.

Conclusion

The interactive, collaborative and participatory approach applied in this study through PAR helped to acquire new knowledge[23] on the intersection between illegal dumping, environmental citizenship and employment. It also enhanced communication between the community, local government and other relevant and interested stakeholders on inclusive solid waste management.

It was expressed by various stakeholders that illegal dumping can be curbed if the community and the authorities support each other. The community expects that the City provides the same service as that offered in adjacent suburbs so that they do not feel left in the margin, while the City also expects the community to take responsibility for what is available.

This study revealed that communities participate in illegal dumping when they feel that they are left behind, or the authority does not care or cater for them. This makes them feel less useful and worthy and they ignore their responsibility to keep their space tidy. They leave all the responsibility to the authorities which in turn only work on a fixed schedule as they service area to area. This behaviour could not be interpreted and understood by either side until both parties were brought to the table and intentionally engaged on the issue.

In this study, engagement and conversation were revealed to be the channels through which the issue of illegal dumping and its contributory factors could be resolved.

The participatory interviews revealed the community's most pressing problems – such as poverty, unemployment, lack of housing (overpopulation) and exclusion – are associated with the occurrence of illegal dumping. For many community members, the problem of illegal dumping is, therefore, a concern but not a priority.

The PAR process used in this study facilitated the complementary engagement on illegal dumping between the community, academics, local government and other interested stakeholders.[23] Van den Bergh[49] emphasised that, for an environmental problem, a centralised discussion is not enough. Instead, there is a need for ongoing pressure, involvement and follow-ups and for different approaches and the inclusion of multiple stakeholders in this process.[49] It is therefore recommended that multiple avenues and spaces for engagement be considered when attempting to resolve societal problems. The methods presented here present a way of including multiple voices from stakeholders who are otherwise often left on the margins of their circumstances.

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Competing interests

We have no competing interests to declare.

Authors' contributions

R.V.N.: Conceptualisation; methodology; investigation; data collection; writing – original draft preparation; writing – reviewing and editing. C.J.S.: Conceptualisation; methodology; investigation; supervision; resources; writing – reviewing and editing.

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Waste as property: The law's role in maximising value

The concept of waste is explored against the background of the law of property. Drawing on the work of Eduardo Peñalver, this article addresses how waste is a form of property, property for which the law heavily regulates disposal. Conceptualising waste in such a manner is possible, as it is possible for property to have not only a positive value but also a negative value. How the law regulates the disposal of our unwanted property has important ramifications for the waste cycle. Restricting the disposal of waste can encourage practices such as recycling, and ensure waste is directed to the waste streams in which maximum value can be extracted therefrom. This contribution aims to illustrate the above through the example of mine waste, as the value of mine waste is context-sensitive. It is possible for this form of waste to take on a positive or a negative value, depending on context. Furthermore, it is crucial that such waste be adequately regulated, to ensure the extraction of maximum value, both economic and social.

Significance:

- Waste can be conceptualised as property, and the law strictly regulates the disposal of all forms of property. The law can play an important role in ensuring that maximum value is realised from waste.

Introduction

It is doubtful that the average person views the contents of their bin, or their bag of recycling, as their property. There certainly is no emotional attachment or sentimental feeling that makes one point to a soiled food container and say 'that is my property'. But one's lack of emotional attachment to or economic investment in property is of no interest to the law, which regulates ownership of our property, including determining the exact point at which such ownership can be said to begin and be terminated.[1,2] As far as the law is concerned, the food waste in your bin is as much your property as your laptop, and your ownership thereof can only terminate in the circumstances prescribed by law.

The concept of waste as property in respect of the value of waste is explored here. The paper addresses how the law, rather than empowering owners to dispose of unwanted property as they please, strictly regulates how property may be disposed of[3], from soiled food wrappers to obsolete electronics. In this respect, the law seeks to ensure waste achieves its maximum value. Maximum value is sought through reducing the negative value of waste that lacks the essential qualities necessary to be reclaimed, or through ensuring that waste is recycled and the valuable components thereof are used to their full potential.

First, the concept of value in the law of property, in particular the different kinds of values that property can accrue, is discussed. Of central concern is how property can come to accrue a negative value for its owner. Then, the law's strict regulation of how we may dispose of our property is explored, which is vital in ensuring the negative value of waste is reduced and any potential positive value is captured. Finally, the contextual nature of the value of waste is discussed, with a particular focus on mine waste.

Property, value and disposal of waste

An object must have use and value to fall within the scope of the law of property (i.e. be considered a 'thing', as such objects are referred to).[4,5] Value, however, need not be purely a positive economic value. It can also include a positive sentimental value, as well as a negative economic value or a negative sentimental value.[6] An example of property with a positive economic value and a positive sentimental value would be expensive jewellery received as a gift from a partner. However, such property can take on a negative sentimental value should the relationship sour and end.[6] Property with a negative economic value (in that it takes up space while providing no economic benefit), but a positive sentimental value, could include certain family heirlooms.[6] Finally, waste such as soiled food containers would be a clear example of property with both a negative economic value and a negative sentimental value.[6]

A consideration of the above role of value makes it clear that waste can fall within the scope of property law. It also serves to illustrate the manner in which the law strictly regulates how we may dispose of that waste we no longer want.[3] It is difficult to conceive of how one may (legally) dispose of one's unwanted property outside of the prescribed means, such as municipal collection of residential waste or dropping off one's recycling. It is true one may leave property which may be quickly claimed on the sidewalk, or other public place, in which circumstances property may be considered abandoned, and become the property of the person who takes it away.[6] However, the law does not countenance the depositing (dumping) of objects that are unlikely to be claimed. An old couch, for which someone else may have use, is one thing. A wholly broken and soiled couch, which it will then fall to the municipality to remove at cost to the public purse, is another. In the latter case, the owner must either take the unwanted object to the appropriate disposal site or pay someone else to do it. Abandonment can function to allocate ownership to the person who takes unwanted property, but not as a means by which an owner may simply avoid and pass on the costs of disposal to the public purse.[3]

The definition of 'waste' in South African law is wide, with section 1 of the *National Environmental Management: Waste Act 59 of 2008* stating 'waste' includes:

> *any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered.*

Such a definition is wide enough to include a soiled food container as well as an obsolete but otherwise functional laptop. Regardless of the nature of the property, as soon as it is unwanted, and the owner intends to discard it, it falls within the scope of that part of the legal framework which regulates waste and its disposal. The owner, thus, remains the owner until the law permits official termination of the relationship, at the point the waste is directed to the correct waste stream.

The disposal of solid waste is an area over which local government exercises legislative competence in terms of Part B of Schedule 5 of the Constitution.[7] As such, one will need to consult municipal by-laws for the details of waste disposal. For example, the City of Cape Town's Integrated Waste Management By-law requires anyone who generates waste to follow its rules in the disposal of any waste, depending on the nature of the waste.[8] The definition of 'waste' in the by-law mirrors the definition in the aforementioned Waste Act. Regarding normal waste, section 4 of the by-law requires separation of recyclables and non-recyclables, and the disposal of that waste through either the City's own waste removal services or an accredited service provider. Recyclables and non-recyclables must be disposed of separately, as must different categories of waste such as garden waste. Only by complying with these obligations does the law allow an owner – the waste generator – to terminate their relationship with property that constitutes waste.

How property may accrue a negative value varies, depending on the nature of the property in question. In respect of immovable property (land)[9], the duty to maintain immovable property is a primary driver of negative value where the land holds no other positive benefits for a landowner.[10] For example, property may accrue a negative value due to the locale in which it is located.[11] An inner-city building surrounded by urban decay may accrue a negative value, in that the owner cannot derive any benefit therefrom (especially if unlawfully occupied) while the property continues to be a financial burden.[11,12] A property developer may purchase a piece of land in the hope of clearing it for a new development, but be denied permission to demolish an otherwise derelict building that has been accorded heritage status.[13] A landowner may have a mining right granted over their land in favour of a third party, who then fails to rehabilitate the land.[11] Land in certain areas may also accrue a negative value due to the growing impact of climate change. For example, drought and wildfire may leave the locale vulnerable to mudslides when rain finally does come.[11,14]

In respect of movable property (i.e. anything not attached to land[9], such as your pen, laptop, or car), property accrues as a negative value for different reasons. Unlike immovable property, negative value will likely not stem from taxes or an obligation to maintain.[10] One is, for example, perfectly entitled not to service their vehicle (although its inevitable lack of roadworthiness will preclude one from using it on public roads). Rather, the negative value of movable property will flow from the fact that it takes up space, and the duty to store that rests on the holder thereof. Perhaps the best example of the duty to store causing property to accrue a negative value occurred in the wake of lockdowns following the global spread of COVID-19.[15] The cost of storing oil in the USA was so exorbitant in the absence of demand for the resource that producers were forced to pay buyers to accept the commodity.[15]

The case of oil surplus in the wake of the COVID-19 pandemic is an extreme example. However, the principle is true in respect of any movable object, particularly in light of the restrictions on disposing of one's property that exist in law. For example, your waste in your bin has a negative value, in that it takes up space while providing you with no benefit, and you pay municipal rates to have it taken away. And suppose you produce excess waste that exceeds the capacity of the bins assigned to you by your municipality. In that case, you can expect to incur excess charges in disposing of your waste. Even recyclable waste can have a negative value, even if you do not contract a service provider to remove it for you on a regular basis, as you are required to expend time and even money on petrol to take it to a drop-off point. The disposal process can be more time-consuming depending on the nature of the object, for example, old electronics (e-waste) which require specialised recyclers. Extended producer responsibility may place most of the cost of disposal on the producer.[16] Nevertheless, the time and effort required on the part of the consumer to dispose of objects that would otherwise take up space in their living space is a factor towards according such property a negative value.

Certain objects may have no value, and thus not be of concern to the law of property, due to being so insignificant and taking up so little space. A single dead leaf would serve as an example.[4] However, once dead leaves accumulate in one's garden, and are put into a large pile, the pile of leaves itself can accrue a negative value. As garden refuse, an owner is obligated to dispose of such a pile in a particular fashion (separately from normal residential waste, as noted above). Once again, negative value stems from the duty to store, even for objects that would otherwise have a neutral value as an individual unit.

The most important takeaway from the above is that by restricting the disposal of our unwanted property, the law plays a role in ensuring the optimum value is extracted from waste. Inevitably, some forms of waste are destined for the landfill, and will continue to have a negative value stemming from their continued use of space. However, such negative value can be nullified should the landfill eventually be reclaimed and turned into a space beneficial to the community, such as a park.[17] Until then, it is important that the negative value be ameliorated as much as possible. In respect of some property, the reclamation of positive value is possible through recycling, whereby valuable resources whose value would otherwise be lost or lie dormant can be put back into the economy, ultimately reducing our reliance on the extraction of virgin resources.

Waste and the law of abandonment

Waste provides the most obvious example of how the law strictly regulates the circumstances in which we may dispose of our unwanted property. It is difficult to conceive how one may simply dispose of movable property that qualifies as waste outside the disposal streams prescribed by law. That is, without falling foul of the provisions of the Waste Act or local by-laws regulating littering and dumping, such as the City of Cape Town's Integrated Waste Management By-law discussed above. The one exception, as noted above, is the depositing of objects in a public place, such as a sidewalk, which may be claimed quickly by people who may find it useful, such as old but usable furniture. Otherwise, if one wishes to dispose of property which would not be claimed readily, the only means through which this can be done is to follow the prescribed rules, which inevitably requires cooperation with a third party. Effectively, abandonment of property, in the true sense of the word (being a purely unilateral act), operates in a narrow set of circumstances to allocate ownership to parties willing to take responsibility for unwanted objects.[3] While the claimant of unwanted property may acquire ownership of unwanted property, abandonment does not serve as a defence against a charge of dumping or littering for the original owner.

According to the law of abandonment, all that is required for the abandonment of an object is physical relinquishment of possession coupled with the intention to no longer be the owner.[1,2] The rule effectively remains unchanged from its Roman law and Roman-Dutch law origins.[18] However, as aforementioned, the rule finds its application limited in contemporary society. In a society which produces increasingly larger amounts of waste, that is increasingly unwilling to reuse and repair when new items are increasingly disposable[19], strict rules for the disposal of unwanted objects are necessary. Where these rules are followed, such as the depositing of an unwanted item in a rubbish bin or at a dump, it can be assumed that the owner has the intention to give up ownership of such an object.[20] The doctrine of abandonment's continued relevance only appears to operate in circumstances in which another person lays claim to, and is willing to take responsibility for, a particular object.[3,18] Even the unlawful disposal of an object meets the requirements of abandonment; until a third party takes possession thereof, the law considers the original owner the responsible party.

It is important to note that, in respect of certain categories of property, there may be no intention to relinquish ownership, even if the object is deposited in a bin or directed to the correct waste stream. Sonnekus[20] uses the example of an artist who puts his sketches in the rubbish to be collected by the municipality. The artist likely intends that the sketches will be eventually destroyed or irretrievably lost in a landfill, with no intention that a passer-by may come along and claim it from his municipal bin.[20] A more modern example may apply to the disposal of a computer's hard drive. The owner of the hard drive likely does not intend that another party take ownership thereof after disposal, and attempt to retrieve data therefrom. Rather, the owner intends the party to which the old hard drive is directed to take the necessary steps to destroy it.

Destruction provides a unilateral form of disposal in respect of some objects of property.[21] But, for a private person, such an act would be limited to burning one's personal papers in a fireplace, for example, given the limited effect such an act has on third parties. Many categories of property cannot simply be destroyed by private individuals in a way that completely stops them taking up space. One cannot simply start burning one's unwanted property without falling foul of laws on air pollution and causing a nuisance for one's neighbours.[22] The right to destroy[21] – as with the right to abandon – is heavily circumscribed.

What is critical about the law's approach to the disposal of unwanted property is that it can be used to instil important values into society at large.[3] Requiring separation of recyclables and non-recyclables before waste is collected can impress the importance of recycling upon society at large.[3] Strict rules for the disposal of certain kinds of property, such as e-waste, can assist in the development of a circular economy.[23] While South Africa may not have the resources to enforce recycling norms like societies such as Switzerland[24], there are still important measures that can be taken. These measures would include effective extended producer responsibility for waste such as e-waste[16], and supporting important players in the recycling industry, such as waste reclaimers. While the practice of waste reclaiming is viewed in a negative light by some[20], the practice of removing inappropriately disposed of recyclables from the general residential waste stream is an overall good, especially in a society in which the means to enforce recycling norms are lacking. To the extent the practice does violate the law[20], the law should change, as it fails to ensure the value of recyclables is maximised, rather than lost.

The contextual nature of value

Conceptualising 'waste as property' becomes more complicated depending on the nature of the waste. Waste itself has the potential to become valuable depending on context and technological advances. For example, e-waste – which may otherwise simply take up space in one's home – can become valuable when its potential for the reclaiming of valuable resources can be realised. Old electronics, which may otherwise sit around people's homes, can be tapped as a source of metals and minerals which may otherwise need to be extracted as virgin materials from the earth.[25] A unique example of e-waste being turned into valuable items (in a particular context) is the production of medals for the 2020 Tokyo Olympics.[26]

Mine waste provides just such an example of property whose value can fluctuate from negative to positive depending on context. Much mine waste, in the form of mine dumps, will likely retain its negative value indefinitely, at least until rehabilitated. In the meantime, such dumps will continue to take up space (often resembling small hills due to their size), and pose threats to both the environment and human health.[27] Due to the nature of mine dumps, they may be viewed as straddling the line between movable property and immovable property, and thus the duty to store (as they take up space) and the duty to maintain (often being a significant feature of the land on which they are deposited).

Value can be won from certain kinds of mine dumps. The possibility of using the gold mine tailings of the Witwatersrand for brickmaking has been explored, and, although found initially wanting, is worth researching further due to the potential benefits to environmental conservation and waste management.[28] A study from Brazil reported on the possibility of using iron ore tailings as pigment for the production of sustainable paint for buildings.[29] With technological advancements, other metals and minerals can be extracted from tailings initially created for the purpose of mining another resource. For example, it has been suggested that Australia could maintain its position as the top producer of lithium (a component of batteries) – not through opening new and expensive mines – but by re-using existing tailings.[30] New techniques make it possible to recover lithium from lower-grade materials, meaning tailings can be re-mined rather than simply becoming useless mine dumps.[30] It would also avoid the exorbitant costs of opening new mines (estimated at AUD150 million to AUD2 billion) as well as the environmental harm that results therefrom.[30]

A recent initiative by the Resilient Futures Community of Practice explored the possibility of remediating mining land by planting of fibrous plants (for example, flax, hemp and bamboo).[31,32] The initiative has the potential to not only remediate mining land through the use of these plants, but also create an agricultural sector to support surrounding communities, where such a sector would otherwise not exist.[31,32] Again, property which would at one point have a negative value – land that would effectively be waste – can accrue a positive value. In fact, the initiative goes further, effectively seeking to prevent such land accruing a negative value in the first place through introducing fibrous plants during the life cycle of the mine rather than waiting until operations have officially ceased.[31,32] Such an initiative is critical in a context in which mining land is rarely effectively rehabilitated, and may otherwise remain a threat to both human health and the environment.[31,32]

What is evident is that the value of waste – from e-waste to mine waste to mining land – is forever fluctuating, depending on technological advancements and human initiative to tap into the value of waste. What may otherwise be waste with a negative value one day, could be a resource with a positive value the next. It is vital that initiatives such as the Community of Practice: Waste to Value evaluate and identify the optimal means through which a positive value can be realised from negative-value property.

Conclusion

Regardless of its value, waste is property. Waste is property because – among other things – it has value[4,5], although that value more often than not is a negative one. How it accrues this value depends on the circumstances and nature of the waste, but especially in the case of movable waste, the negative value stems largely from the fact that it takes up space. An owner has a duty to store the waste, at least until such a point at which it is directed to the correct waste stream. The law of abandonment effectively only operates in limited circumstances, often to settle ownership disputes over useful property that may be readily claimed, in a modern society that needs to regulate the disposal of waste strictly.

Examining waste through the lens of property law provides an otherwise neglected perspective. As Peñalver explains, the idea that one is simply permitted to terminate one's relationship with property at will is largely an illusion[3], at least in contemporary society in which the law strongly dictates the terms on which property may be disposed of. The law has a unique role to play in ensuring that the optimal value is realised from waste (both that which needs to be recycled and that which is destined for the landfill), and it does so through regulating the circumstances in which our relationship with property can end. An owner of property is not simply entitled to terminate their relationship with an object. This observation applies regardless of whether the property still has any residual positive value (such as an obsolete but otherwise functioning cell phone), or has accrued a negative value due to the duty to store it (like the contents of our municipal bins waiting for collection).

What is critical in realising the optimal value of waste, is ensuring effective enforcement of existing laws, as well as providing support to import role players in the waste sector. The law can simultaneously require that waste be directed to the proper stream, while empowering parties such as waste reclaimers, who play a critical role in directing waste to the proper stream where enforcement of existing legal rules falls short.

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Competing interests

There are no competing interests to declare.

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The myth of livelihoods through urban mining: The case of e-waste pickers in Cape Town

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Waste pickers are widely acknowledged as an integral part of the formal and informal economy, diverting waste into the secondary resource economy through urban mining. Urban mining in itself is considered to be a source of livelihoods. We investigated the livelihoods of e-waste pickers through 110 surveys in Cape Town, South Africa. Waste pickers often indicated that they were engaged in the sector not by choice but by necessity, expressing that earning money is the only enjoyable aspect of their job. The results from the study substantiate that it is unlikely that waste pickers could survive on e-waste picking alone as 83.3% of reported incomes were below minimum wage, with 22.9% below the food poverty line. Thus, the majority of waste pickers collected a wide array of recyclables. We also found that the waste pickers in Cape Town engage in multiple e-waste related activities, including collection, dismantling and processing to a lesser extent. They work long hours in arduous working conditions which present multiple hazards for their health and safety. Ultimately, e-waste pickers' incomes cannot be considered commensurate with the nature of the work. Further, e-waste picking cannot be regarded to significantly contribute to livelihoods, but is rather a survivalist strategy. The survivalist nature of the work does not allow for waste pickers to move upwards in the waste value chain and benefit from greater income opportunities. Furthermore, their lack of skills prohibits waste pickers' transition to formal employment. With a lack of options, it is necessary to ensure that the waste sector provides opportunities for decent work to enable workers to lift themselves out of poverty.

Significance:

- E-waste pickers participate in multiple activities across the e-waste value chain including collection, dismantling, processing, and repair and refurbishment.
- E-waste pickers in Cape Town cannot make a living on e-waste alone, and supplement their income from collecting other recyclables.
- E-waste pickers work long hours in difficult working conditions which pose a threat to their health and safety.
- E-waste picking is a survivalist strategy.

Introduction

Urban mining denotes the systematic reuse of anthropogenic materials from urban areas.[1] This reuse is achieved through the reclaiming of compounds, elements and energy from waste and obsolete products that have been discarded, often to landfills, in urban areas.[2-4] Urban mining introduces the reclaimed raw materials back into the manufacturing economy and thus has potential to create jobs and improve livelihoods.[5-7] Jobs created in the waste electrical and electronic (e-waste) economy are a subcategory of green jobs. There is much interest in estimating these circular economy jobs, especially in the Global North whose economies are largely formal; yet there are concerns about total factor productivity and wage stagnation in the sector. According to Barford and Ahmad[8]: 'In low- and middle-income countries, waste pickers underpin the recycling loop of the circular economy'. The contributions of waste pickers have been studied internationally by Gutberlet and Carenzo[9], Buch et al.[10] and Amorim de Oliveira[11], amongst others. Waste pickers are broadly defined as small-scale, self-employed people who are mostly active in the urban informal economy.[12]

The informal economy is as old as humankind itself as historically all employment was informal until policies were introduced that created the divide between formal and informal.[13] In 1973, Keith Hart coined the term 'informal economy'.[14] Chen and Carre[13] and the International Labour Organization[15] estimate that up to 61% of all people worldwide are working informally, and around 80% of the workforce in developing countries consists of informal workers. Originally, informal work was considered by economists as a transitory or temporary phenomenon which would decline when economic growth took place. That expected transition never happened. Clearly, the complexity of informality needs to be viewed with a much more multi-perspective lens.

Polese[16] and Banks et al.[17] argue that it depends on the theoretical (e.g. socio- economic, political, geographical) perspective that is taken on how informality is viewed and responded to. If informality is seen as the abnormal and inferior in relation to the 'formal' as the norm, the policy responses will be repressive, such as evicting of informal street vendors.[17] Marxist academics view the informal sector as integral to capitalist dynamics, while for Polese[16], informality is seen as the art of bypassing the state where informality steps in to provide where the state has failed to provide. We agree with Banks et al.[17] and Roy[18] that we should start to value and recognise the potential and merits of informality and view urban informality as 'an organising logic, a system of norms that governs the process of urban transformation itself' and as 'a series of transactions that connect different economies and spaces to one another'[18]. Polese[16] further argues for considering informality-centred approaches as a way to reshape the political order of a system. Informality-centred approaches are taken as a starting point for critical exploration of the relationships, attitudes, agency, and strategies. Only then, according to Banks et al.[17], can we reveal deeper insights into the broader spectrum of actors involved in urban informality, including their roles, relationships, and strategies.

To summarise, to be able to research, understand and respond to the complexities of informality, requires transdisciplinarity. Transdisciplinarity or transdisciplinary research is defined as 'knowledge production activities spanning across disciplinary boundaries and meaningfully involving non-academic partners'[19]. Transdisciplinary research transcends separate disciplinary sectors, transgresses disciplinary and institutional boundaries, and is context specific.

In accepting that informality is here to stay, the International Labour Organization focus on the promotion of decent work and the elimination of the negative aspects of informality, while preserving the significant job creation and income generation potential of the informal economy.[20]

The notion of 'jobs' in the informal e-waste recycling sector can be contentious because of how the word 'job' is defined, i.e. a piece of work or task performed regularly for an agreed price. Chen[21] indicates that informal employment can be divided into two categories: informal self-employment and informal wage-employment. According to this categorisation, informal e-waste pickers would mostly fall under informal self-employment. They can be considered to be the subcategory that is working on survivalist strategies as opposed to the better-resourced self-employed entrepreneurs. In general, self-employed workers have to deal with various social risks, including the risk of poverty in old age, the risk of disability, and the risk of unemployment.[22] Thus, informal e-waste recyclers would be plagued by several challenges typical of the nature of their employment, one of which is low incomes which are not sufficient to reduce poverty.[12] Consequently, there is a high chance they would get caught in a poverty trap, i.e. a self-reinforcing mechanism whereby poverty begets poverty in the absence of a significant external injection of capital. This situation is cause for concern and should be reviewed, with strategies put in place to address the sustainability of incomes and livelihoods in the sector.

There has been a debate in the literature regarding informal employment that has spanned decades.[23-25] Questions revolve around whether informal employment is both a symptom and a reproductive and perpetuating factor of precariousness, inequality, and of social and individual poverty. Or, in contrast, 'is it a reflection of economic initiative and business potential, which, if channelled and fostered properly, could contribute to social and economic development?'[23]. Viljoen et al.[12] analysed the livelihoods of street waste pickers in South Africa and cited high levels of unemployment to be the driver for pursuing waste picking, despite the hardships, unbearable working conditions, and poor income. Similarly, researchers in Ghana[26,27] and Nigeria[28] have reported on the difficult working conditions and the related risks faced by informal e-waste recyclers. Informal e-waste recycling is a physically demanding type of work that entails lots of lifting, carrying, pushing and pulling, with workers covering significant distances, usually on foot.[29,30] As such, in Ghana, e-waste workers were found to have a high risk of musculoskeletal disorders and disabilities.[29] They are also exposed to arsenic and heavy metals which could have adverse effects on their health.[31-33] Questions around satisfaction from this type of work arise, and considerations regarding the waste pickers' awareness of their contribution to the developing e-waste economy are relevant, as this could feed into job satisfaction, i.e. an awareness that one's line of work contributes to a greater good.

Waste picking is a form of urban mining and is recognised to generate an income stream and be a source of livelihood for many people in the developing world.[6,7,12,34-36] E-waste is a fraction of urban waste that contains valuable metals and sells for relatively higher value compared to other recyclables, and thus the urban mining of e-waste is of interest from both a solid waste management perspective and from achieving circularity in the metals industry. However, the overall contribution of e-waste to livelihoods may have some nuances relative to other waste streams. It is important to understand the extent of participation of e-waste pickers in the value chain, their motivations and remuneration to determine to what extent the practice contributes to sustainable livelihoods.

The South African government recognises what they refer to as 'the pioneering role of waste pickers in the development of recycling collection systems in South Africa' and this recognition is in line with the new global best practice on waste picker integration[6,37-39], with the publication in 2020 of the 'Waste picker integration guideline for South Africa'.[39] The guideline provides a framework for integrating waste pickers into local and regional waste management systems and recycling economies.[39] South Africa has taken the first step by including the incorporation of the informal sector and the recognition of their value in its National Waste Management Strategy 2020.[40] Furthermore, the country has created provision for a collection service fee to be paid to all registered waste pickers under the Extended Producer Responsibility (EPR) Regulations.[41]

Recent research has covered various aspects of the informal sector in South Africa – such as socio-economic conditions[12], well-being[42,43], health risks[44] and integration[39,45-47]. However, there has been little distinction between the different resources with which the waste pickers work. Thus, the extent to which different waste streams contribute to waste pickers' livelihoods remains vague. This study is the first to focus on e-waste activities in the informal economy.

We aimed to investigate the claim that waste picking can be a source of livelihoods for waste pickers, using the case of e-waste pickers in the City of Cape Town, South Africa. We argue that this claim is a myth, using evidence from this informal e-waste sector. This paper contributes to the development of an understanding of the nature of these informal jobs related to e-waste activities and the extent to which they contribute to livelihoods. These insights will provide a realistic perspective on the livelihoods of e-waste pickers.

Methods

Primary data were sourced via questionnaires administered to informal e-waste pickers in Cape Town. The questionnaire was adapted from that developed and used by Viljoen[48] in several studies in South Africa. It included both quantitative and qualitative questions. The questionnaire explored several themes including waste pickers' motivations for operating in this sector, the activities in which they participated (collection, dismantling, processing), and the earnings derived from these activities.

Six experienced fieldworkers were recruited and trained to administer the questionnaires. The training was conducted online whereby the fieldworkers were familiarised with the questionnaire and trained on how to approach certain questions that may be considered sensitive. The fieldworkers consisted of a core group who were involved in other studies on informal waste pickers in Cape Town. The leader of the fieldworkers was a retired teacher who is knowledgeable about the townships and how to navigate and negotiate with the waste pickers. The other fieldworkers were postgraduate students from the University of South Africa and the University of the Western Cape.

Buy-back centres play an important role in connecting informal sector activities with the formal economy of recyclers.[49] In addition, some scrap metal dealers play a similar role. Thus, the surveys were conducted at buy-back centres and scrap metal dealers where e-waste pickers are known to sell their wares. A combination of convenience and availability sampling was implemented. Interviews were conducted from 10 May 2021 to 27 May 2021, and adhered to COVID-19 requirements as prescribed by the University of the Western Cape. In total, 110 surveys were conducted; each survey took 5–15 min per participant depending on the fieldworker. The data were digitised through entry into SurveyMonkey by a research assistant.

Following completion of the surveys, a 90-min focus group was held with the fieldworkers. During the focus group, the fieldworkers gave accounts of their experiences and observations whilst conducting the surveys. These accounts were recorded and transcribed.

Open-ended qualitative questions were analysed using ATLAS.ti v9.1. A priori thematic analysis was employed whereby the themes were identified during development of the questionnaire. Statistical analyses were conducted on quantitative questions using Statistica software. Multiple regression analysis was used to investigate the relationship between income, education and collection days. The relationship between income and happiness was investigated using the Spearman's Rank test.

Whilst 110 surveys were conducted, only 85 were completed. Furthermore, the waste pickers did not respond to questions that were not relevant to them. Thus, the results presented are based on the responses received.

The research was approved by the University of Cape Town Engineering and Built Environment Ethics Committee and the University of the Western Cape Research Ethics Committee.

Results

Demographics

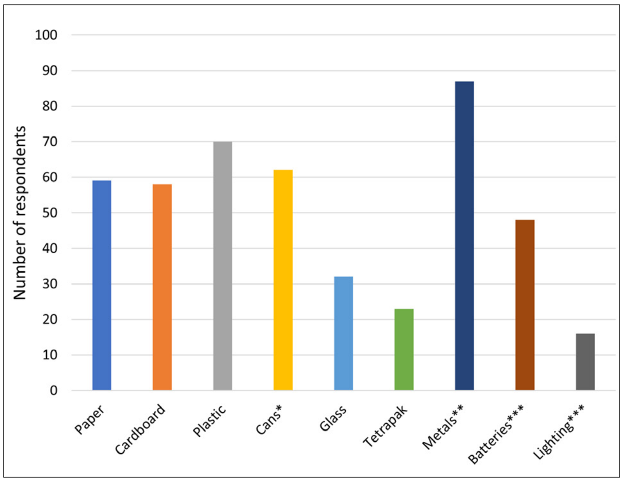
Almost all the people interviewed were South African, with 88.7% born in the Western Cape and 9.4% from the Eastern Cape. Only two respondents were from other countries, namely Namibia and Mozambique. Afrikaans was the predominant language spoken, with English to a lesser extent. The majority of respondents (87.7%) did not complete high school; only one person had proceeded to tertiary education, although they did not complete their qualification. In terms of gender, 75% of respondents were male.

Activities

Respondents were asked about their participation in various e-waste related activities, specifically collection, dismantling, processing (metal recovery), repair and refurbishment, and the sale of the e-waste.

Collection

Respondents sourced e-waste from a variety of sources, including industrial areas, directly from shops/businesses, landfills and schools. The most popular sources were reportedly dustbins outside houses and directly from residents. Some respondents had built relationships with residents, who then kept items aside for them. It was reported in the focus group discussions that a few respondents had admitted to stealing items. Respondents collected a wide variety of items including screens, cables and household appliances. Copper, printed circuit boards and other metals were perceived to be the top three most valuable fractions. Most waste pickers do not primarily specialise on e-waste alone, which was also reflected in this study as 98 respondents indicated that they also collected other types of recyclables (Figure 1).



**Cans are often collected and sold separately which is why they were considered a separate category*

***Metals which are not e-waste related*

****In South Africa, batteries and lighting are considered separately from e-waste*

Figure 1: Other types of recyclables collected by respondents.

Of the respondents, 70.1% reportedly collected e-waste at least 5 days a week, with some working daily. They worked a mean($\pm$standard deviation) of 9.1 ± 2.8 hours a day. As shown in Figure 2, 48.4% of respondents had been collecting e-waste for less than 5 years, whilst 22.1% had at least 10 years' experience. For those also collecting other recyclables, 50.6% had less than 5 years of experience; 56.0% of respondents collecting both e-waste and other recyclables started collecting them at the same time, whilst 21.3% started by collecting e-waste before moving onto other recyclables.

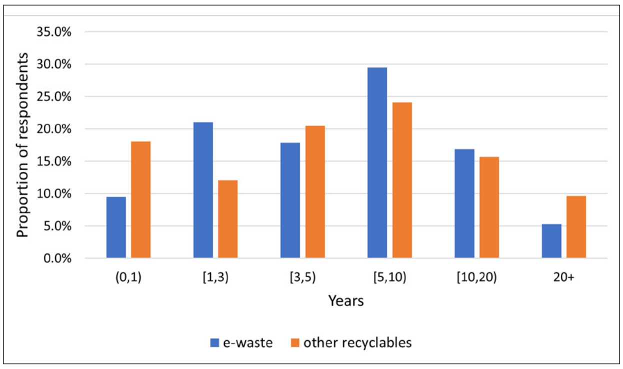


Figure 2: Years collecting e-waste and other recyclables.

Most respondents (60.4%) stated that they decided to collect e-waste to generate an income, which included their primary livelihood, because they received a higher profit compared to other recyclables, or as an additional income. Another 20.8% of respondents indicated that they engaged in e-waste collection because they were unemployed and could not find other work. Other reasons were because family and friends had been doing it, cleaning the environment, and being self-employed.

Dismantling

The results show that 82.7% of the interviewees indicated that they dismantled e-waste. Almost none of them reported any formal training, with only one receiving training on-the-job while working at a buy-back centre. The most commonly used tools for dismantling were hammers and screwdrivers (examples shown in Figure 3). Left-over materials deemed to have low economic value are commonly dumped in the area in which they are working. The majority indicated that they dismantled the goods at home (88.5%) whilst some dismantled at buy-back centres. The primary motivation reported for dismantling is that they can obtain higher prices for the different fractions of dismantled goods.

Photo: Professor Mapendere

Figure 3: Examples of tools used for dismantling.

Processing

Whilst 81.4% of respondents indicated that they participated in processing, when asked what they process and how, it became clear that some respondents misunderstood the distinction between processing and dismantling. The most common form of processing was the burning of cables to recover copper (as demonstrated in Figure 4). Processing was conducted at home or in open spaces. None of the respondents had received any form of training. No other methods of pre-processing laminated or insulated copper materials was mentioned by informal recyclers, giving the impression that, in the informal sector, cables were either sold with the insulation intact or the insulation was removed through open burning. Similarly to dismantling, the motivation for processing was to obtain higher prices.

Photo: Brenda Diedericks

Figure 4: Demonstration of copper burning by waste pickers.

A minority of the respondents (24.5%) cited that they found nothing difficult about processing e-waste. Of those who reported difficulties, the health and safety risks they faced during the process were reported by 30.0% of respondents. The respondents' challenges related to access to appropriate tools, space and the process itself, which may also be attributed to the lack of appropriate equipment.

Repairing and refurbishing

Fewer than half the respondents reported collecting goods for repair or refurbishment, of which 82.2% would repair or refurbish the goods themselves; none of them received any training, formal or informal. The goods were either kept for personal use or resold for income.

Selling of e-waste

Respondents sold their e-waste at a variety of places. The majority sold e-waste to e-waste buy-back centres (60.0%) and general buy-back centres (56.2%) as well as scrap metal dealers (42.9%). Relatively fewer respondents (29.5%) sold directly to e-waste recyclers.

Cooperation amongst workers

When it comes to cooperation amongst e-waste workers, 51.7% of respondents indicated that they worked alone when dismantling. Slightly less cooperation was reported during processing, with 60% of respondents indicating they worked alone.

Health and safety considerations

Respondents were aware of the health and injury risks associated with their activities, particularly dismantling and processing. Injuries reported included cuts, scratches, burns, and broken appendages. Other reported health risks emanated from inhalation of fumes during processing.

Respondents are also vulnerable to gang activity in the areas where they operate. Gangs reportedly charge workers a 'tax' to operate, which constitutes a fraction of their daily earnings. This 'tax' serves as a form of protection money or a licence to operate; without it, workers risk attacks from the gang members. Respondents also indicated risk of robbery and attack.

Only one respondent openly admitted that they collected e-waste to support their drug habit.

Income

Respondents reported average weekly incomes ranging from less than ZAR10 up to ZAR4500 (USD0.70–315.35). The mean weekly income from e-waste activities was ZAR537.71±653.62 (USD37.68±45.80), and median was ZAR377.50 (USD25.45) (Figure 5). Gender differences in income were observed, with women earning a mean weekly income of ZAR333.13±347.93 (USD23.34±24.38) whilst men earned a mean of ZAR605.90±716.62 (USD42.46±50.22). No relationships were observed between e-waste income and education ($p>0.05$), nor income and total working hours ($p>0.05$).

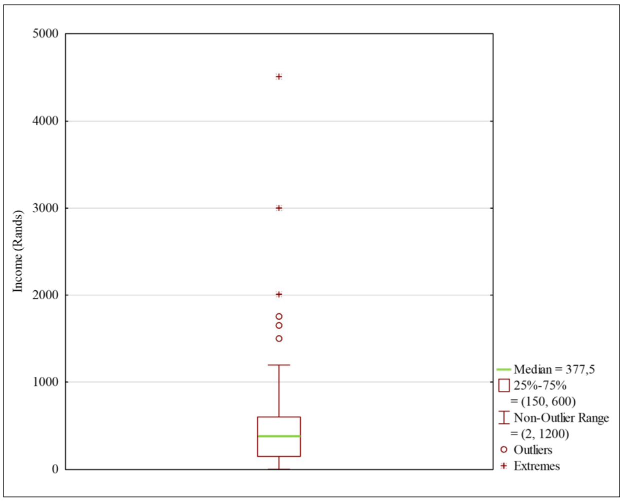


Figure 5: Average self-declared weekly incomes from e-waste collection.

For those respondents who collected e-waste along with other recyclables, the mean weekly income was ZAR805.20±680.73 (USD56.43±47.70). E-waste contributed a mean of 53.2±19.1% to the total income. As shown in Figure 6, the contribution of e-waste to total income ranged from 16.7% to 90.9%. About half (47.2%) of respondents obtained more than 50% of their income from e-waste, whilst 18.1% of respondents earned at least 75% of their income from e-waste alone.

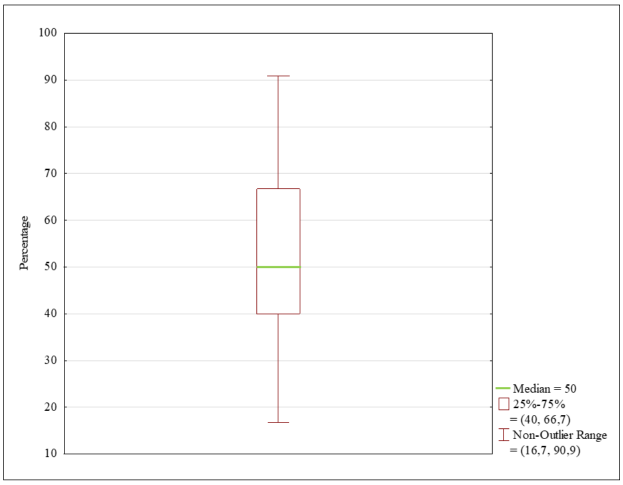


Figure 6: Percentage contribution of e-waste to total income for respondents collecting both e-waste and other recyclables.

Based on the income from e-waste alone for all respondents, 83.3% earned less than the national minimum wage of ZAR21.69 (USD1.52) per hour, which equates to USD243.20 per month (shown in Table 1). Furthermore, 22.9% were earning below the food poverty line of ZAR585 (USD41) per person per month. When considering respondents who collected a wide array of recyclables, fewer earned below minimum wage. A considerable difference was observed for food poverty, with 4.2% in food poverty. 75.6% of those who solely collected e-waste earned below minimum wage, with 17.1% facing food poverty.

Table 1: Proportion of incomes lower than the 2021 national minimum wage and 2020 poverty datum lines on a monthly basis

	Minimum wage	Food poverty line	Lower bound poverty line	Upper bound poverty line
E-waste income from all respondents	83.3%	22.9%	36.5%	44.8%
Income for respondents collecting e-waste and other recyclables	67.3%	4.2%	6.3%	12.5%

Buy-back centres were observed to rarely display prices for e-waste, unlike other materials such as plastic and cardboard. Furthermore, price disparities were observed for similar items across buy-back centres. Thus, the income earned by respondents is also dependent on which buy-back centres they sell to.

Subjective well-being

The pioneers of 'subjective well-being' or happiness studies are Easterlin et al.[50] Since the term was coined, economists, in particular, have shown much interest in determining or measuring happiness and whether an increase in income will lead to an increase in happiness.[51] Researchers like Easterlin et al.[50], Diener[52] and Proctor[53] are of the opinion that subjective well-being can be determined when a person reports on their own experiences of satisfaction or happiness. Diener[52] states that subjective well-being can be defined as the cognitive and effective evaluations of one's life. This means that the respondents give their own view of how happy they are with their current life situation.[51]

In this study, we requested the waste pickers to rate how satisfied or happy they were with life collecting e waste, on a scale of 1–10, with 1 being the least happy. A mere 29.7% reported scores of 9 or 10 whilst 38.6% reported scores of 5 and below. There was no correlation between income and happiness (r_s=0.17, p>0.05). Van Wyk et al.[51] also found in their study on landfill pickers that there was no relationship between income and happiness; however, in this study, when asked what they enjoy about their work, money was mentioned by 48) respondents whilst 9 specifically mentioned income as an enabler to put food on the table. The second most common response was 'nothing' which was given by 24 respondents. Only six respondents mentioned that the environmental aspect (i.e. diversion of waste to recycling) was what they enjoyed the most. Another aspect that was mentioned was that the work kept them 'away from trouble'; it kept them occupied so they did not engage in criminal activity.

Discussion

This study was an attempt to understand some of the roles, relationships and activities of informal e-waste collectors. The informal sector is characterised by impoverished workers who have been drawn to it as a matter of survival[27,54,55], and where the state has failed to provide safety nets[16]. It has a low barrier to entry, with no educational requirements (respondents learn on the job) and no start-up costs.[12] This makes it an attractive option for people without the necessary skills to enter the formal labour market. In Cape Town, only 12.3% of respondents had completed high school; this is similar to a previous study conducted in Cape Town in which 16% had completed high school.[56] In addition, a study conducted in Ghana found that only 5% had completed high school, and 65% had no formal education at all.[57]

Respondents participated in multiple activities, including collection, dismantling, processing and refurbishment. This is characteristic of the e-waste informal sector, with similar activities observed in Ghana[58], Kenya[59] and Nigeria[60]. Respondents in Cape Town played a multitude of roles and participated in various activities. This is unlike the sector in Ghana, whereby workers had distinct roles and could be categorised according to their activities.[27,61] The primary reason cited for participating in multiple activities was the prospect of higher incomes. The differences in net monthly income per activity were demonstrated during a study conducted in Kumasi, Ghana, wherein waste pickers earned USD122.76, refurbishers USD135.56 and dismantlers USD372.3 per month.[27]

Working with e-waste is associated with many health and safety risks. It is a physically demanding job requiring lots of pushing, pulling, lifting, walking and standing for long periods of time.[62] In addition, unsafe dismantling and processing practices expose workers to more hazards including smashing and breaking goods and open burning of materials. In Cape Town, respondents had a superficial understanding of the risks associated with their work. They reported short-term risks such as experiencing cuts or scratches, or broken bones. However, they did recognise that smoke from burning should not be inhaled. A multitude of serious health risks have been identified for those working in e-waste, including respiratory issues as well as musculoskeletal, neurological and genetic disorders.[33,62] Workers are also at risk of developing disabilities.

The mean income for all recyclables collected was ZAR805.20±680.73 (USD56.43±47.70), which equates to approximately ZAR3221 (USD225.72) per month. This is slightly higher than the average monthly income of ZAR2900 (USD217.95) reported in a previous study conducted in Cape Town in 2017.[56] An earlier national study on waste pickers conducted in 2016 found an average weekly income of ZAR505.06 (USD61.52).[12] These differences may be attributed to changes in market dynamics over time increasing the value of recyclables or simply differences in the value of the recyclables collected. In comparison to Ghana, the mean weekly income from e-waste alone (USD37.65±45.77) in this study was higher than that found for Ghana by Oteng-Ababio et al.[55] who estimated weekly incomes of USD14.00–24.50. Whereas in Kenya, Tocho and Waema[59] estimated monthly earnings of USD217.12–325.50. This suggests that the potential income opportunity presented by e-waste is region dependent.

When considering the extent to which waste picking activities can contribute to livelihoods, in Cape Town, the likelihood of surviving on e-waste activities alone is low. In this study, of those participating in e-waste picking alone, 22.9% were below the food poverty line. In addition, 83.3% of them reported earnings below minimum wage. Those who collected a wide array of recyclables fared better, with only 4.2% under the food poverty line. When we go beyond the income and consider the health and safety risks of waste picking, the risk is not commensurate with the reward. Thus, in reality, e-waste picking can be considered a survivalist strategy – a finding which is supported by the results of a study conducted in Ghana.[26] This finding is characteristic of informal self-employment, a category of informal employment where the focus is on survivalist strategies.[21]

The low incomes may be attributed to limited access to waste streams. Large businesses and institutions and the government commonly have contracts directly with e-waste recyclers or stockpile e-waste not knowing what to do with it.[63] This represents a large proportion (80%) of the e-waste generated in South Africa.[63] Furthermore, waste picking on landfills is prohibited in Cape Town, unlike in other large cities such as Johannesburg and Pretoria.[64] However, 18.8% of waste pickers admitted to accessing them. As such, workers primarily rely on scavenging in dustbins or obtaining e-waste directly from residents who only generate 20% of e-waste.[63] This urban mining is conducted at the generation level and the e-waste is not given the opportunity to be locked into 'urban mines' such as landfills. Instead the 'urban mines' may be considered to be households and businesses where the e-waste is locked in stockpiles, which is aligned with the definition put forward by Cossu and Williams[4]. With limited access to large mines (i.e. landfills), waste pickers are forced to diversify their income stream by collecting a variety of recyclables. This is not a necessity in areas with a steady stream of readily accessible e-waste such as Agbogbloshie, Ghana, the largest global open dump for e-waste exclusively.[65]

Despite informal workers being recognised as playing a vital role in the recovery of recyclables, as an occupation, waste picking is not officially recognised.[54] Informal work does not have the protections afforded those in formal employment. They work long hours under unpleasant working conditions and are vulnerable to exploitation. They are at the lowest tier of the recycling value chain, earning the least value for their goods.[12] The recently enacted EPR Regulations recognise the potential for exploitation of informal workers and aim to mitigate this through the implementation of a 'collection service fee' to all waste pickers registered on the National Registration Database.[66] However, the regulations do not provide guidance on how this fee will be determined. The integration of waste pickers into EPR systems has been implemented around the world in various forms.[37] For example, in Brazil, municipalities can hire waste picker collectives as a private service provider in the municipal solid waste system.[6,67,68]

The question of how the informal sector may be integrated into the formal sector has been a focus area in many countries.[59,60,69] A number of motivations have been cited for the incorporation of the informal sector, such as an avenue to further grow the formal industry and create jobs, as well as a way to encourage safe dismantling and processing practices. In addition, waste picker integration may be viewed as a way of ensuring decent work by improving their working conditions, increasing wages and ensuring job security.[45] South Africa has adopted the International Labour Organization recommendations for formalising the informal sector targeted towards ensuring decent work, that is, work that is:

> *productive and delivers a fair income, security in the workplace and social protection for families, better prospects for personal development and social integration, freedom for people to express their concerns, organize and participate in the decisions that affect their lives and equality of opportunity and treatment for all women and men.*[20]

Waste picker integration guidelines[45] have been developed, and are targeted at those who work with waste pickers, including industry and local governments. Furthermore, the National Waste Management Strategy 2020, which is a statutory requirement of the *National Environmental Management: Waste Act (No. 59 of 2008)*, prescribed waste picker integration in all metropolitan municipalities by 2021[40] – however, this is yet to be accomplished. Ultimately, waste picker integration may be considered inevitable in South Africa and should be a goal to which to aspire.

Conclusions

Waste collection is widely touted as an opportunity for income. However, the nature of the job is hardly discussed alongside the 'income opportunity'. Waste pickers work long hours in arduous working conditions which present multiple hazards for their health and safety. This presents the question of whether their income is commensurate with the work they do. In this study, 83.3% of the waste pickers surveyed reported incomes from e-waste alone that were below minimum wage, with 22.9% below the food poverty line. When considering the total income from all recyclables, 67.3% of incomes were below minimum wage. Along with low income, it was found that there was no relationship between how many hours they worked and how much they earned. This brings into question the extent to which waste pickers can sustain a livelihood from their urban mining activities.

Workers may be considered to be trapped in their situation. The survivalist nature of the job does not afford the waste pickers the opportunity to move up the value chain as incomes do not allow one to save for start-up costs. Furthermore, waste pickers have limited opportunities to transition into the formal economy due to their lack of skills and the current unemployment rate in South Africa. Whilst waste picker integration seems to be on the horizon, it is essential that key interventions are implemented in the meantime. These interventions include providing space for waste pickers to work, providing opportunities for safe dismantling and processing practices, and guaranteeing fair compensation for their work. Ultimately, there is a necessity to ensure that the waste sector provides opportunities for decent work, as highlighted by the International Labour Organization, that enables workers to lift themselves out of poverty, for the myth of livelihoods through urban mining to become a reality.

We have attempted here to unravel the lives, roles, relationships and activities of the e-waste pickers. We have, by far, not addressed all the complexities of the informal 0e-waste pickers in the waste economy. The way forward will require researchers to move in the direction of more qualitative and transdisciplinary research and Polese's[16] informality-centred approach in search of collaboratively developed support systems.

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Competing interests

We have no competing interests to declare.

Authors' contributions

T.Y.C.: Conceptualisation; methodology; data analysis; writing – the initial draft; writing – revisions; project management. T.M.: Methodology; writing – the initial draft; writing – revisions. K.G.: Methodology; writing – the initial draft; writing – revisions. C.S.: Conceptualisation; writing – revisions; project leadership; funding acquisition.

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Barriers to recycling e-waste within a changing legal environment in South Africa

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Electronic waste (e-waste) recycling presents an opportunity to reclaim materials from a secondary resource and to create jobs and other economic opportunities. E-waste consists of various materials such as metals, plastics, glass, and other chemical substances. Some of these materials are hazardous if processed or disposed of improperly. Therefore, e-waste is classified as hazardous in South African law up until the hazardous components are removed. With the appropriate infrastructure and technology, a large portion of materials contained in e-waste can be reclaimed, and any adverse impacts of irresponsible management prevented. The private sector has played a proactive role in shaping the South African waste economy, and the government is taking strides to draw up enabling regulatory frameworks. Through a literature review and stakeholder engagements, this paper unpacks the organisation of the South African e-waste recycling industry. We consider whether the legal environment drives a common vision for a circular e-waste economy and probe the barriers to e-waste recycling across the value chain. The findings indicate that the development of the e-waste recycling sector in South Africa is dependent on a robust collection network and the enabling of local end-processing, refining, and manufacturing capacity. The availability and quality of input material and the development of local refining and manufacturing capacity are co-dependent and should be addressed simultaneously.

Significance:

- E-waste recycling is an emerging industry in South Africa and the enablers and constraints for the development of this industry are still being explored.
- The legislative environment with regard to e-waste recycling is evolving and needs to be continuously reviewed to assess its ability to enable/activate the development of the sector.
- Local end-processing is currently limited to very small volumes of selected fractions of e-waste. The potential to activate upper levels of the e-waste value chain, such as end-processing, is important to the development of the sector.

Introduction

Electronic waste (e-waste) refers to discarded end-of-life and end-of-use electrical and electronic equipment (EEE). The e-waste stream is the fastest growing waste stream in the world, with 53.6 million tonnes generated globally in 2019 alone, and this figure is expected to increase to 74.4 million tonnes by 2030.[1] The growth of this waste stream is fuelled by higher consumption rates, shorter product life spans and limited options for repair of EEE. Technology is important in the modern world, and its role in the energy transition cannot be overstated. However, the growing demand for EEE and its disposal at end-of-life or end-of-use demand increased extraction of the primary resources used in the manufacture and create environmental and social challenges.

In 2019, South Africa generated an estimated 416 kt of e-waste, and this should be regarded as a conservative estimate as data collection in the waste sector is generally poor.[1] E-waste streams contain various materials which include metals, plastics, glass and ceramics. High-value components, such as gold and copper, can be economically recovered through well-established recovery technologies, while low-value materials, including some plastics, cannot. Those components that can be economically recovered locally could drive the growth of a secondary resource economy. The recovery of metals reduces reliance on the extraction of virgin metals and avoids the potential negative social and environmental effects of traditional mining practices. E-waste recycling, although not a solution to these ills, provides an alternative source for the development of further technologies.

In South Africa, e-waste is classified as a hazardous waste stream and its toxic components, including certain metals, pose a threat to health, well-being and the environment if poorly managed. As such, the *National Environmental Management Waste Act 2008* (NEMWA) requires various environmental authorisations and licences when carrying out certain waste management activities to manage the potential harm.[2] The South African Department of Environmental Affairs, now known as the Department of Forestry, Fisheries and Environment (DFFE), is the national regulatory department that issues these authorisations and licences. However, these regulatory measures may promote or inhibit e-waste recycling in South Africa, and frequent regulatory changes create legislative uncertainty, which adversely impacts the fledgling e-waste recycling sector.

The National Waste Management Strategy (NWMS) has driven a shift in legislation towards promoting the circular economy and the waste management hierarchy.[3,4] Extended producer Responsibility (EPR) has contributed to the shift towards circularity. NEMWA defines EPR measures as '[an extension of] a person's financial or physical responsibility for a product to the post-consumer stage of the product'[2]. The shift is in line with the global shift to recognising waste as a resource, not only from an energy recovery perspective but also for the reduction, reuse, recovery, and recycling of materials. In a circular economy, products, parts and materials are used and cared for, repaired, reused and recycled as much as possible with the aim to avoid producing waste or pollution.[5] The waste management hierarchy provides a framework for preferential consideration of sustainable waste management options from most to least preferred. This hierarchy is accepted locally and internationally as a guide for prioritising waste management practices. It is made up of five ranked options in order of desirability, namely prevention, reuse, recycle, recovery, and disposal.[3,4,6]

In the South African context, there is a gradual shift away from the age of the landfill, which was focused on disposal as the least preferred strategy in the hierarchy, towards the local recycling of e-waste. Through this paper, we aim to provide insights that can support South Africa to fully participate in higher tiers of the waste hierarchy while also providing opportunity for economic development and local job creation. Furthermore, we draw on insights gained through site visits and interviews to map out e-waste recycling networks and identify barriers to full participation in e-waste value chains in South Africa. However, while the aim of South Africa's legislation on e-waste management is shifting, the existing waste infrastructure remains weak. Limited fractions of recyclable e-waste are collected and much of it is exported for processing elsewhere[6-9], thus limiting the development of the e-waste recycling sector locally. It is therefore crucial to understand what is currently inhibiting this development. We outline how the e-waste sector is organised and identify the current barriers to an effective e-waste recycling sector. We also consider developments in legislation and the potential impact on the growth of the sector in South Africa.

Methods

All data and information gathering in this study were of a qualitative format, based on research done by Sadan[6]. The data were obtained through a literature review, formal interviews, informal conversations with stakeholders and observations made during site visits to local e-waste processing operations.

Desktop study

The literature review provided insight into the global and South African contexts of e-waste legislation, value chain activities and stakeholder information. Most of the studies on the status quo of the sector were done more than 10 years ago.[10-13] However, the sector has undergone significant developments since then, which is highlighted in the technology landscape report by Mintek in partnership with the Council for Scientific and Industrial Research (CSIR), published in March 2017.[14] This particular report provided a comprehensive study on the sector and is used as the foundation upon which this research has been built.[14]

Interviews and site visits

The literature review was complemented with primary data collected through interviews and site visits.[6] The initial interaction with the e-waste industry was via the Southern African E-waste Alliance (SAEWA), which is an e-waste industry network and voluntary industrial association. SAEWA was contracted to organise and facilitate site visits to e-waste recyclers in the Gauteng (February 2017) and Western Cape (April 2017) regions. The sites were chosen based on the company profile, size of operation, e-waste activities, location as well as availability and willingness to participate in the research. Interview questions were drawn based on themes and knowledge gaps identified during a preliminary literature survey. The questions used are provided in the Appendix and the detailed approach taken to draw up the questions is reported by Sadan[6]. Interviews and site visits provided insights on health and safety practices in the industry, material flows of feedstock and products, agenda and motivations of the recycler, perspectives on waste legislation, technology and operations, and other peripheral information that may have implications on the e-waste recycling operations. Ethical approval for the study was granted by the University of Cape Town.

Table 1 gives information on the interviews and site visits conducted; further details can be found in Sadan[6]. The data collected during site visits and interviews were coded manually using thematic analysis.[15,16] Figure 1 shows images from the data unpacking process.

Table 1: Interviews and site visits conducted

Interviewee descriptor	Location	Description of role and organisation	Description of information gathered
Susanne Karcher	Cape Town	Environmental consultant and coordinator of the Southern African E-waste Alliance (SAEWA)	High-level overview of the e-waste recycling sector; environmental legal compliance; product market and trade information
Environmental Risk Officer	Cape Town	Environmental Risk Officer at a higher education institution	Organisational perspective on e-waste management; waste information registration and requirements
Business owner – NC Electronix	Western Cape	Owner and manager – small-scale e-waste business operating outside of Cape Town Central Business District	Insights into small-scale e-waste recycling operations, flows, product markets, value chain and stakeholder interactions
Business owner – Square Mobile	Western Cape	Owner and manager – small-scale start-up focusing on mobile phone collection and recycling	Insights into e-waste collection logistics; e-waste awareness campaigning and community-based mobilisation; perspectives on the legislative procedure for a start-up e-waste recycler
Business owner – Cape E-waste	Western Cape	Owner and manager – medium-scale e-waste recycler and collection agent to Desco	Perspective on barriers in obtaining full legal compliance; comparison of regional differences in the e-waste business
Business owner – Smiley's Electronics	Western Cape	Owner of an informal refurbisher and reseller	Informal sector perspective
Mark Dittke	Cape Town	Managing Attorney, Dittke Attorneys – specialising in Health, Safety and Environment	Insights into policy and legislative framework in South Africa; auditing services
Manager – TraX Interconnect	Cape Town	TraX Interconnect (Pty) Ltd – manufacturer of PCBs	Insights into nature of raw materials, offcuts, scrap and effluent streams
Owner and manager	Gauteng	One of two lighting recycling companies in South Africa, with growing capacity	Insights into specialised stream recycling, the processes and challenges in establishing the business
Divisional manager	Randburg, Gauteng	Mintek – Government-funded research institution	
Anonymous 1	Gauteng	Sindawonye – Large-scale e-waste recycling company	Insights on large-scale recycling dealing with tenders from a telecommunication company
Anonymous 2	Gauteng	Desco Electronic Recyclers cc – Large-scale e-waste recycling company	Insights on the e-waste value chain, collection and pre-processing; export of value fractions and disposal of residuals
Anonymous 3	Bangalore, India	Government funded e-waste recycler and researcher	Insights on innovation and technology development in a developing country

Figure 1: Interview matrix unpacking and theme grouping.

Research limitations

A constraint on this research was that the stakeholder engagement took place during a dynamic and transient time in the legislative context of the South African e-waste industry. The transient nature called for regular check-ins with newly published literature and follow-ups with interviewees. Examples of such changes are the call, and subsequent withdrawal of the call, for Industry Waste Management Plans (IndWMP) and the import ban of foreign recyclables to China (2018) during the study.[17,18] Changes after the study include the consultation process for, and subsequent publication of, regulations regarding EPR.[19,20] The 2020 NWMS was also published after the researchers' stakeholder engagement took place.

Also, only a limited number of site visits and interviewees could be consulted, with a bias towards Cape Town due to relative ease of access to the participants. Furthermore, the diversity of the types of businesses, i.e. large, small or medium scale and the formal, semiformal or informal nature, also led to disparity in responses to interview questions as each type experienced the industry differently.

Results and discussion

E-waste legislation and governance in South Africa provides historical markers of a shift in perspective on e-waste as a potential source of value. Shifting away from disposal towards recycling, reuse and reduction, the intention of legal developments looks towards moving up the waste management hierarchy. As the law develops, these changes may have unintended consequences and a common vision acts as a guide. Understanding the barriers to recycling e-waste in South Africa from an industry perspective can assist in guiding the implementation of the law in achieving circular economy initiatives.

In the following sections, we discuss the results by outlining the legislative and governance of EEE and the resultant e-waste in South Africa and the recent inclusion of the circular economy concept within the law. The inclusion of the concept is unpacked in relation to the EPR Regulations and the product-specific notice for EEE, as well as the impact of the e-waste landfill ban. The changes to the law address some of the barriers identified; however, the barriers to the common vision to recycling is only one aspect of the waste management hierarchy and barriers at other points within the EEE value chain are beyond the scope of this paper.

E-waste legislation and governance in South Africa

South Africa has three spheres of governance – national, provincial and municipal. There are policies and legislation on waste regulation and management set by all three spheres. In this paper, we only look at national waste policies and legislation, which are established by DFFE. There is not much specific waste legislation set by the provincial sphere, whereas the municipal sphere has several items of relevant municipality-specific waste legislation in the form of by-laws.[6] However, municipal by-laws are guided by, and must align with, national legislation.

Four key stages in the development of the waste economy were identified through the mapping of waste legislation and policy in South Africa: (1) the age of landfill, (2) the emergence of recycling, (3) the flood of regulation and (4) the drive of EPR. Before 1999, South Africa's waste economy was firmly rooted in the 'Age of the landfill', meaning disposal using a landfill remained the dominant choice for both general and hazardous waste.[21] Recycling, as an alternative to landfill, was first formally presented in the first NWMS document in 1999, and then in the White Paper on Integrated Pollution and Waste Management (IP&WM) in 2000. However, commitment towards recycling was only made by the government in the Polokwane Declaration, published in 2001, which marked the beginning of the second stage of waste management legislation in South Africa, 'the emergence of recycling'. The Declaration set targets for government, business and civil society: 50% reduction in waste generated, a 25% reduction in landfill volumes, and a zero-waste plan by 2022. Although there was no legislation enforcing these targets at the time, there has been growth in the recycling industry, primarily through the efforts of the private sector.[21]

In 2008, the promulgation of the NEMWA marked an important milestone for the waste management sector in South Africa. The Act was followed by a 'flood' of related regulations and norms and standards to control and minimise the negative environmental and health impacts of the waste sector. These include regulations on waste management activities, waste information and waste classification, as well as norms and standards regarding waste storage and assessment of waste for landfill disposal, among others. South Africa's waste recycling economy is largely driven by the informal sector of 'waste pickers' and the private sector. The new and continuously evolving legislative environment has placed, and continues to place, a significant burden on businesses who, among other things, face growing costs of compliance administration. This places substantial administrative and legislative burden on businesses operating outside the disposal stage in the waste management hierarchy, and there is no clarity on whether the materials they handle continue to be regarded as waste once they have been processed.

Prior to the EPR Regulations, voluntary EPR initiatives in South Africa were largely driven by private industry and non-profit organisations (NGOs). In 2012, a government-led mandatory model for EPR started with the promulgation of the Waste Tyre Plan. The scheme, referred to as the Recycling and Economic Development Initiative of South Africa (REDISA), was funded through a levy charged to the producer on tyres sold. REDISA managed to make some contributions to the establishment of depots and waste tyre processing facilities, and invested in research and development in the waste tyre sector.[22] However, REDISA was eventually liquidated following allegations of mismanagement and misappropriation of funding. Subsequent legal battles have highlighted various governance issues within organs of the state. As a consequence, there appears to be a continuous lack of trust from recycling industries regarding the South African government in allocating and distributing funds towards industry development and this impacts the e-waste sector.[6]

To address some of the waste management challenges, the national government published the National Pricing Strategy for Waste Management (NPSWM) in 2016.[23] The NPSWM introduced a suite of economic instruments to action the polluter pays principle, reduce waste and its resultant environmental and social impacts, and grow a secondary resource economy. EPR is considered one of the upstream economic instruments.[23] The NPSWM provides guidance on the two streams for implementing EPR schemes in South Africa: an EPR fee managed by industry or an EPR tax managed by government.[24] Regardless of the stream, the implementation of effective EPR will require cooperation between the public and private sectors.

In 2020, the DFFE published the EPR Regulations under the authority of section 18 of NWMWA. The Regulations were accompanied by product-specific notices for EEE, lighting and paper, packaging, and some single-use products. The Regulations require an EPR fee to be established and applied proportionally to all members by the producer responsibility organisations, or by an individual producer that establishes their own fee. The Minister of Forestry, Fisheries and the Environment must concur with the Minister of Finance on the motivation and justification of the fee submitted by producer responsibility organisations or producers.[25] Therefore industry will be required to play a leading role in implementing EPR alongside government as the regulating authority.

The ever-changing legislative environment through the enactment, and subsequent superseding, of various regulations, continues to cause instability in the waste sector, thus becoming a hindrance for technology development and innovative recycling initiatives.[8]

Changes towards a common vision – a circular economy of e-waste

South Africa must redefine waste as a valuable resource.[26] This will not only help implement the upper rankings of the waste management hierarchy, i.e. prevention and re-use, but also ensure the development of the recycling industry, and the growth of a secondary resource economy. The Department of Environmental Affairs indicated its aim to drive the agenda of waste diversion from landfill, including but not limited to:

- diverting more waste from landfills towards other waste management options,
- increasing institutional capacity for managing waste streams,
- supporting the implementation of EPR schemes,
- encouraging the integrations of the informal sector, and
- developing small and medium enterprises in the alternative waste management technology solutions space and driving 'radical socio-economic transformation'.[27]

Thus, the drivers for waste diversion from landfill are not only from an environmental stewardship perspective but are also to promote socio-economic opportunities such as job creation and economic opportunities. Although the view of waste from an environmental liability perspective remains unresolved, waste is increasingly seen as a potential resource and economic contributor.[6,27]

Insights from the interviews conducted in the study suggest that this can be considered a common view among private industry, NGOs, and researchers, who have seen the potential economic opportunities associated with a circular economy for e-waste.[6] However, a legislative environment that supports it is required. Notably, South Africa is taking strides to update its legislation in this regard, although questions remain as to whether these changes adequately reflect and align with concepts of e-waste as a resource.

Redefining waste in a circular economy

The definition of waste according to the *National Environmental Management: Waste Amendment Act* (NEMWAA) is:

> *any substance, material or object that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered… .*[28]

Within NEMWAA, there are priority waste streams that can be declared so by the Minister of Environmental Affairs. This has not been expressly done to date. Thus, the priority status of e-waste has been inferred by the way the stream is regulated, and this 'inferred priority' status is confirmed in the NWMS 2020 and the Waste Research, Development, and Innovation Roadmap (the Waste RDI Roadmap is a South African government initiative aimed at supporting South Africa's transition to a circular economy) which both explicitly refer to e-waste as 'priority waste streams'.[4,29]

In 2018, waste exclusion regulations were established to guide what waste streams or portions of waste did not fall within the ambit of the Waste Act to encourage diversion from landfills. Further clarity on what constitutes waste was provided in 2020. The Supreme Court of Appeal, in the case of *Minister of Environmental Affairs and Another v ArcelorMittal South Africa Limited*, held that basic oxygen furnace (BOF) slag does not fall within the definition of waste because it is not unwanted, rejected, or abandoned and therefore no waste management licence was required.[30] The purpose was to sell the crushed and screened BOF slag which constitutes recycling under the Act. Therefore, there are legal movements to exclude economically viable by-products from the definition of waste, moving from waste to an economic resource. What constitutes waste, and consequently what requires a waste management licence to handle, is changing in the law. Therefore, there is scope to have e-waste redefined as a resource worth 'mining' for its various mineral value fractions. If e-waste is redefined and managed as a resource, the circular economy is more likely to be implemented.

Legal developments towards circularity

South Africa has aligned its policies and strategy with the circular economy concept. South Africa is a founding member of the African Circular Economy Alliance whose ambition is to spur Africa's transformation to a circular economy that delivers economic growth, jobs and positive environmental outcomes at the national, regional and continental levels.[31] The Chemical and Waste Economy Phakisa, a presidential programme aimed at addressing environmental damage and unlocking the economic potential within the hazardous waste, identified e-waste as a key waste stream to valorise. The NWMS emphasised the programme as a commitment to the implementation of the circular economy as a municipal waste management sphere initiative.[4]

The circular economy concept has also been adopted as a systemic approach to combat environmental degradation and climate change by the White Paper on Science, Technology and Innovation.[32] The concept also appears in the EPR Regulations. The purpose of EPR Regulations is to 'encourage and enable the implementation of the circular economy initiatives'.[25] The EPR Regulations have a specific product notice for EEE, connecting the law with e-waste circularity.[2] These legal developments reflect a common vision of e-waste circularity adopted by South African legislators.

The EPR Regulations define the circular economy as a 'a regenerative system in which resource inputs and waste, emissions, and energy leakage are minimised by slowing, closing, and narrowing energy and material loops which can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling and which is in contrast to a linear economy which is a 'take, make, dispose' model of production.'[25] The definition emphasises long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling, thereby aligning with the waste management hierarchy. The specific product notice for EEE requires producers to take responsibility for the post-consumer stage of the product.[33] The definition of the circular economy and the purpose of the EPR align. However, measures put in place by producers should focus on designing long-lasting EEE with maintenance and repair options available, rather than focusing on e-waste management and recycling, if the circular economy is to be implemented.

An example of downstream management of e-waste external to the EPR Regulations is the e-waste landfill ban.[34] The ban came into effect on 23 August 2021. However, a ban on EEE going to landfill does not require the reclaiming of existing e-waste present in the landfill or in the environment. It encourages an increase in discarded EEE stock to be managed through alternative waste management measures, such as refurbishment, remanufacturing, and recycling.

The EPR Regulation, the EEE product-specific notice, and the e-waste landfill ban further the ambitions of the circular economy to minimise resource inputs and waste. However, the common vision might result in a blind spot regarding environmental and social externalities. If the cost of waste management is externalised to the product cost, and therefore placed on consumers, the incentive to innovative product and process design is lost. Therefore, the vision towards a circular economy must account for consumer protection.

The legislative landscape is progressive and responsive to global trends; however, this has not effectively trickled through to practice yet. In 2017, only 6.3% of the collected hazardous waste was recycled, with the remaining 93.7% sent to landfill.[35] As previously mentioned, e-waste falls under the hazardous waste category; only 9.7% of e-waste was recycled in 2017, with the balance (90.3%) being landfilled.[35] This suggests that South Africa is still in the age of the landfill. However, there appears to be some concerted efforts towards realising a circular economy within the e-waste industry in South Africa, but its emergence has been slow. In the following section, we identify the current e-waste recycling network in the South African context and highlight the challenges faced by different actors within this network which may explain further why this progress has been slow.

Identifying the barriers to recycling e-waste in South Africa

The spheres of operation of the South African e-waste collection network have been mapped as shown in Figure 2. The large-scale recyclers are aggregators and distributors of bulk e-waste, whereas the small- and medium-scale recyclers, whose operations can be informal, semi-formal or formal, are collection and dismantling agents; they are cut off from international markets. It was noted from the interviews that small-scale recyclers provide a free collection service for small volumes of e-waste to ensure feedstock for their recycling activities. Furthermore, it is very common for recyclers to buy e-waste from waste generators directly. This can be done through purchasing of obsolete equipment or via a recycling rebate, as done, for example, by GreenOffice, a printing equipment recycler. Transport costs remain the highest expense for many small- to medium-sized recyclers due to their necessarily large collection radius (NC Electronix, Cape E-waste interviews).[6] On the other hand, larger e-waste generators, such as Telkom, would pay for the recycling service and would offer long-term contracts to e-waste recyclers through a tender system. But such contracts generally exclude small-scale actors, especially if they are operating informally or semi-formally. Semi-formal in this case refers to actors that have not met the full legal requirements but whose activities follow the formal rules. These operations were found to have registered with voluntary industry associations such as SAEWA who use a tier system to rank their members, with semi-formal operations being of a low tier and benefiting from receiving mentorship towards formalisation.

Overall, the e-waste chain converges on the large recyclers who aggregate collected material and send it to end-processing (metal extraction), mostly to copper smelters overseas where the key metal fractions (principally copper and gold) are recovered and refined for resale, and non-value fractions are incinerated or stabilised in inert residues such as smelter slag.

The formal e-waste recycling sector is currently not a significant employer and also not a significant contributor to South Africa's waste economy (estimated to be worth ZAR24.3 billion annually).[14,35] This is attributed to the low volumes of e-waste currently processed and to most of the high-value metal processing happening overseas. However, there is recognition that at an estimated 25 jobs/1 000 t of e-waste handled, the sector has significant employment potential when more e-waste is reprocessed.[14]

Figure 3 summarises the barriers to local end-processing. The lack of adequate end-processing and refining capacity in South Africa is principally attributed to insufficient e-waste volumes available to operate technologies that have proven to be successful internationally at the necessary economies of scale. This brings to attention the key challenge of supply. South Africa's e-waste collection network and infrastructure are currently built on the large population of informal waste pickers and small-scale recyclers who provide diverse collection strategies and a wide network of e-waste sources. Estimated numbers of informal waste pickers in South Africa range between 60 000 and 90 000 and even up to 215 000.[21] However, as individually processed volumes remain low and supply is unreliable, the activity is overshadowed by financial insecurity.

The EPR Regulations require measures to integrate the informal collection networks and to compensate those who register with the National Registration Database. The landfill ban can also assist the required economies of scale to achieve a more circular approach to EEE and e-waste management. However, one cause of the low supply volumes is that most e-waste generated is not thrown away but stored in national and provincial government departments, business entities and households.[14] Lydall et al.[14] attribute this to issues to do with data security, the perceived value of EEE (economic and sentimental) and a culture of refurbishing and passing down EEE to members of the family or less privileged communities. Besides e-waste being inaccessible, there is an inability to predict volumes due to incomplete waste data and non-compliance regarding waste information systems.[36]

The lack of adequate local end-processing and refining capacity may also originate from an inherent local culture of exporting unrefined value fractions for final product refining and manufacturing elsewhere.

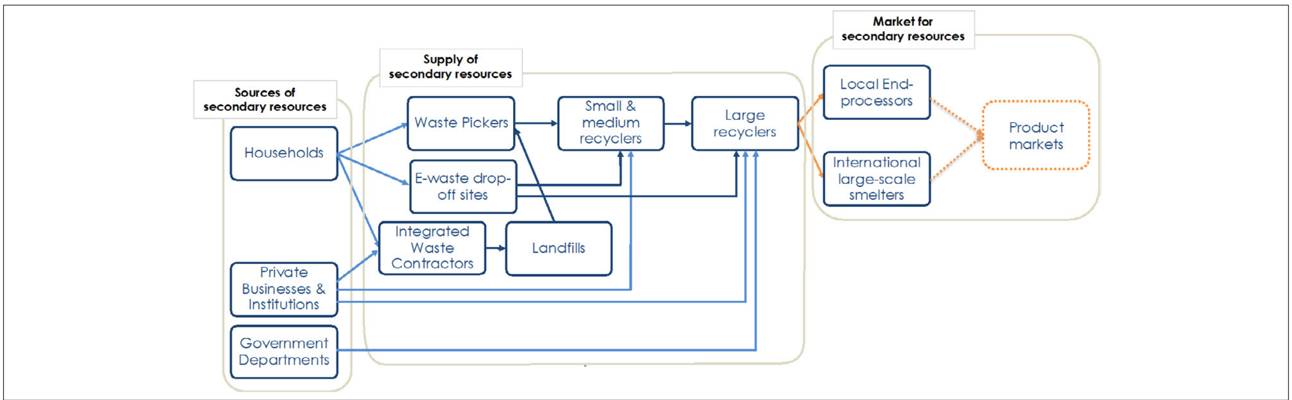

Figure 2: E-waste collection and recycling network in South Africa.[6]

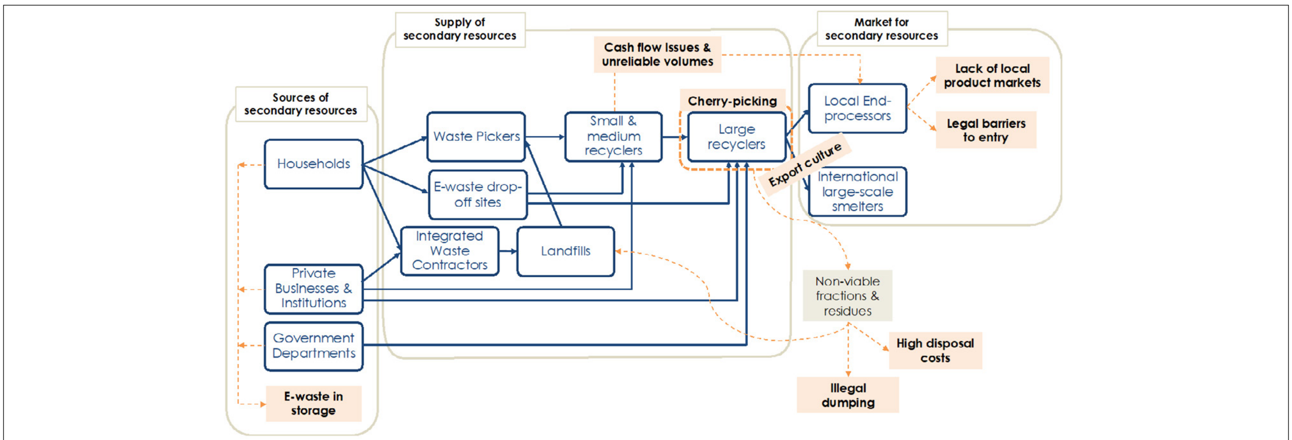

Figure 3: Barriers to local end-processing of e-waste in South Africa.[6]

When assessing metals value chains from the extraction of primary minerals locally, the export-based nature of the local metals industry becomes apparent. High prices in international markets make local end-processing and manufacturing economically unattractive.[37] But there are disadvantages to the current practice of exportation, for example in the context of printed circuit board (PCB). The PCBs are collected, classified into different grades, pre-processed via size reduction then shipped overseas to an importing company that uses their internal assay methods to determine the precious metals content and thus price for the consignment.[6] Consequently, pricing negotiations fall outside the control of South African recyclers. During the interviews, South African recyclers who exported PCBs did not disclose details of the exporting deals, such as the names of the importing companies, or concentration ranges of metal found in the different grades of PCBs. Also, pricing estimates for the different PCB grades were not shared. This was pointed out to be the basis of ensuring competition among recyclers (Anonymous 2 interview) and thus the industry as a whole.[6]

A further barrier includes the impact of China's 'National Sword' policy, which imposed a ban on the import of plastics. The ban impacted South Africa's e-waste recycling industry because most plastics separated from e-waste used to be exported to China (Anonymous 1, Karcher interviews).[6] The ban, and the industry's lack of alternatives, resulted in recyclers either stockpiling plastics or disposing of them in municipal landfills at unprecedented scale. The recycling of plastics from e-waste thus presents an additional value extraction opportunity for South Africa. However, one of the main challenges is the difficulty in the separation of plastic materials, as they are mostly unlabelled and generally composed of mixed grades. Consequently, plastic recyclers in South Africa will not accept these fractions (Anonymous 1 interview).[6] Furthermore, much of the plastics in e-waste contain brominated flame retardants that result in toxic emissions when treated using thermal recycling technologies, which require further treatment.[38] Technological research thus needs to focus on plastic separation techniques, solutions for mixed-grade plastics, as well as treatment of plastics containing brominated flame retardants. Ultimately, of course, the need to recycle and manage the waste stream should be reduced in the first place. To achieve this, waste prevention at the product design stage must be the overarching aim.

In South Africa, most activities in the e-waste value chain are concentrated at the lower end, with most recyclers involved in the collection, dismantling and pre-processing in preparation for export of the value fractions. The volumes generated are insufficient to warrant investment into local end-processing given business models and technologies suitable for the local context. To date, there is only one known operational PCB end-processing plant at SA Precious Metals Ltd which has developed a hydrometallurgical technology for metal extraction from PCBs, with a daily capacity of 2 t. It is unclear whether this technology is financially competitive with international smelters.

Furthermore, to operate economically, a minimum batch volume of 10 t of high-grade PCBs is required by SA Precious Metals. However, this invariably excludes smaller individual aggregators of recycled materials. An example is an unsuccessful collaboration between SA Precious Metals and Square Mobile, a small-scale entrepreneur based in the Western Cape (Square Mobile interview).[6] The challenges that led to the failure of this collaborative effort include:

- Accumulation and storage of the minimum of 10 t of PCBs would usually stretch over several weeks with the associated costs (space, legal compliance) borne by Square Mobile.
- Square Mobile would also need to pay for the shipping of the PCBs from the Western Cape to Gauteng where SA Precious Metals Ltd is located.
- Waiting periods for the profits to be split; profits would be paid only 3 months later.

All these factors resulted in cash-flow problems for a small operator like Square Mobile, forcing them to abandon the venture.

A further limitation faced by the e-waste recyclers is that those who successfully run end-processing operations have the option of choosing only high-grade or high-value materials. This propagates a culture of cherry-picking, leaving the non-viable fractions or residues for disposal elsewhere. This reflects in the local pricing of PCBs by large recyclers, pushing the tendency to cherry-pick to the smaller recyclers and even the waste pickers. A consequence is the informal dismantling/burning of waste EEE, often in public spaces, to liberate these high-value fractions, and illegal dumping of the residue.

Over and above the waste-related licencing costs arising for an end-processor, there are also significant legal barriers and associated licence costs for the trade in precious metals. Also, there is a lack of local markets for products from end-processing, which disincentivises investment in that part of the value chain.[39] An example would be the copper recovered from the copper plating solutions at a local PCB manufacturer which is not of sufficient purity and volume to enable re-sale to any industry using copper as input material (piping, wiring, sheeting) at full market value, and hence it is sold off as scrap at low prices.

To address these barriers, the South African government has taken strides towards investing in research and development through various instruments. The Waste RDI Roadmap and the Technology Innovation Agency funded the University of Johannesburg's Process, Energy and Environmental Technology Station (UJ-PEETS). Other examples include the various National Research Foundation funded waste research chairs, such as the South African Research Chair Initiative (SARChI) Chairs in Waste and Society and Waste and Climate Change. The different research instruments address various areas such as understanding the e-waste value chain and its stakeholders, research into technology development for recovering value materials, life-cycle analysis of technology and social aspects of the e-waste sector, and potential for industrial symbiosis in e-waste processing, to name but a few. Although academic researchers have actively been testing out different technologies and process models, these have been largely confined to bench-scale and concept studies. Assessment of the viability of the proposed approaches requires research to move from bench to pilot and to demonstration scale. Similarly, several baseline studies have been conducted on the social aspects to e-waste recycling but there has been no follow-through to establish if proposed solutions can indeed drive the desired change.

Conclusions

The e-waste industry in South Africa, although not a significant contributor to the waste economy, is recognised to have the potential for growth. However, the extent to which the sector will mature is dependent on the organisation of its collection network as well as the development of local refining and manufacturing capacity. The availability and quality of input materials, and the development of local refining and manufacturing capacity are co-dependent. On the one hand, implementation of context-appropriate technologies at appropriate economies of scale is only possible with sufficient e-waste volumes. On the other hand, the expansion of the industry to downstream processing will encourage an improved and robust collection infrastructure to obtain necessary volumes. Therefore, these two factors would need to be dealt with simultaneously to ensure the sustainability of the industry.

The South African waste sector in general is operating in a transient legislative environment. Although new regulatory instruments are being devised to promote the responsible development of a circular e-waste economy, there are concerns about hindering this desired growth and squeezing out the informal and small-scale operations. These operations currently provide much-needed support, especially on the lower end of the value chain. Interventions of the South African government to drive research, development and innovation in the sector are visible; however, some of the outputs are yet to trickle down to the different tiers of e-waste recycling activities.

To overcome the barriers to a circular economy for e-waste in South Africa, further research to explore policy and legislation mechanisms as well as technology transfer and infrastructure development is recommended.

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Competing interests

We have no competing interests to declare.

Authors' contributions

Z.S.: Conceptualisation; methodology; data collection; sample analysis; data analysis; validation; data curation. T.M.: Writing – the initial draft; writing – revisions. A.L.: Writing, referencing, and revisions, restructuring and inclusion of 'Redefining waste in a circular economy', 'Legal developments towards circularity', and 'E-waste legislation and governance in South Africa'. J.P.: Revisions; student supervision; project leadership; project management; and funding acquisition.

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Appendix: Sample interview questions

Materials received and produced

- What types of e-waste do you deal with?
- Do you deal with any hazardous substances? If so, what is it and what type of e-waste devices does it come from?
- What waste streams do you have? How do you manage your waste streams?
- What product streams do you produce?
- Where do you sell your products?
- What/who are your sources of e-waste (e.g. public or private sector, households)?
- What is your average annual volume of e-waste handled?
- What type of device do you receive the largest volumes of?

Technology and operations

- What e-waste management activities do you do?
- Describe your e-waste collection infrastructure and logistics.
- Has/have your business/operations grown over the years you have been operating?
- Elaborate on the possible reasons for this.
- What sources of income do you have?
- How large is your collection radius?
- What technology do you use?
- How many employees do you have and how are they organised?
- Do you have plans for growing your business? If so, what are they? If not, why?
- How do you communicate with your clients (buyers/ sellers)?
- How do you attract new clients (buyers/ sellers)?
- How is your financial/ business model structured?
- If you could have anything to improve your business operations, what would it be and why?
- Describe the initial steps you took to start up your business.
- What skills did you require to start and maintain this business?
- What skills did you develop through running your business?
- What health and safety procedures do you follow?
- Do you have any traceability procedures to keep track of devices from collection to the time it leaves you?

Trade and legislation

- Do you have any issues with the current legislative framework? If so, what are they?
- If you could change any part of the policy and legislative framework regarding e-waste, what would it be and why?
- What trade regulations do you currently deal with?
- What was the first legal step you followed to set up your business? Describe what the experience was like.

The interview structure varied from interview to interview depending on the flow of discussion. The interviewer allowed for the personal experiences of the interviewee to come up and for them to lead the discussion. Therefore, the above questions did not always follow this order and not all of the questions were always asked or answered. Where deemed pertinent, follow-up interviews were scheduled in order to obtain missing information. Face-to-face follow-up interviews were preferred; however, telephonic and email interviews were mostly done depending on the availability and preference of the interviewee/research participant.

Check for updates

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Transitioning towards a circular bioeconomy in South Africa: Who are the key players?

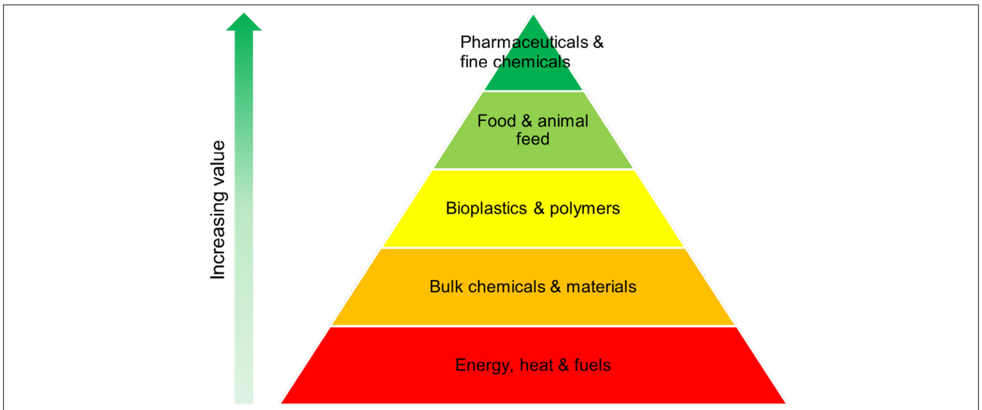
The transition towards a circular economy is becoming a priority in many countries globally. However, the circular bioeconomy has received relatively less attention. In South Africa, the valorisation of organic waste is a priority area as demonstrated by national goals to divert organic waste from landfill. To support the growth of the organic waste value chain it is important to gain an understanding of the different value chain actors and their activities. Through a series of semi-structured interviews across the industry, this paper unpacks the organic waste value chain including the roles of different actors and the interlinkages amongst them. Interviewed actors were those involved in the waste treatment sector, including consultants, composters and technology providers and installers. The value chain is characterised by a number of partnerships, including sub-contracting and outsourcing, which enable value chain actors to offer services that they do not necessarily have the in-house skills or capacity to deliver on their own. The majority of actors were not directly engaged in activities related to the treatment of waste, with many of them engaging in support activities to facilitate the treatment of waste. This finding may be attributed to the fact that support activities have relatively lower barriers to entry. This has the potential to create a bottleneck, in which there will be limited capacity for waste treatment as new entrants opt for engaging in support activities. Greater investment is needed from both private and public sources in the waste treatment sector, including support for new entrants. This investment will help enable the country to meet its goals for organic waste diversion whilst contributing to job creation.

Significance:

- The majority of participants in the organic waste value chain were engaged in support activities.
- The organic waste value chain is characterised by a series of partnerships.
- Greater investment is needed for the development of waste treatment facilities.

Introduction

Circular bioeconomy is a concept that is gaining popularity amongst academia, industry and policymakers. The term 'circular bioeconomy' first emerged in 2015 and has been increasingly used since 2016.[1] It may be considered as the intersection of bioeconomy and circular economy with an emphasis on resource efficiency and the use of residues and wastes as a resource.[1,2] A key aspect of circular bioeconomy is the cascading use of resources in products that create the most value over time to optimise the value of the resource over multiple lifetimes within the circular bioeconomy.[1-3] However, strictly adhering to cascading use may not be possible for economies based on differing priorities (e.g. energy production) or financial constraints.[2,4] To provide guidance for optimising the value of biomass over time, Stegmann et al.[1] present a bio-based value pyramid. This pyramid illustrates the increasing value of bio-based products in relation to the number of resources that can be utilised (Figure 1). The pyramid may also be seen as a one-dimensional view of cascading use, whereby the use of resources cascades downwards from high-value products.



Source: Adapted from Stegmann et al.[1] under licence CC-BY 4.0

Figure 1: Bio-based value pyramid.

From a value perspective, it is recognised that so-called 'low-value' applications may result in greater environmental and socio-economic benefits depending on the context.[1] Furthermore, circular bioeconomy has been identified as a potential avenue for the realisation of some Sustainable Development Goals including those related to responsible consumption and production (SDG 12) and climate change (SDG 13).[5-7]

Sustainable organic waste management is an integral aspect of the circular bioeconomy.[1,3,8,9] In South Africa, the enhancement of waste management practices was highlighted as a priority area in the South African Bioeconomy Strategy released in 2013.[10] In 2017, it was estimated that approximately 19.2 million tonnes of organic waste was generated in South Africa.[11] The National Waste Management Strategy 2020 (NWMS) identifies diversion of organic waste from landfills as a priority area, setting a national target of 40% diversion within 5 years.[12] The need to reduce organic waste to landfill is for a number of reasons including rapidly dwindling airspace. For example, the Western Cape Province, in order to preserve their remaining airspace, has set goals to divert 50% of organic waste from landfill by 2022, with a total landfill ban in 2027.[13] In addition, the waste economy is gaining more traction nationally as a potential avenue for job and income creation as well as for economic growth.[12,14] Ultimately, progress in organic waste diversion from landfill will see an increase in the circularity of the bioeconomy in South Africa.

Circular bioeconomy research is often focused on the treatment and/or production of different bio-based products in the context of the circular economy. With the promulgation of bioeconomy policies and strategies in recent years, research has emerged on the analyses of these, particularly in European countries.[1,7] In South Africa, the majority of research concerning organic waste has focused on treatment options from the lens of technical or economy feasibility.[15] Relatively fewer studies have been conducted into the practicalities of implementing different treatment options including investigations into the value chain. Thus, there is limited understanding of the functioning of the value chain. This presents a limitation during the development of strategies and policies aimed towards the organic waste sector.

Approaches for the prioritisation of different bio-based products differ; for example, implementation of cascading use or implementation of different processes simultaneously depends on the priorities of the different stakeholders.[4] Thus, it is important to establish the different stakeholders and their roles, rights and responsibilities. However, this identification remains an understudied area of research in the organic waste sector.

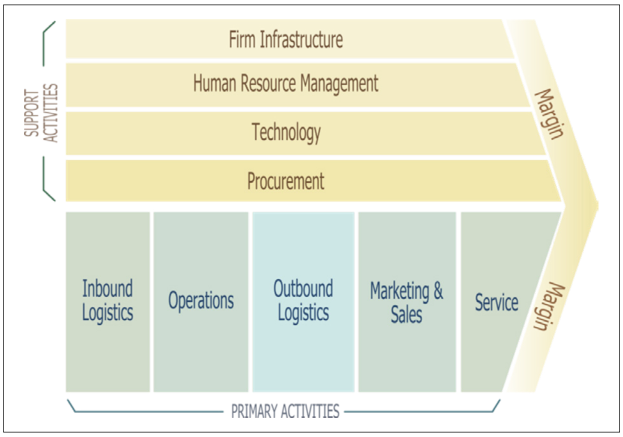
A functional value chain analysis provides a detailed profile of the industry including operations.[16] However, such an analysis is yet to be applied to the organic waste value chain. This paper presents the results of a functional value chain analysis conducted on the South African organic waste value chain from collection to treatment, including identification of value chain actors, their activities and the interlinkages amongst them. In addition, the services which support the value chain are explored. The results are analysed in the context of South Africa's national priorities.

Value chain analysis

A value chain can be described as the full range of activities required to bring a product or service from conception (design) through the different phases of production to delivery to final customers and final disposal after use.[17] The concept was initially introduced by Porter[18] as a tool to enable a firm to assess its activities in order to identify potential sources of competitive advantage. Porter[18] proposed that a firm's activities could be categorised into primary and support activities according to Figure 2. There have been a variety of concepts developed for chain activities and end products similar to value chains: 'supply chains' is a generic term used for the input-output structure of value adding activities from raw materials to finished product, 'commodity chains' place emphasis on internal governance structures, and the French filière approach has generally been applied domestically on primary agricultural export commodities as well as value streams.[17,19] The value chain approach is perceived to encompass all the tenets of the full range of possible chain activities and has gained importance globally in industry as well as in policymaking.

Value chains can be mapped and analysed using value chain analysis which focuses on the dynamics of interlinkages within sectors.[20] A functional value chain analysis aims to provide a detailed profile of the industry,[16] including the identification of actors, activities and the physical flows of commodities.

The analysis can include both qualitative and quantitative tools. Hellin and Meijer[20] recommend a combination of both tools whereby the quantitative study is preceded by a short qualitative study. A purely qualitative research approach is also recommended (for data collection) in scenarios where funds and time are limited, with the reasoning that prices and quantities can be sourced from questionnaires and secondary sources such as national statistics.[20]



Source: Based on Porter[18] under licence CC-BY-SA 3.0

Figure 2: The generic value chain.

Value chain analysis is commonly applied as a strategic management tool used to enhance a firm's competitive advantage.[21] It has also been applied in studies of international trade from a political economy focusing on different actors in the chain and their differential capacities for wealth appropriation.[17,21] However, both applications are concerned with identifying opportunities for profits to be sustained over time. Value chain analysis not only helps to identify bottlenecks and weak links that require attention[16,22], it also brings to light knock-on effects and complex interdependencies along the chain[16,17,22].

Value chain analysis is gaining importance as an analytical tool for policymakers, at national and local levels, who are required to make important social and economic decisions, particularly in countries that are trying to upgrade their industries.[22] Value chain analysis for policymaking can be described as follows[16]:

- Assessing a value chain according to its sustainability performance, including social, environmental and economic criteria.
- Identifying areas of potential improvement that could be implemented via public policy measures.
- Assessing the likely sustainability impacts of the available measures along the value chain.

Organic waste treatment in South Africa

In order to contextualise the value chain, it is important to have an understanding of the organic waste sector in South Africa. According to the State of Waste Report, in 2017, an estimated 49.2 % of managed waste was recovered/recycled.[11] However, it is important to note that there is a notable proportion of waste that is mismanaged in South Africa with Stats SA reporting that in 2020, 37.4 % of households did not have access to refuse removal which often resulted in dumping.[23]

There are a variety of treatment methods for the valorisation of organic waste. In South Africa, the level of development of these options ranges from research and development to commercially established as shown in Figure 3. There a number of factors influencing the selection of a treatment method including feedstock composition, technology availability, and economic, policy and regulatory aspects.[15,24,25] Feedstock availability and quality are critical to the development of sustainable industries; different treatment options require different feedstocks and have different tolerances for variations in quality.[3] In general, treatment

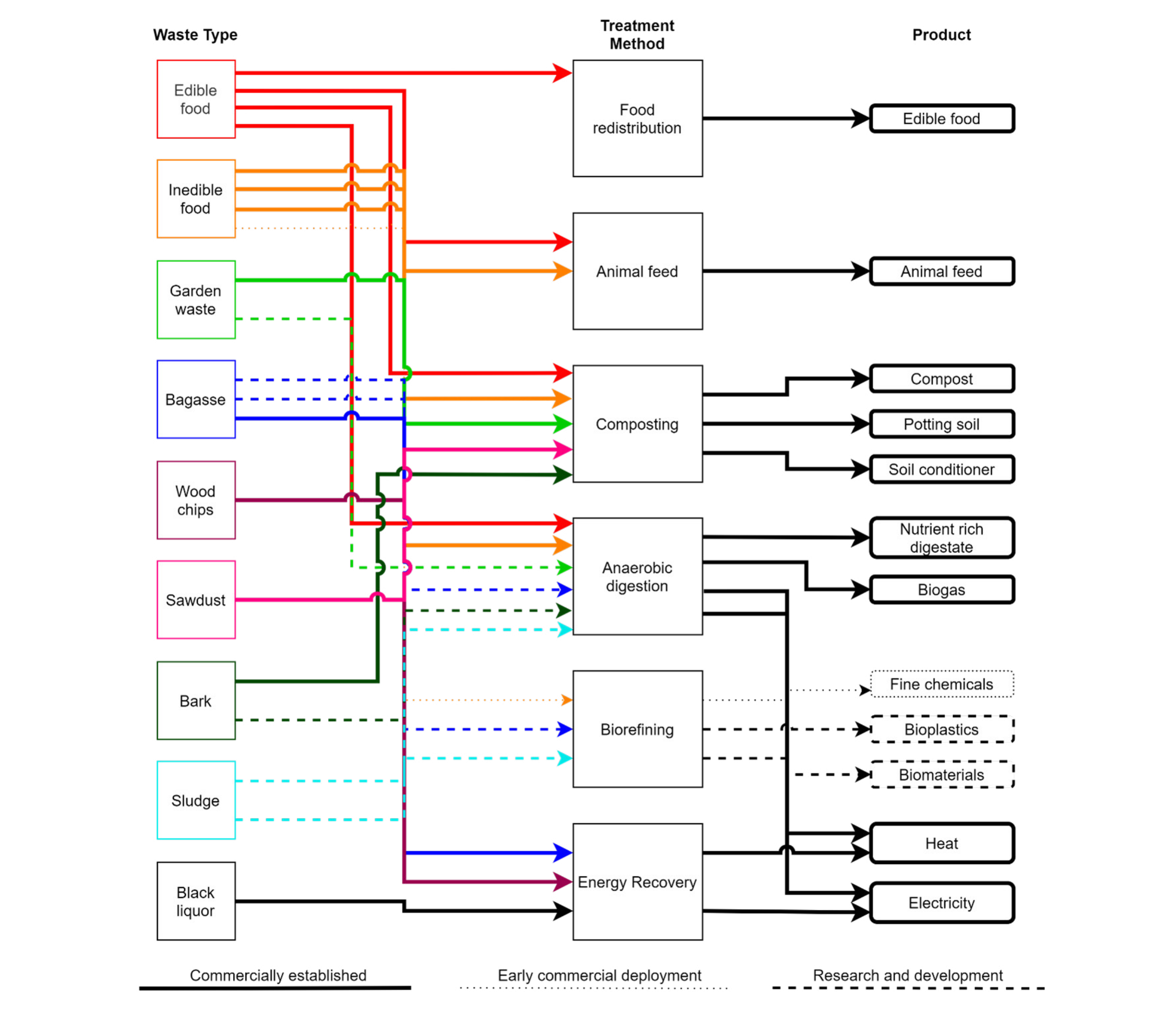


Figure 3: Organic waste treatment methods in South Africa, characterised according to technology maturity.

methods using more advanced technology are associated with higher capital expenditure and operating costs.[15,24-26]

Food redistribution

Food redistribution can take place at various stages of the food supply chain, depending on whether the generated output is fit for human consumption. In South Africa, food redistribution is dominated by two major non-profit organisations (NPOs): FoodForward SA and SA Harvest. These NPOs serve to facilitate the redistribution of surplus food to those in need via services such as soup kitchens and food pantries.[27,28]

Animal feed

Both edible and inedible food may be used as a feedstock for animal feed. The food may be done directly without any conversion or it may be further processed. For example, food waste is utilised as a feedstock by Agriprotein (South Africa) for the commercial production of black soldier fly larvae which provide a source of protein for animals.[29]

Composting

A number of composting methods are employed in South Africa, including open windrow, vermicomposting and in-vessel. A survey conducted nationally in 2012[30] found that open-windrow was the most popular method employed. This popularity may be attributed to its relatively lower capital and operating costs and low skills requirements.[24,31]

Composting is the primary treatment method for garden waste in South Africa.[11] However, there are different methods for its diversion from municipal landfills. Municipalities may contract a company for the chipping and composting of waste or they may set up an in-house composting facility. The model employed depends on a variety of factors including the infrastructure and finances available to the municipality. Further to garden waste, composting is also used to treat wood waste (e.g. sawdust, bark and wood chips), food waste, and manure and poultry droppings.[11,30,32]

Anaerobic digestion

Anaerobic digestion is a well-established technology in South Africa, with adoption dating back to the 1990s.[15] In 2018, a review estimated that there were over 700 installations across the country including domestic and industrial digesters.[33] Digesters can process a variety of feedstocks including harvesting and abattoir waste, manure and food processing waste.[34,35] Digesters can also be used to treat wastewater from breweries and distilleries as well as sludge from wastewater treatment plants.

Biorefining

Biorefining has been identified as an opportunity to develop South Africa's bioeconomy, particularly in relation to the sugar industry.[10,36-38] Sugarcane bagasse can be utilised as a feedstock for the manufacture of chemicals including bioethanol, lactic acid and furfural. Globally, South Africa is one of the largest bio-based furfural producers.[38,39]

The potential for biorefining is not isolated to the sugar industry, with other residues from agriculture and food production being potential feedstocks. For example, Brenn-o-kem utilises grape pomace from the surrounding winelands to produce calcium tartrate, wine spirits, grape seed oil and tannin.[40]

Energy recovery

Waste produced during industrial processes is often used as an energy source within the process. For example, in sugar mills, bagasse is used as a feedstock in boilers to supplement the plant's energy requirement.[38] Similarly, wood offcuts and residues in the forestry, paper and pulp industries are used as a source of process heat.[41]

Methods

The study was informed by primary data collected via interviews with key value chain actors. Semi-structured interviews were conducted from March to August 2021. Semi-structured interviews were selected as they have open-ended questions which allow for the interviewer to ask probing questions to elicit further information.[42] Interviews were conducted electronically or telephonically in adherence with COVID-19 protocols. The interviews lasted from 30 min to 60 min depending on the activities of the participant. Audio recordings were made of each interview which were later transcribed. Interview analysis was conducted using the software Atlas.ti 9. A priori analysis was employed whereby themes were identified when preparing the interview protocol based on the aims of the research.[43]

Value chain actors' roles in the organic waste value chain, including their activities and their business journeys, were explored through the interviews. The value chain actors were all from the waste treatment sector, including consultants, composters, and technology designers and installers. Value chain actors were selected based on their role in the organic waste value chain with the aim of ensuring a diverse sample pool. This selection was combined with availability sampling as not all contacted value chain actors were willing to participate in the study. Snowball sampling was also used, whereby some interviewees were willing to introduce the researcher to other actors in the sector.

Not all interviewees' companies were focused solely on organic waste related activities. However, their other activities were also waste related. In such cases, they were interviewed only about their organic waste related activities.

In total, 15 interviews were conducted. As shown in Table 1, the interviewees had varying years of experience in the sector. The interviewees' head offices were based in three provinces: Gauteng, KwaZulu-Natal and the Western Cape. However, it should be noted that many of them operated nationwide depending on the feasibility of the activity. For example, consultants are able to provide their expertise nationally whilst composters are restricted to the location of their operations. The activities of the actors are shown in Table 2.

Table 1: Interview participants, their years in the sector and head offices at the time of the interview

Participant	Years in sector	Head office
A	10+	Western Cape
B	<2	Western Cape
C	2 – 5	Gauteng
D	2 – 5	Gauteng
E	2 – 5	Gauteng
F	2 – 5	Gauteng
G	5 – 10	KwaZulu-Natal
H	10+	Gauteng
I	10+	Gauteng
J	10+	Western Cape
K	10+	Western Cape
L	<2	Western Cape
M	10+	Western Cape
N	5 – 10	KwaZulu-Natal
O	5 – 10	Gauteng

The participants' identities have been anonymised and efforts have been made to exclude any identifying information.

This research was approved by the University of the Western Cape Humanities and Social Science Research Ethics committee (number HS18/2/5).

Table 2: Participants' self-reported organic waste related activities

Participant	Collection	Consulting	On-site waste management	Reporting	Technology design	Technology provision/ distribution	Technology installation	Waste brokering	Waste treatment/ conversion	Treatment method
A	✓								✓	Composting
B	✓	✓	✓	✓				✓		
C	✓	✓	✓	✓				✓		
D	✓	✓	✓							
E						✓	✓		✓	Composting
F		✓			✓			✓		
G		✓								
H	✓				✓	✓	✓			Composting
I		✓			✓					Anaerobic digestion
J						✓	✓			Composting
K		✓								
L									✓	Waste to energy
M	✓				✓	✓			✓	Waste to energy
N							✓			Anaerobic digestion
O							✓			Anaerobic digestion

Results and discussion

Business origins

Participants had various motivations for entering into the organic waste management sector. Some participants had a direct interest in organic waste beneficiation which motivated them to enter the sector. Participants B and D cited their personal experiences with waste as their motivation whilst Participant H stated it was a personal home project that expanded. Two of the participants were already working in the broader waste sector so expanding their services into organic waste was a natural progression for them.

The desire to contribute to the transition towards a circular bioeconomy was only brought up by two participants: A and K. They emphasised the importance of putting in place solutions that close the loop in the circular bioeconomy. Nonetheless, all participants were participating in the circular bioeconomy, regardless of intent.

Sector activities

Actors in the organic waste value chain often participate in multiple activities related to the recovery of organic waste, as shown in Table 2. Treatment options have been shown for those who participate in waste treatment and/or technology design and/or installation as part of their activities. It is interesting to note that the majority of treatment methods encountered mirrored those that are emphasised by the NWMS, namely composting and anaerobic digestion.

On-site waste management

On-site waste management services often relate to the recovery of source separated and can extend to its on-site treatment. Common services offered are the provision of sorting bins and training of on-site staff. The separated organic waste is then transported off-site for treatment. In some cases, waste generators may opt for an on-site treatment option, depending on their waste generation rates and their internal needs for the products (e.g. compost, biogas).

Consulting

The increasing popularity of a circular economy has placed a spotlight on responsible waste management. When coupled with the national goals for the diversion of organic waste from landfill (as discussed in the Introduction), waste generators are under increasing pressure to find solutions. To address this, they have been turning to waste consultants for answers.

Waste consultants offer a myriad of services, including developing strategies for waste management which are aligned with the waste hierarchy and, more recently, the circular economy. Potential solutions consultants may present include waste minimisation strategies as well as recommendations for more sustainable waste treatment methods. Consultants also facilitate connections between clients and companies offering the treatment options of interest. Essentially, consultants have carved out a space to act as intermediaries between waste generators and treaters, thus eliminating the direct communication line between the two. However, according to Participant G, in the initial phases, 'There was suddenly push back… they were like, why can't we deal with the decision makers directly?'.

Waste consulting was a popular activity amongst interviewed actors. This popularity may be attributed to a low barrier of entry, as consulting does not require high start-up costs or a lot of infrastructure. However, actors highlighted that the key to being a successful consultant lies in having 'connections' within the industry to bolster their reputation. Participant D stated succinctly, 'Your network is your net worth'.

It is important to note that not all participants were consulting as their primary activity of choice. Participant F expressed that they were only consulting as a means of keeping their business afloat until their activities of choice grew enough to be their primary source of income. They described consulting as a 'means to an end'.

Waste brokering

A broker is a person who arranges or facilitates the sale and purchase of goods between actors. Waste brokering is not a practice that is unique to South Africa.[44-46] Globally, waste brokers facilitate the transboundary movement of waste, largely from developed to developing nations.[45] In the organic waste sector, brokers can be considered intermediaries who do not physically handle the waste but facilitate its treatment or diversion to a manufacturing process. This facilitation may be done through a series of partnerships or via subcontracting (discussed further under 'Interlinkages amongst actors').

Similarly to consulting, waste brokering can be considered to have a low barrier of entry from a financial and infrastructure perspective. As stated by Participant C:

> *You know if you're going to be a waste treater, you have to have access to land – you've got to lease or you own it. You've got to service that. You've got to get people to go there. A waste broker can sit behind the phone; if he's got the connections he can connect A and B.*

He further emphasised the importance of having industry contacts to become a waste broker:

> *No, you can't become a waste broker until you've got contacts, and contacts take years to develop. So you've got to pay some school fees for a couple of years. Unless you've been in a similar or related industry or something. You can't just suddenly become a waste broker.*

Technology design, distribution and installation

The technology aspect is broken down into specific activities as a company may not participate in the entire process from design to operation. Some actors have seen an opportunity to become distributors for international technologies. This was particularly noted in the composting sector for in-vessel composters. For anaerobic digestors, technology providers are more likely to be involved in the design aspect. For example, Participants N and O were technology installers working in partnership with an anaerobic digester provider. It was noted that the anaerobic digestion technology providers and installers did not operate the technology; instead they chose to train on-site workers to operate the equipment. Participant I specifically cited their desire to contribute to capacity development in the sector, supporting small operators who install their technology. At most, a provider may monitor the technology off-site and conduct maintenance. Participant J had a similar hands-off approach:

> *The only thing to do is support from a technical perceptive, we don't provide any operator on site, assistance apart from training, we don't measure and we don't record. We don't have anything to do with the day-to-day operational systems that they put in place.*

Waste treatment

Waste treaters are actively engaged in the treatment of waste, converting it from its original form to a different product. Whilst technology providers provide the means for waste treatment, they are not involved in the day-to-day running of the process. In essence, they facilitate the treatment of waste. Furthermore, the product of these technologies may require further treatment. For example, some in-vessel composting units produce a precursor to compost which still needs to be further composted in open composting facilities.

As mentioned previously, composting and anaerobic digestion are well-established technologies in South Africa. Furthermore, the NWMS specifically cites these methods when it comes to the treatment of organic waste.[12] Thus, unsurprisingly, the majority of interviewed waste treaters were involved in these sectors (Table 2). Furthermore, those not involved directly in waste treatment referred to these methods.

When discussing organic waste treatment options, the same waste treaters were mentioned multiple times by different actors. This suggests a relatively small waste treatment network. Cost is a major factor when selecting waste treatment methods. Significant start-up costs are required when developing a waste treatment facility. A study conducted in 2014 estimated capital costs for small scale windrow systems with capacities of 5–500 kt/year to range from ZAR6 million to ZAR10 million.[26] As the technology requirements increase, so do the capital costs. For example, the aforementioned study estimated capital costs of ZAR120 million to ZAR220 million for a 2500 t/year plant.[26] When looking at operating costs, a similar trend is observed whereby open windrow composting is associated with lower operating costs than anaerobic digestion.[47]

There is relatively less focus on the production of high-value goods (Figure 4) in South Africa. Whilst biorefining of organic waste is a priority research area[48], this has not translated to industry action as of yet. For example, residues from sugar mills can be used as feedstocks for a variety of chemicals and thereby provide an opportunity to develop the local bioeconomy.[10,36-38] However, a study found that the economic returns were not high enough to attract investment.[36] Thus, it may be suggested that, from an economic perspective, low-value treatment options are more attractive due to lower capital and operating costs.

Organic waste value chain

The activities that occur in a value chain may be categorised into primary and support activities. In the organic waste value chain, the primary activities are the generation of waste and its separation into desired fractions followed by its collection and transportation to waste treatment facilities (as shown in Figure 4). For firms which opt for on-site treatment, transportation to a facility is not necessary. The same activities were identified by Campitelli and Schebek[44] in a review of waste management systems.

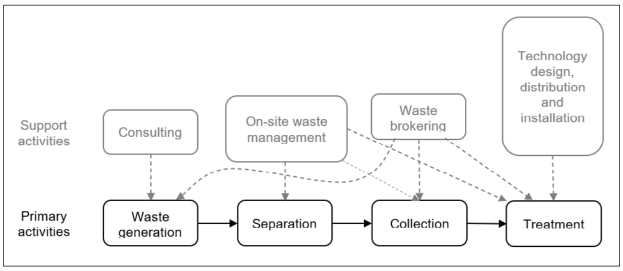


Figure 4: The organic waste treatment value chain, depicting both primary and support activities.

Support activities facilitate the functioning of the value chain. As outlined in the section on 'On-site waste management', this aspect comprises a suite of services across the value chain. All the primary activities can take place on the same site as waste generation. Consulting services provide support to waste generators through advising on how they can best manage their waste. Whilst waste broking facilitates the linkages between the waste generators, transporters and treaters.

As demonstrated above under 'Waste treatment', in comparison to waste brokering and consulting, setting up a waste treatment facility is associated with higher start-up costs. Furthermore, as the technology requirements of the treatment methods increase, so do the capital and operating costs.[49] The high costs may serve as a barrier for new entrants into waste treatment. Thus, new entrants in the sector may opt to engage in support activities. This scenario creates the risk for a bottle neck to develop in the value chain, whereby there will not be enough capacity for the treatment of organic waste, but many actors to facilitate its diversion from landfill.

Interlinkages amongst actors

The functioning of the value chain is underpinned by the relationships that exist between actors. The relationships can take multiple forms including symbiotic relationships, informal as-needed relationships and more formal arrangements. Whether or not money flows between actors in a partnership is highly dependent on the situation. Common partnerships that exist are those between consultants and technology providers and waste treaters. As consultants do not necessarily have the infrastructure to treat the waste, they must rely on others in order to make this offering to their clients. Thus, a consultant may partner with a technology provider on the understanding that the consultant gets paid a commission for each successful recommendation. A consultant may also partner with a waste treater such as a composter; they may or may not be charged gate fees depending on the arrangement.

A common partnership that was raised by a number of participants is that with waste management companies. Participant H stated: 'the [Their] business model is to partner with waste companies, rather than compete against them.' Waste management companies often have existing contracts with commercial clients. Thus, to market their services to the client, actors must work with the existing waste management company. This work may include training their employees in the separation of waste or the operation of their technology offering.

In some cases, an actor may need to bring on other consultants who need to be paid for their work. This may be considered to be a form of subcontracting. Subcontracting is not an unusual practice in the organic waste sector. Larger companies may also subcontract smaller companies that have the expertise to deliver on the services the former has advertised. Outsourcing is another common practice within the organic waste sector. It is particularly prevalent for transportation for the collection of waste from the generator.

Partnerships are not unusual in supply chains.[50] One of the key motivations for partnerships is the focus on core competencies, whereby a business may choose to develop partnerships for activities that they do not deem to be their core competencies. As such, it is not unusual for actors in the sector to advertise services they do not have the in-house expertise to fulfil. They instead rely on outsourcing, subcontracting or partnering with other companies to fill the gap. This situation creates an interdependency amongst actors in the organic waste sector. Only one participant, Participant M, spoke negatively about partnerships: 'No its a recipe for disaster that. No, I've been there, done that, got burnt.'

Employment

The majority of participants had direct employees within their firms but Participants B, F and K worked alone. Participants D, N and O also worked alone but hired people on an ad-hoc basis. For Participant C, creating employment was not a high priority:

> *From a commercial point of view, employment is less important, not saying it's not important because we employ a lot of people... but that's not the reason we're in business, primarily we're looking for solutions.*

Participant H held similar views: 'So the objective of our business is not employment, the objective, we see ourselves as a technology business not as an operating business.' In contrast, Participant I considered creating employment opportunities as part of their business model. They partnered with SMMEs (small, medium and micro enterprises) to install the technology, providing training and business mentorship.

In South Africa, the waste economy is commonly touted as an opportunity for job creation.[12,14] Participant A holds the same view: 'The green economy, bio-economy, has a massive role to play in job creation in sustainable economic inclusion, in developing countries around the world'. However, in the organic waste sector, the question really comes down to where these jobs exist. Many large commercial waste generators often already have either an in-house waste management system or a contract with a waste management company for the separation of recyclables from general waste. Should an actor wish to pitch their services for organic waste treatment, this might include working with the already present waste management company (as mentioned above). In such cases the existing on-site staff would be trained on the new system and/or technology. Thus, there is a reduced need to bring in new employees and low potential for job creation. Moving further down the value chain, the potential for job creation increases, especially for off-site waste treatment. There are potential employment opportunities for the transportation of waste as the volumes increase.

When comparing the job creation potential of different waste treatment options, open windrow composting is associated with higher potential in comparison with in-vessel composting and anaerobic digestion.[47] For anaerobic digestion, jobs are created for the construction and operation of the digestion. However, it must be noted that construction jobs are not necessarily permanent jobs as people may be recruited from the surrounding area to complete the task. According to the Southern African Biogas Industry Association[51], significantly more jobs are created during the construction phase in comparison to direct permanent jobs. For composting, low technology composting methods require more employees.[30] Labour is required not only for tending to the windrows, but also for separation and unpackaging of pre-consumer waste.

It is important to take into consideration the types of jobs that may be created and the associated skill level. Participants involved in waste treatment stated that there are job opportunities for unskilled workers as on-the-job training is provided. Specifically, Participant A stated:

> *I think the waste sector has such an important role to play in job creation for people with no or little skills that can be easily transferred where they can earn a decent wage, support their family back home in the Eastern Cape, get the kids though school, and start contributing to tax and income tax, and all of those attributes lacking in most of the sectors in the economy.*

Participant J expanded on the issue of skills requirements:

> *So the school level is, from our point of view, is it's all self taught and self learnt. So you don't have to have a degree; you don't have to have a diploma. You just have to have a laptop and read and absorb and understand the process. But I think a lot of it is learnt through practical, observing and seeing.*

These sentiments are supported by research conducted in the biogas sector[34] and composting sector[30,52].

Conclusions and recommendations

The results indicate that there are relatively more value chain actors participating in support activities than in primary activities. This finding may be attributed to the relatively higher barriers to entry for primary activities (e.g. waste treatment). This scenario may potentially lead to an imbalance in the sector, whereby there are more actors who recommend alternatives to disposal than there is treatment capacity. Furthermore, as the sector grows, there is a risk that new entrants will shy away from treatment activities, creating a potential bottleneck in the organic waste value chain.

To facilitate the transition towards a circular bioeconomy, interventions are required to ensure the growth of the waste treatment sector. Whilst the South African government has set national goals for the diversion of organic waste from landfill, there has been little guidance provided as to how these goals will be achieved. Specific focus should be on the development of capacity in the treatment sector in the form of new waste treatment facilities. Capacity development should not be limited to the private sector, but should include participation from provincial and local governments. Furthermore, the focus on the treatment of waste will also facilitate the creation of jobs and income opportunities.

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Competing interests

We have no competing interests to declare.

Authors' contributions

T.Y.C.: Conceptualisation; methodology; data collection; data analysis; writing – the initial draft; writing – revisions; project management. C.S.: Conceptualisation; writing – revisions; project leadership; funding acquisition.

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Definitions matter: Including the socio-economic dimension as a critical component of SADC circular economy definitions

Globally, scholars agree that there is a lack of clarity on the notion of the circular economy (CE) and a lack of consensus on a foundational definition of the term. Some definitions place greater emphasis on the socio-economic dimension of the CE than others. In Africa, notions of the CE are still evolving. This paper highlights the salient aspects of texts defining or informing the CE in the Southern African Development Community (SADC). In Africa, the transition to circularity is motivated by the need to stimulate job creation and income generation. At the same time, concern over mounting environmental impacts is increasing. Economic and population growth on the continent, continued urbanisation, and the resulting proliferation of municipal waste contribute to these economic, social and environmental challenges. African governments, business communities, civil society and academia need to collaborate on initiatives that build on circularity principles to advance sustainable development in pursuit of equitable and just societies. This exploratory semi-systematic literature review contributes not only to developing notions of the CE in Africa, but also to the dialogue on circularity in the Global South. In particular, it investigates the extent to which the socio-economic dimension is incorporated in notions of the CE. Moreover, it argues that a strong emphasis on this dimension is imperative in the conceptual development of circularity on the African continent. We argue for the future foregrounding of definitions of the CE that are consistent with social transformation as an aspiration in regional legislative and regulatory frameworks.

Significance:

- Contributes to conceptualisation of the CE in the Global South.
- Indicates how SADC policy dictates the importance of the socio-economic dimension as a regional priority, and therefore signals the primacy of this aspect in the development of a contextual notion of CE.
- Includes a review of grey literature related to the SADC region in the analysis of the notion of the CE.

Introduction

Researchers have acknowledged that there is a lack of a universally accepted definition of the circular economy (CE).[1-3] Furthermore, conceptual analysis reveals a plethora of definitions[4,5], and definitions emerge from multiple epistemological fields[3]. Several scholars have described the concept of the CE as an 'empty signifier'.[6,7] The notion of the CE accommodates various interpretations and approaches (D'Amato[4] refers to 'conceptual plasticity') and underlines the conceptual difficulties presented by the diversity of perspectives (see Kirchherr et al.[5]) and the risk of collapse or deadlock stemming from 'permanent conceptual contention'[5]. This is not the case only in the Global North (GN), but also in the Global South (GS), where it is even more pronounced.

The definitional challenges are compounded by the broad diversity of critical sub-themes of the CE, the differential rates at which the CE has gained traction globally, and a research focus that is highly biased towards the GN. Developing countries in general[8], and the GS in particular, have also been underrepresented in conceptual analyses of the CE[2,9,10] (see, for example, Kirchherr et al.[5]; Winans et al.[11]; Ghisellini et al.[12]). In a recent bibliometric analysis of articles on the CE published between 2004 and 2020, available from the Scopus database, Muchangos[13] found that the majority (over 80%) of articles pertained to the GN and China, and that the growth in CE articles related to the GS has become noticeable only since 2016. Moreover, research indicates that the meanings and motivations connected to the CE diverge in the GN and GS.[13] In the GS, as Kirsch[14] states with reference to Schröder et al.[15], the focus is on the reduction and eradication of poverty, and the enhancement of wellbeing, while minimising harm to others and the environment. In the GN, the emphasis is on the reduction of carbon emissions and waste. This thematic divide is confirmed by Muchangos[13], who concludes that research related to the GS emphasised waste as a resource and collaboration in the creation of joint value, while future-oriented design received the least attention.[13] Where similar themes were explored in both the GS and GN, for example waste as a resource, the common denominator was research attention to e-waste.[13] However, studies on GS locations also focused on other aspects of the theme of waste as a resource, such as municipal solid waste management and socio-economic aspects related to waste reclaimers, while GN studies gave equal attention to bio-waste treatment and e-waste.[13] Similarly, Gutberlet et al.[16] highlight social inclusivity (in particular of waste reclaimers) and participation in public policy formulation, implementation and evaluation as important CE themes in the GS, while acknowledging that the GN pays attention to the challenges of improving engineering and governance related to resource loops. These differences are related to the dynamics and relational politics involving governments, business and residents in the two geographical regions.[14] Kirchherr and Van Santen[8] also point out that differences of approach to the CE may be due to 'different policy environments, availability and access to funding, levels of educational and professional development, as well as available infrastructure',[8] while Winans et al.[11] ascribe the dissimilar evolution of the concept to different cultural and socio-political systems. Hofstetter et al.[9] and Turing[17] argue that the inclusion of the experience of the GS may highlight the importance of doing more with fewer resources and practising frugality.

Comparatively, the social dimension of the CE appears to play a more predominant role in the motivation for the development of the CE in the GS. Recent literature from the GN on the conceptualisation of the CE confirms that this dimension is generally not well integrated[18-20], and advocates more attention to social aspects[21-23]. Mies and Gold[19] mention four reasons for inadequate attention being paid to the social dimension of the CE, namely an absence of conceptual clarity regarding the social dimension; blurred boundaries of the social, environmental and economic aspects of the CE; problematic operationalisation of indicators for the social dimension; and a predominantly instrumental approach to the CE. The question is whether this inadequate consideration of the social dimension in the conceptualisation of the CE is also true for the GS, Africa and southern Africa. This study aims to investigate this question by first determining the significant characteristics of CE definitions in the Southern African Development Community (SADC) region, and then relating these to the social dimension of the CE.

This exploratory semi-systematic review investigates the salient characteristics of CE definitions in the GS, with an emphasis on socio-economic components. The focus is on the SADC region, which comprises Angola, Botswana, Comoros, Democratic Republic of the Congo, Eswatini, Lesotho, Madagascar, Malawi, Mauritius, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia and Zimbabwe.[24] It is 30 years since the adoption of the SADC Treaty in 1992. The preamble to the treaty states the resolve of SADC countries to alleviate and ultimately eradicate poverty by means of integration and sustainable economic growth and development.[25] According to Article 12(2)(a)(i), (iii) and (iv) of the SADC Treaty[25], three of the core areas of integration are trade, industry, finance and investment; food, agriculture, natural resources and environment; and social and human development. Article 21 further lists areas of cooperation necessary for integration, including food security, land and agriculture; trade, industry, finance, investment and mining; social and human development and special programmes; science and technology; natural resources and environment; and social welfare. The Regional Strategic Indicative Development Plan (RISDP) 2020–2030 highlights six strategic priority areas for SADC, which include industrial development and market integration, social and human capital development, and several cross-cutting issues such as environment and climate change.[26] Although the development of a regional CE strategy is listed as an outcome of the RISDP 2020–2030, it is still in its initial stages. This document does not define or foresee operationalisation of the term apart from distinguishing it from the SADC Green Growth Strategy and Action Plan and the SADC Blue Economy Strategy.[27]

It is therefore clear that integration and sustainable development are key to the aims of SADC, and that the promotion of green growth and of the blue and circular economies forms part of its strategic priorities. Because the CE is instrumental to the achievement of sustainable development, investigating salient characteristics of the notion in this region is necessary in order to evaluate the compatibility of interpretations of the concept, and ultimately to advance integration of the member states of SADC as an international organisation. Further research in this regard is necessary to critically assess the viability of translating the CE into practice in the GS. In this regard, Kirchherr and Van Santen[8] have already observed that businesses 'are beginning to lose interest in CE again – it's just too difficult to implement'. Unless the concerns of SADC practitioners receive consideration, the realisation of the strategic priorities of SADC for the next decade are also under threat, and the integration of member states remains problematic. This article is an exploration of the salient characteristics of the CE definitions in an attempt to contribute to conversations about compatible understandings of the notion, and ultimately to stimulate strategic approaches to conceptual engagement in the interests of regional integration.

Methodology

The research methodology used for this study can be categorised as an explorative semi-systematic literature review. Frederiksen et al.[28] describe an exploratory review as a review intended to provide a broad approach to the research topic, and they add that the emphasis is on breadth rather than depth of topic coverage in order to achieve a general orientation towards the topic area. In Snyder's[29] typology of approaches to literature reviews, the semi-systematic review similarly provides an overview and tracks the development of a research topic in terms of, for example, themes, state of knowledge, history or

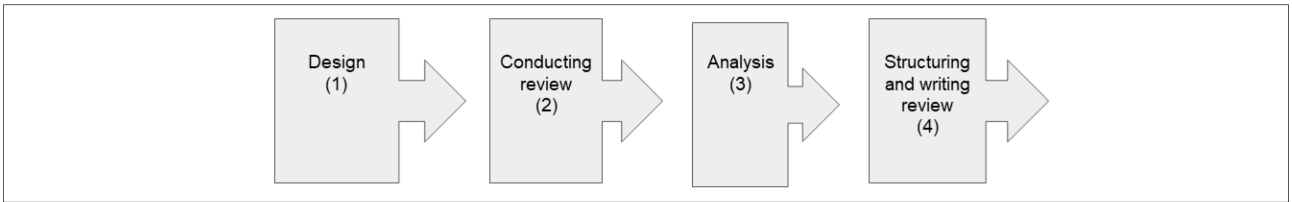

Figure 1: Literature review process based on Snyder[29].

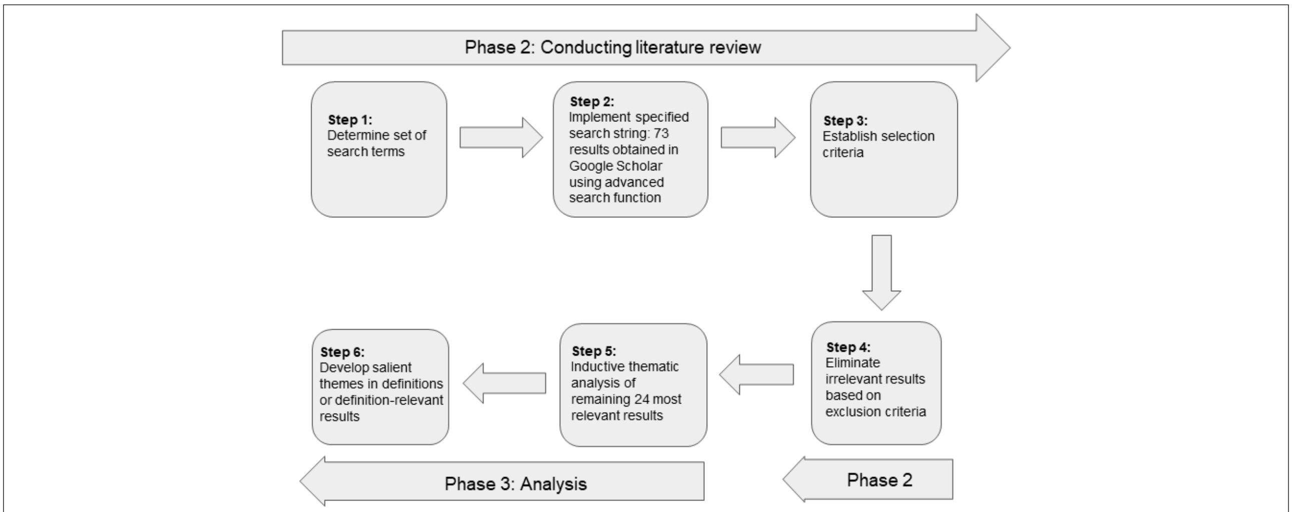

Figure 2: Detail of Phases 2 and 3: Process and figure partly modelled on Snyder[29], Lutz et al.[30] and Brown et al.[31]

research agendas over time. The qualification that this type of review must track development over time might be interpreted as disqualifying research themes that are currently developing and trending, are fairly recent or demonstrate uneven conceptual development across various geographical regions. Therefore, we have opted for hybrid terminology based on Frederiksen et al.[28] and Snyder[29]. In this study, the phases of this review are modelled on a synthesis of the description of the research process by Snyder[29], Lutz et al.[30] and Brown et al.[31]

Snyder[29] distinguishes four phases of the review process, namely design, conducting the review, analysis, and structuring and writing the review. The schematic presentation of the exploratory literature review by Lutz et al.[30], and their approach to data abstraction, informed the succession of procedures included in Phase 2 (conducting the review) and Phase 3 (analysis), as identified by Snyder[29]. We also drew on the discussion of inclusion and exclusion criteria by Brown et al.[31]

During Phase 1 (design), we decided on the exploratory literature review as our research methodology. The decision was made to use Google Scholar as the relevant database for this review in order to include grey literature and to counter the limited results returned when searches are restricted to academic sources. A search on Google Scholar provides the added benefit of returning more recent research results in terms of grey literature sources that are not subject to the time lag experienced in the publication of traditional academic articles and books. Grey literature is defined as:

> *manifold document types produced on all levels of government, academics, business and industry in print and electronic formats that are protected by intellectual property rights, of sufficient quality to be collected and preserved by libraries and institutional repositories, but not controlled by commercial publishers, i.e., where publishing is not the primary activity of the producing body (12th International Conference on Grey Literature, 2010, cited in Bonato[32]).*

Grey literature was included because academic articles on the definition of the CE in Africa are scarce, and a 'coherent body of high-quality, relevant, peer-reviewed articles'[33] is not yet available. Other benefits of not limiting the search to white literature include the richness of source material, the availability of data that cannot be located in commercially published literature, the reduction of publication bias and the improved currency of information on trending topics that would not have been subject to lag time due to long publication processes.[34]

Phase 2 (conducting the review) consisted of four steps. In Step 1, we determined a set of search terms to be employed in the literature search. The following search terms were used in a string search on Google Scholar during September–October 2021: 'definition', 'circular economy', 'SADC' and 'socio-economic'. We used this specified search string to identify academic articles, e-books and grey literature. The results were limited to publications from the last five years.

Initially, in Step 2 of Phase 2 of our review, 76 results were obtained based on the search using the specified search string. The grey literature consisted of situation analysis papers, dissertations and theses, technical reports, white papers, background reports, draft white papers, policy reports, inception reports, team reports, conference abstracts and proceedings.

During Step 3 of Phase 2, selection criteria were established. These criteria were then applied to narrow down the results in Step 4 of Phase 2 of the review. Sources were excluded based on accessibility constraints, citations of a source without linking to the source, duplication of sources, or citations to literature without links to the sources. Other sources that were excluded had a global scope and did not specifically refer to Africa in relation to a CE definition. Lastly, sources were only selected if they provided a definition of CE, or if seminal aspects of the definition of CE could be derived from the source. Eventually, 52 sources were excluded (one of which was a duplicate result). Table 1 lists the remaining 24 results.

Table 1: Results remaining after the application of exclusion criteria

Source	Literature type
Cloete and South African Institute of International Affairs (SAIIA)[41]	Situation analysis paper (between a policy briefing and an occasional paper)
Turing[17]	PhD (International Development)
Grant[49]	Academic article
Ramsarup and Ward[37]	Source book to support skills planning for the green economy by skills planning entities
Kadhila[38]	MPhil (Environmental Management)
Ozor and Nyambane[39]	Technical report
DST[43]	White paper
Colombo et al.[62]	Background document for 13th Annual Meeting of the Infrastructure Consortium for Africa
Martins[44]	Academic article
Frost[36]	LLM
Haimbala[55]	MSc
DST[50]	White paper (earlier version of DST, 2019[43])
Ndlovu[45]	MPhil dissertation
Manjengwa[57]	Master of Engineering (Metallurgical Engineering)
Hlophe-Ginindza et al.[70]	E-book
Kühlmann and Agutu[42]	Academic article
Lydall et al.[58]	Technical report
Van der Westhuizen[48]	MBA research project
Zulu[71]	Master in Public Administration dissertation
South African Technology Network and National Scientists and Organisations[47]	Position paper
Trimble et al.[40,66]	Conference proceedings
Van Niekerk et al.[72]	Technical report
Izaaks[73]	Master in Engineering Management minor dissertation
Sutcliffe and Bannister[56]	Report

Phase 3 of the review involved analysis. In Step 5, we used inductive thematic analysis (see Vaismoradi et al.[35]) of the remaining 24 most relevant results, while we developed the salient themes of the definitions or definition-relevant results in Step 6. Thematic analysis was chosen due to the lack of previous studies covering this theme in the SADC region as a whole, and categories were deduced from the data in the selected sources (Vaismoradi et al.[35]). In addition, thematic analysis enabled consideration of both latent content (developing themes) and manifest content (developing categories). As Vaismoradi et al.[35] state, thematic analysis does not depend on quantifiable measures, but instead pays attention to salient aspects linked to the research question. Finally, after concluding our analysis, we structured and wrote the review in Phase 4.

Results and discussion: Trends in definitional approaches

The following salient aspects or trends in definitional approaches emerged from the inductive thematic analysis.

1. Adherence to canonical definitions

In terms of reliance on established definitions of the CE, some sources referred particularly to what may be termed 'canonical definitions' in the sense that they are generally recognised as the most important and influential. These include the definition proposed by the Ellen MacArthur Foundation (EMF) as well as the definition developed by Kirchherr et al.[5] on the basis of the analysis of 114 definitions of the CE. It appears that the EMF definition is quite prominent. Investigation showed that definitions cited from other sources often originated from the EMF definition, for example, the World Economic Forum's definition of CE referred to by Frost.[36] Although the EMF definition seems to be a common point of departure, there is evidence that it is not accepted entirely without criticism, as illustrated by Ramsarup and Ward[37] and other authors, for example Kadhila[38], who rely on the more comprehensive definition by Kirchherr et al.[5] Comprehensive definitions that do not neglect the social dimension of the CE are more strategically aligned with the objectives and priorities of SADC, as noted in the introduction.

2. Linking the CE to larger discourses on the green economy, sustainability and eco-innovation

A salient theme in the selected sources is the association with more familiar, and sometimes older but also broader, concepts such as sustainability,[17,39-45] the green economy[39,43,46-49] and eco-innovation.[39,50] Andriamahefazafy and Failler[10] note that the CE has been implemented under the umbrella of concepts such as the green and blue economies. This has been pointed out by scholars (D'Amato & Korhonen[51]; Andriamahefazafy & Failler[10]; Turing[17]; Johansson & Henriksson[52]; Geissdoerfer et al.[18]) with reference to the concept of sustainability. The CE serves as one of the ancillary narratives, and not as a substitute for sustainable development.[10] A problem with the narratives of the circular, green and bio economies is that they 'have been developed and largely used in a siloed manner and often disjointed from the overarching framework of strong sustainability or global net sustainability'.[51]

The conceptual complexities of sustainability and the CE, as well as the relationship between them, have received much attention in the academic literature.[46] Moreover, pinpointing the relationship between these two concepts has become a dominant theme in the discourse.[53] Relationships vary from conditional (where the CE is seen as a condition for sustainable development), to beneficial (where sustainable development benefits from the CE) or to a trade-off (where CE has both positive and negative effects on sustainability).[18]

The green economy (GE) supports the leveraging of ecological processes to benefit humans without endangering ecosystem sustainability.[51] The concept is not new and has been acknowledged in the scientific literature, although there seems to be renewed interest spurred by various organisations, such as the United Nations, the Organisation for Economic Co-operation and Development, the International Monetary Fund, the World Bank, the World Trade Organisation and the World Business Council for Sustainable Development.[51] The definition of the GE by the United Nations Environment Programme (UNEP) underscores the importance of human wellbeing, poverty reduction, social equity and inclusivity.[51] Ramsarup and Ward[37] also emphasise that the GE amounts to more than an economic growth agenda in that it advances sustainability and provides a pathway to attain the goals of the 2030 Agenda for Sustainable Development. These objectives also play an important role in SADC objectives and strategic priorities for the next few decades. It is therefore understandable that this concept has traction in the selected literature. In fact, in terms of sustainability, D'Amato and Korhonen[51] note that from a comparative perspective, the GE recognises the inevitable dependence of society and the economy on the global biosphere, while the CE recognises this only to a degree.

Ozor and Nyambane[39] define eco-innovation (EI) as:

> *the creation of novel and competitively priced goods, processes, systems, services, and procedures designed to satisfy human needs and provide a better quality of life for everyone with a whole-lifecycle minimal use of natural resources (materials including energy and surface area) per unit output, and a minimal release of toxic substances.*

The authors concede that this concept seems to be novel, and that the narratives of sustainable development and the green economy have been accepted and integrated to varying degrees. Similarly, De Jesus et al.[54] identify a lack of analysis of the nexus of CE and EI. Some points of departure in clarifying this intersection include viewing EI as an essential driver of change towards sustainability, and singling it out as a pivotal aspect in developing competitive technologies as well as institutional forms.[54] These generate environmental benefits such as efficient consumption and resource use, labelling it as a catalyst of the CE and key to the transition from a linear economy to a CE.[54] De Jesus et al.[54] conclude that EI presents a pathway to a process premised on 'cooperation and multi-actor "systemic" integration'. The CE, they propose, is contingent on this process.[54] Again, the social dimension, also evident in the selected literature[39], is significant and complements the agenda of SADC.

It should be noted that another concept that would fall under this heading, namely the blue economy, was mentioned as ancillary to the CE, and not necessarily the other way around (see Haimbala[55], and compare with Andriamahefazafy and Failler[10]). This hierarchical divergence can contribute to confusion.

3. Contrasting the CE with the linear economy

The CE is also defined in juxtaposition to the linear economy (LE). Some authors take a more neutral point of departure in explaining the contrast between the LE and the CE. Sutcliffe et al.[56], for example, still describe the CE as an alternative to the LE. Other authors portray the CE as a concept associated with a transition to a different system (DST[50]; D'Amato & Korhonen[51]; Frost[36]; Manjengwa[57]; Lydall et al.[58]) or as a replacement for the LE, as illustrated in the work of Frost[36], and Ramsarup and Ward[37]. Some sources express a strong resolve to move away from the LE (Ramsarup and Ward[37] phrase it as a commitment) and point to the damage caused by the LE[40].

4. Foregrounding the life cycle approach

Consideration of a life cycle approach, also described as life cycle thinking (LCT), that takes into account the entire physical life cycle of products, starting with production from raw materials right up until the end of life (Heiskanen[59]), and includes consideration of their environmental, social and economic impacts (Petit-Boix et al.[60], drawing on the Life Cycle Initiative of UNEP and the Society of Environmental Toxicology and Chemistry [UNEP-SETAC][61]), has been part and parcel of the consideration of environmental burdens for decades. Some of the sources in the selected literature incorporate LCT into their definitions.[62] An example that demonstrates this approach is the conference paper by Trimble and Phuluwa[40]:

> *CE calls on a new view of design and deployment of technology, which promotes a continuous life cycle that avoids waste and system degradation and optimises utilisation of energy and other resources.*

Another source links the CE and the life cycle approach, with the former being instrumental in the realisation of the latter (see, for example, the position paper by the South African Technology Network & National Scientists and Organisations[47]).

5. Adapted definitions to incorporate socio-economic aspects such as growth and the drive for social equity and justice

One of the most important aspects of CE definitions in the selected literature is the adoption of definitions that incorporate socio-economic aspects. Globally, scholarly literature covering the last five years, which was excluded because these sources fall outside the parameters of this study, confirm that consideration of the social dimension of the CE is often lacking.[3,4,52,53,63] Neglected aspects of the social dimension that require attention include governance, justice and cultural change.[2] Moreover, within the existing research that does cover the social dimension of the CE, certain geographic regions are underrepresented. A 2020 global systematic literature review examining research on the social dimension of the CE from 2009 to March 2019 found that 70% of the relevant studies included were conducted in Europe, 23% in Asia and a mere 7% were geographically linked to Africa, North America and Latin America combined.[64] However, there is evidence that some canonical definitions include this aspect (see, for example, Kirchherr et al.[5]). A further challenge is the classification of social issues. Padilla-Rivera et al.[64] point out that there is no consensus in this regard and refer to social thematic areas proposed by the EMF[65], including labour practices, decent work, human rights, society and product responsibility. Each of these thematic areas includes detailed social aspects based on the Social Life Cycle Assessment methodology. We propose that this classification system is a useful point of departure, although as a caveat we would add that the classification of specific social aspects and the division of broader thematic areas might need to be adjusted to align with the legislative frameworks of specific regions and countries. Certain social aspects, for example, well-being, diversity and equal opportunity, are also explicitly aligned with constitutional human rights in certain SADC countries and do not relate only to the theme of labour practices and decent work. Some authors of the literature selected for our study acknowledge that a social dimension seems to be lacking in the framework and principles of the CE, or opt for definitions specifically crafted to incorporate social aspects. Although evidence of the choice for this definitional alliance is emerging in the CE literature concerning the SADC region, it appears to be in its infancy. However, in some of our selected sources, the CE is positioned as instrumental in achieving social objectives (see Kadhala[38]; Madyira et al.[66]). Madyira et al.[66], for example, view the CE as a measure to achieve the realisation of human rights. In particular, the authors highlight access to clean energy and clean water, poverty alleviation through job creation, and entrepreneurial opportunities as promoters of social equity.[66]

Economic growth is another socio-economic dimension that is integrated in the interpretation of the CE. The CE is posited by some authors as a source of growth, providing economic opportunities associated with new services and business models (see, for example, DST[50]). However, growth should be decoupled from the use of limited resources.[46]

Conclusion

This article presents the results of an exploratory semi-systematic literature review based on a search conducted with a specified search string of terms in order to return results that could be fully included within the limitations of the current publication. This study does not claim to be comprehensive, but serves to stimulate discussion about the conceptualisation of the CE and its alignment with the objectives of regional policy frameworks, as well as the inclusion of the social dimension in CE definitions applied in and related to SADC member states. It also emphasises the need for critical evaluation of the compatibility of various interpretations of the CE with SADC objectives. This is necessary to guide meaningful implementation, recognising that, in the SADC region, the CE ought to transcend a narrow focus on the environment and account for its impact on society.

In this regard, we highlight five aspects emerging from the selected literature, and they are not mutually exclusive. The first is an adherence to canonical definitions, including both traditional and more conservative definitions, as well as more recent and comprehensive definitions that include the socio-economic dimensions. Secondly, the literature links the CE concept to established narratives, such as the overarching sustainability narrative and the green economy, although the CE is also tied to more novel notions such as eco-innovation. Thirdly, the CE is also defined by contrasting it with the LE. Although some sources approach this comparison in a neutral way and present the CE as an alternative to the LE, a more decisive commitment towards a transition is also evident. Fourthly, the life cycle approach is also foregrounded in definitions or linked to the CE by means of association. Finally, some authors demonstrate awareness of the lack of a social dimension in the interpretations of the CE, and accordingly respond by depicting the CE as a measure to attain socio-economic objectives such as social equity through the promotion of human rights and economic growth. These socio-economic objectives are commensurate with the objectives and strategic priorities of SADC mentioned in the introduction. Based on these five trends, we conclude that although there is an emerging awareness of the importance of the social dimension of the CE, and some authors deliberately opt for a canonical definition that includes social aspects, this is not yet the norm, as is evident from the dominance of the EMF definition of the CE in the selected literature. However, even if the social dimension is not explicitly acknowledged in definitions, it is supported by the network of other broader, sometimes older, but more familiar concepts such as sustainability, the green economy and eco-innovation. These concepts acknowledge social benefit, social needs, and, in the case of sustainability, even contain a social component or pillar. By recognising that these concepts all contribute to the CE discourse and conceptualisation, and by drawing attention to their common social concern, the social dimension of the CE in the SADC region can be amplified. Highlighting social impacts within life cycle thinking could have a similar effect. Finally, deliberate, vocal and critical positioning in relation to the LE also has the potential to contribute to the promotion of the social dimension of the CE. The trends that emerge in the selected literature can therefore be interpreted as open to the cultivation of a pro socio-economic stance in SADC. Given the socio-economic objectives of SADC as a region, we would recommend the amplification and promotion of socio-economic dimensions in conceptualising the CE. Critical reflection on the inclusion of the social dimension in the choice of definitions, consideration of the origin of CE definitions, and the conceptualisation of the CE in the SADC region could serve as a starting point for such a realignment. However, this project should not be undertaken by academics alone. There are broader African CE networks consisting of a wide range of stakeholders, including specialists and coalitions led by governments, whose objectives align with those of SADC but are not explicitly linked in the literature. Their input could play a valuable role in this regard. These networks include, for example, the African Circular Economy Network (with wide membership categories and CE experts), which envisions:

> *a restorative African economy that generates well-being and prosperity inclusive of all its people through new forms of economic production and consumption which maintain and regenerate its environmental resources.*[67]

Another example is the African Circular Economy Alliance (ACEA), a coalition of African nations led by governments, promoting the transformation to a circular economy in order to deliver 'economic growth, jobs, and positive environmental outcomes'[68] to address the challenges of 'poverty, poor infrastructure, and unemployment'[68]. The ACEA also states that its support for the CE could consist of policy development[68], and that it could thus potentially be involved in highlighting the social dimension of the CE.

This study is subject to certain limitations, including the length restriction of the publication, as well as the limitation on references that inevitably rules out the application of search strings that would return a large corpus of results. Further research could therefore incorporate results from less constrained search strings and include search strings from several databases, such as the Web of Science, although some studies indicate that most of the literature in the Web of Science can also be found using Google Scholar.[68] Moreover, although Google Scholar is frequently used as a web-based search engine, in particular where researchers also need to rely on grey literature, and generates a substantial quantity of results, the incorporation of other resources could be beneficial as the application of similar search strings does not overlap considerably.[69]

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Competing interests

We have no competing interests to declare.

Authors' contributions

L.G.: Conceptualisation; methodology; data collection; writing – initial draft. C.S.: Writing – revisions; methodology; student supervision; funding acquisition. D.B.: Writing – revisions; methodology; referencing.

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Circular closed-loop waste biorefineries: Organic waste as an innovative feedstock for the production of bioplastic in South Africa

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The impact of landfills on the environment has come under increasing scrutiny in recent years due to the confounding effects of climate change and water scarcity. There is an urgent need to reduce from landfills the greenhouse gas emissions that cause climate change, and to provide effective treatment solutions for waste, thereby diverting it from landfills. With an estimated 80 million tonnes of plastic waste entering the world's oceans annually, the accumulation of marine plastic has become a global crisis. Plastic pollution threatens food safety and quality, human health and coastal tourism, and contributes to climate change. For these reasons, there is an urgent need to explore a bioplastic biorefinery process. This review paper examines the potential of organic waste as an alternative carbon source in the efficient and feasible microbial production of polyhydroxyalkanoate (PHA) and polyhydroxybutyrate (PHB), which are precursors for bioplastic. More specifically, this paper presents a concept for a bioplastic biorefinery from a technological perspective, based on data from previous studies. Biofuel production processes are also assessed with the aim of integrating these processes to construct a bioplastic waste biorefinery. Garden refuse and food waste have been shown to be feasible feedstocks for the production of PHA and PHB in singular processes. Diverting these wastes away from landfills will significantly ease the environmental impacts currently associated with their disposal.

Significance:

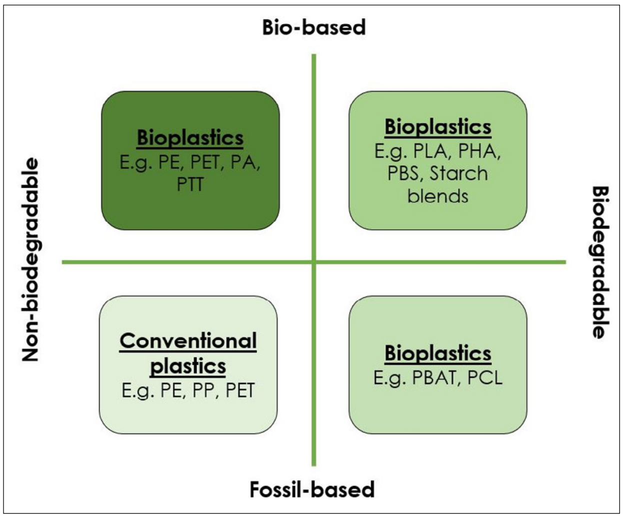
- A bioplastic biorefinery is a viable alternative to treat municipal organic waste.
- Several biofuel production processes can be integrated into a bioplastic biorefinery system.
- Organic waste is poorly managed in South Africa, resulting in greenhouse gas emissions.
- Several barriers and considerations must be overcome before implementing the technology at full scale.

Introduction

Large-scale plastic manufacturing began approximately 70 years ago, and since then an estimated 8.3 billion tonnes of plastic has been manufactured.[1] This sum is growing at an accelerated pace.[2] Most of this plastic cannot be reprocessed efficiently on a worldwide scale, and therefore it still exists in some form.[1,3] The ubiquity of plastic waste on the earth's surface has prompted some to argue that it might be regarded as a geological indication of the Anthropocene era because of its prevalence.[4] Because of advances in waste management systems over the last few decades, more end-of-life alternatives for plastic have become available, and collection rates have increased as a result.[1] The ultimate destination of many plastic goods is still unknown, particularly in underdeveloped nations.[5] Some of the reasons for this include a lack of global statistics, a lack of official collecting mechanisms in many areas, and unreported waste disposal, including unlawful dumping and unsupervised burning.[2]

Current estimates of where today's plastics will be discovered in 20 years' time reveal that the vast majority have been thrown away, including all packaging. There will be some recycling (mostly downcycling) or incineration of plastics, but the bulk will end up in landfills, and some may become unmanaged litter and end up in the ocean. Packaging is a major contributor to litter and ocean plastic, especially in developed countries. After plastic has entered the ocean, it is almost impossible to remove, which means it quickly accumulates.[6] By 2050, approximately 20% of global oil consumption may be devoted to plastics manufacturing, resulting in 15% of greenhouse gas (GHG) emissions. Plastics are also expected to outnumber fish in the seas by then, according to some projections.[7] Up to 12 million tonnes of plastic ends up in the ocean each year, and 50% of marine litter is made up of single-use plastic products.[7] The indiscriminate use of fossil fuels continues to increase atmospheric carbon dioxide levels. It is therefore imperative that alternatives such as bioplastics are investigated. 'Bioplastic' can have several different meanings, including (i) biobased but not biodegradable, (ii) biodegradable but not biobased, and (iii) biodegradable and biobased, as illustrated in Figure 1. This paper will focus on bioplastics that are biobased and biodegradable. Biobased plastics are generally considered to be plastics that are produced from biological or organic material. For this reason, organic waste has been proposed as a feedstock for the production of bioplastics in a biorefinery setup.

A biorefinery is described as 'The sustainable processing of biomass into a spectrum of commercial goods (food, feed, materials, and chemicals) and energy (fuels, electricity, and/or heat)' by the International Energy Agency (IEA) Bioenergy Task 42.[8] A biorefinery may also be a concept, a facility, a process, a plant, or even a cluster of facilities that combine many different disciplines of expertise, such as chemical engineering, chemistry, biology, biochemistry, biomolecular engineering and others.[8,9] Biorefineries are similar to traditional oil refineries that produce a variety of goods and fuels from petroleum. The IEA emphasises that a biorefinery not only meets the demand for biobased products with functional qualities comparable to those produced from fossil resources, but also provides a distinct advantage by addressing problems of sustainability in all areas – economic, social and environmental. It uses renewable biomass as a feedstock, and reduces biobased product manufacturing costs through economies of scale and the development of green technology. Biorefineries are versatile enough to be used all over the world due to the diversity of local wastes, sugar cane, excess food, straw and aquatic biomass, as well as the biomass component of municipal solid refuse, all of which are potential feedstocks for a biorefinery.[10] Biorefineries have the added advantage of producing carbon-neutral products such as certain biofuels, which ultimately have the potential to reduce the carbon footprint.



PE, polyethylene; PET, polyethylene terephthalate; PA, polyamide; PTT, polytrimethylene terephthalate; PLA, polylactic acid; PHA, polyhydroxyalkanoate; PBS, polybutylene succinate; PP, polypropylene; PBAT, polybutylene adipate terephthalate; PBL, plastic barrier laminate

Figure 1: Different categories of plastics and bioplastics.

This review paper has several objectives. The first is to investigate the potential of organic fractions of municipal solid waste (OFMSW) streams as suitable feedstock for a waste biorefinery process. This is followed by an investigation into the feasibility of bioplastic production from OFMSW. Next, a bioplastic biorefinery is explored based on previous studies, and a bioplastic biorefinery incorporating biofuel processes is proposed. All processes are viewed through the lens of utilising this bioprocess as a tool for waste management in South Africa. Furthermore, all processes are presented from a technological standpoint.

Building blocks for bioplastics

Polyhydroxyalkanoates (PHA) are microbial storage compounds that may be used as polymers for various applications after extraction, compounding and extrusion. The polymer used in the product may be recycled together with other plastics once it has been used. As with other synthetic materials, PHA may be broken down by aerobic and anaerobic bacteria found in soil and water11, which makes it less of a concern during its end-of-life phase. The shift to a post-fossil carbon world necessitates the development of PHA as a viable alternative to traditional plastics. PHA granules are carbon and energy sources for a wide variety of bacteria that can manufacture them intracellularly. When an excess of carbon is available at the same time as a restriction in one or more nutrients, the PHA granules are often generated under imbalanced nutritional circumstances. Nitrogen or phosphorus is usually the medium's only limitation with respect to polymer synthesis. The organism's metabolism shifts from growth to PHA accumulation as a result of this restriction. These compounds are synthesised by a wide variety of microorganisms, including members of the phyla Gram-negative eubacteria, Gram-positive eubacteria, archaea and microalgae. Only the genus Pseudomonas produces mcl-PHA, or medium-chain length PHA. Polymers may range in molecular weight from 50 kDa to 1000 kDa, with a molecular weight distribution of 100–30 000 monomers, depending on the culture circumstances. PHA molecules aggregate within cells into granules due to their apolar nature. Every cell has at least one granule that is passed down via the DNA. Cellular polymer loads may be very high when the granules are combined. Once the cells are full of PHA, all that remains is to remove the polymer and convert it into usable plastic. Because organic solvents have a high recovery rate and purity while still being inexpensive, this technique is often used to extract PHA from residual biomass.

The annual manufacturing capacity of PHA was 900 000 tonnes in 2015. The price of PHA is a significant deterrent to its gaining a larger portion of the market share. PHA is considerably more costly than other biopolymers. In 2014, the price range was between ZAR67 and ZAR79 per kilogram, which was much higher than the prices of other well-established biodegradable and biobased polymer materials.[12] Prices are anticipated to drop if the quantities produced surpass the pilot production scale, because of the savings that come from manufacturing at a larger scale. The price of PHA is also affected by the price of raw materials and the method of extraction. As a result, raw material costs are critical, accounting for up to 50% of total manufacturing costs.[13] The prices of refined sugars or fatty acids/lipids, which are presently used in industrial processes, are just as variable as the raw material costs. They are heavily reliant on oil prices, which have been rising steadily for decades. A search for low-cost raw materials for PHA synthesis has been launched to become less dependent on this significant cost. For this reason, organic waste appears to be an attractive feedstock for this process.

OFMSW as a potential feedstock for bioplastic

The organic fraction of municipal solid waste (OFMSW) has long been demonstrated as a suitable feedstock for many different bioprocesses. However, there is a dearth of knowledge on the production of bioplastic building blocks from OFMSW. This section aims to present the potential of OFMSW as a feedstock for bioplastic production.

OFMSW contains several waste streams, including fruit and vegetable waste, food waste and garden refuse. According to the Food and Agriculture Organization (FAO), 780 million tonnes of fruit and vegetable waste are produced each year.[14] South Africa is a significant fruit-growing country, with annual citrus, grape and apple production totalling 2.1 million, 1.8 million, and 0.79 million tonnes, respectively. Figure 2 shows the respective proportions of these fruits in the primary fruit production of South Africa. Large amounts of waste are produced during the processing of these fruit streams. For example, 25–35% of processed apples, 50% of citrus, and 20% of grapes are projected to be wasted.[15] The bulk of fruit and vegetable waste is generated during the harvesting and processing phases in developing countries, whereas little waste is produced during the consumption stage.[16]

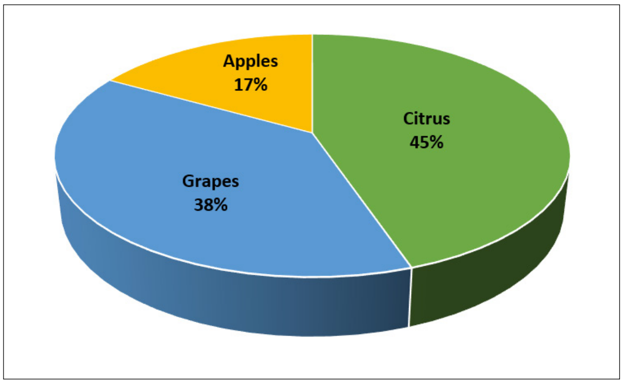


Figure 2: Primary fruit produced in South Africa.

Food waste includes all waste and by-products generated during the manufacturing, processing, wholesale, retail and consumption of food.[17] Although the content of food wastes differs, food waste from comparable sources has a consistent composition.[18] According to the FAO, approximately one third of all food produced for human consumption is lost or wasted worldwide, resulting in 1.3 billion tonnes of food waste each year.[17] Food waste, as one of the most common types of municipal solid waste in many nations, has sparked a great deal of research in recent decades into creating improved valorisation methods to recover energy and nutrients.[19] Composting, animal production, anaerobic digestion and incineration are just a few of the food waste disposal methods that are now accessible on an industrial scale throughout the world.[20] Meanwhile, half of the world's population lives in cities, where waste management is critical for dealing with the massive amounts of food waste produced every day. Innovative solutions are needed to deal with this ever-increasing waste type.

A 2013 study estimated that the annual wastage of food in South Africa amounts to 9.04 million tonnes per annum.[21] Additionally, fruit and vegetable waste is also produced in huge amounts owing to agricultural activities, supermarkets and wholesale marketplaces. In South Africa, a significant portion of this waste is currently diverted to landfills where it poses serious environment problems. The organic material decomposes and forms GHG, such as methane, which is released into the atmosphere. More concerning is the cost associated with the disposal of food waste, with a 2015 study estimating disposal costs at over ZAR3 billion.[22] A more recent estimate, taking into account disposal, clean up and effects on livelihoods, indicated that plastic pollution cost South Africa a staggering ZAR885 billion in 2019.[23] Furthermore, and more alarmingly, some of the biggest cities in South Africa (Johannesburg, Tshwane and Cape Town) have less than 10 years left before their landfills are rendered incapacitated.[24]

OFMSW is generally considered a very rich carbon source for various bioprocesses. For instance, garden refuse, and fruit and vegetable waste are lignocellulosic-based biomass, meaning that they are composed of cellulose and hemicellulose bound by a stiff lignin polymer. Monomeric glucose units and xylose units make up cellulose and hemicellulose respectively. This indicates the material's fermentability, either indirectly via enzyme catalysis, or directly through microbial decomposition. However, the lignin layer is regarded as extremely resistant to degradation, which significantly hampers process yields. For this reason, pretreatment is often a required step in a lignin-based biorefinery in order to enhance the digestibility of the material. Several pretreatment technologies exist and have been applied to a vast array of feedstocks. The type of pretreatment used can have significant impacts on process feasibility and economics.

South Africa has not established a separated waste collection plan. For this reason, OFMSW arrives at transfer stations mixed and contaminated with other microbial species. This is an important consideration, because 'dirty' OFMSW can significantly hamper the process dynamics in many ways. One concern is the introduction of competing microorganisms, which could reduce the productivity of the microbes employed in either saccharification or the fermentation process. Another concern is the cross-contamination of microbes, resulting in premature degradation of the feedstock and thereby reducing the calorific value of the waste. The microbial dynamics of the process therefore require further elucidation to provide clarity on the feedstock quality.

Bioplastic biorefineries

As defined earlier, biorefineries are made up of several different processes that function together to valorise a feedstock and produce multiple products. In recent decades, a multitude of studies have evaluated singular bioprocesses to produce either biofuels (such as bioethanol, biomethane, biohydrogen and biodiesel) or bioproducts (such as pharmaceuticals, enzymes and bioplastic monomers) from organic material. Through analysing the process flow chart of applicable bioprocesses, several singular processes can be strategically combined to create a theoretical bioplastic biorefinery. At the same time, it is important to understand the feedstock and its by-products through every stage of the process in order to ensure its complete valorisation.

PHA manufacturing cannot be industrialised without paying careful attention to the techno-economic environment, for example, the competing uses of raw materials or resources such as land in order to drive it towards economic viability. About a decade ago, the increased production of biofuels sparked a global debate about land use in relation to 'food versus feed'. Since then, a worldwide perspective has been required for every new biobased product. Bioplastics need only a tiny fraction of the world's agricultural land to produce enough feedstock. The amount of land currently being used for the manufacturing of bioplastics is insignificant. However, bioplastics will be increasingly required in the future as the economy moves away from fossil fuels, which could raise the amount of land required 500-fold. A land usage of 5% of global agricultural land or 15% of the world's arable land would be considered to be unacceptably wasteful. Accordingly, substituting bioplastics for petrochemical-derived plastics would require considerably less land than at present. No additional acreage is needed if waste products are utilised as carbon sources. It is possible to turn by-products into a wide range of goods. In reality, an increasing number of stakeholders view industrial by-products as stepping stones to a biobased economy.[26] By increasing competition, the most efficient usage method would benefit. These by-products must be the most competitive usage method for the long-term development of PHA. Cascadic usage is the most essential notion in relation to the utilisation of waste products and virgin biomass. This implies that a biorefinery, which uses biomass holistically, incorporates multiple bio-processes. As described above, the biorefinery is an integrated biobased industry that utilises a variety of technologies to produce products such as chemicals, biofuel, food and feed ingredients, as well as other biomaterials, fibres, heat and power, all with the goal of maximising added value along the three pillars of sustainability.[26] Thus, PHA synthesis would be one stage in the cascading use of biomass, similar to the present plastic manufacturing process in an oil refinery, as previously stated. A biorefinery in Brazil, for example, uses sugar cane to make sugar (sucrose), ethanol and a compound called poly(3-hydroxybutyrate) (P3HB), another building block for bioplastics.[27] Byproduct molasses from the sugar crystallisation stage is transformed to P3HB in this biorefinery. An ethanol distillation by-product called long-chain alcohols is used to extract the polymer from the cells. Bagasse, a waste product, is burned to generate process energy. The polymer can be manufactured inexpensively and with sufficient purity using this improved method.

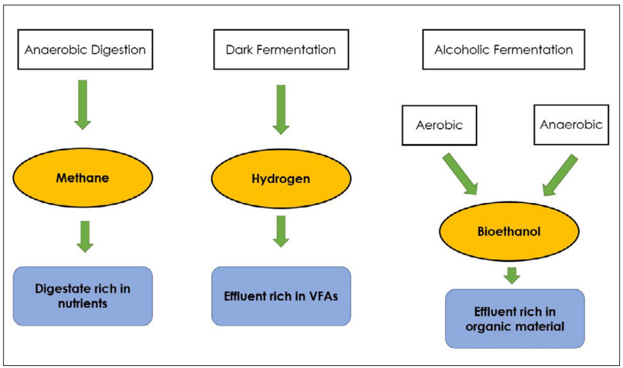
Several studies have examined the production of bioplastic from organic waste, as summarised in Table 1. Ebrahimian et al.[28] explored the production of both biofuels and bioplastics from OFMSW. These authors subjected the feedstock to an acetic acid catalysed ethanol organosolv pretreatment at 120 °C for 60 min to enhance enzymatic hydrolysis. The remaining solid residue following hydrolysis was channelled towards methane production through anaerobic digestion, yielding 23.1 L. The pretreated hydrolysate (containing 498.5 g glucose/kg) was fermented with *Enterobacter aerogenes* PTCC 122 and yielded 139.1 g 2,3-butanediol, 98.3 g ethanol, 28.6 g acetic acid, 71.4 L biohydrogen, and 40 g PHA. Colombo et al.[29] reported on the enhanced production of PHA from OFMSW by employing a mix of microbial consortia from activated sludge. This study optimised the organic acid production, resulting in 151 g/kg, and consequently optimised the PHA fermentation process yielding 223 g/kg. The production of PHA from OFMSW was also investigated at a pilot scale.[30] A combined treatment of OFMSW and sewage sludge was explored in a fed-batch system, resulting in 65 g PHA/kg total volatile solids. This is an important study, as it indicates the feasibility of setting up a large-scale bioplastics bioprocess from OFMSW. Another pilot-scale study analysed the production of PHA from OFMSW at high pH and ammonia concentrations.[31] These authors found that the highest PHA accumulation of 77 wt% occurred as pH increased towards 9 and the ammonia concentration was 500 mg/L.

Table 1: Polyhydroxyalkanoate (PHA) yields from various studies employing the organic fraction of municipal solid waste (OFMSW) as a feedstock

Feedstock	Inoculum	Yield	Reference
OFMSW	*Enterobacter aerogenes* PTCC 22	40 g PHA/kg	Ebrahimian et al.[28]
OFMSW	Activated sludge	223 g PHA/kg	Colombo et al.[29]
OFMSW–sewage sludge	–	65 g/kg total volatile solids	Valentino et al.[30]
OFMSW	–	77 wt% PHA	Mulders et al.[31]
OFMSW	Anaerobic digester effluent	45% PHA	Martin-Ryals et al.[32]

Several biofuel processes, such as biomethane, biohydrogen and bioethanol, result in volatile fatty acid (VFA) production as a by-product. VFAs are precursor compounds that are further metabolised by microorganisms to produce PHA.

There are many technologies that can be integrated into a bioplastic biorefinery, as illustrated in Figure 3. Some of these include anaerobic digestion, dark fermentation and alcoholic fermentation.



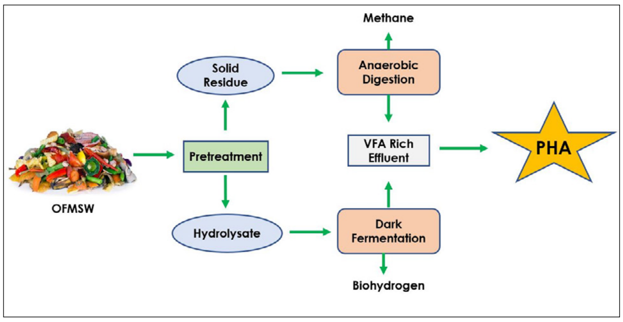
VFA, volatile fatty acids

Figure 3: Schematic of potential biorefinery technologies that are capable of being coupled with bioplastic production.

Anaerobic digestion (AD) is one of the most commonly employed technologies in bioprocess systems owing to its ease of use, scale up and economic outlook.[33] Moreover, AD has the potential to solve one of the most pressing problems confronting modern society: the management of OFMSW. Despite the fact that OFMSW is a potential energy source, obstacles such as the organic fraction's diversion (requiring expensive and complicated equipment), alternative treatment costs and process dependability have hampered landfill diversion.[34] AD allows valuable organic waste, for example garbage that would otherwise end up in landfills, to be utilised, although more research is required to enhance process dependability and economic advantages. Campuzano and González-Martínez[35] demonstrated the potential of OFMSW and an adaptive inoculum in an AD system, reporting a methane yield of 339 NL/kg volatile solids. Another study examined methane production from OFMSW-based bioethanol effluent and realised a yield of 212 mL/g volatile solids.[36] This study has very explicit implications, as it has been demonstrated that multiple biofuels can be produced from OFMSW in a single system.

Another technology is dark fermentation, which is most commonly associated with the production of biohydrogen. This process entails the biochemical breakdown of organic material through complex mixed microbial consortia to produce biohydrogen and an array of VFAs such as propionic and butyric acid. Currently, this process is hampered by relatively lower yields compared to other conventional processes such as fuel cells and steam reforming. Similar to AD, dark fermentation has the advantage of employing a wide range of organic matter as a feedstock, because the complex inoculum possesses the ability to break down the material. Elsamadony and Tawfik[37] illustrated the biohydrogen potential of OFMSW, obtaining a yield of 2.05 mol/mol carbohydrate. Another study explored the production of acetone, butanol, ethanol and hydrogen from OFMSW, yielding 114.1 g, 43.8 g, 15.1 g and 97.5 L, respectively.[28] This study also demonstrated the feasibility of producing multiple products from OFMSW in a biorefinery system. Another commonly considered technology is alcoholic fermentation, the main process responsible for the production of bioethanol. Several studies have examined and reported on the optimal process conditions for high yields. In addition, numerous feedstocks have been employed in the production process. One of the bottlenecks of this process is the requirement of a pretreatment stage to enhance the release of fermentable sugars from organic feedstocks such as garden refuse and agricultural waste. *Saccharomyces cerevisiae* is the most commonly employed inoculum in this process, while other species such as *Pichia stipitis* have also been considered.[38] Fermentation is an integral part of the majority of waste biorefineries because bioethanol is a high-value fuel.

A schematic for a bioplastic biorefinery is illustrated in Figure 4. In essence, the OFMSW feedstock undergoes pretreatment to enhance feedstock digestibility. The solid residue biomass may be suitable for anaerobic digestion, thus producing methane and a VFA-rich effluent. The hydrolysate from the pretreatment can then be directed towards dark fermentation to produce biohydrogen as well as an effluent containing VFAs. At this point, two biofuels have been produced. The VFA effluent from both processes can be pooled and further fermented with an appropriate inoculum to produce PHA. This biorefinery system therefore has the capability to add value to organic waste by producing three products. These products have the potential to ease the burden that current conventional plastic places on the environment, and to mitigate the effect that fossil fuel burning and OFMSW dumping has on GHG emission and climate change. In this sense, coupling a biofuel process with a PHA production process enhances the economic and environmental outlook for the process.



OFMSW, organic fraction of municipal solid waste; VFA, volatile fatty acids; PHA, polyhydroxyalkanoate

Figure 4: A simplified schematic of a bioplastic biorefinery.

As identified earlier, there is currently a lack of studies that explicitly discuss a bioplastic biorefinery from OFMSW. The technologies that would be required in this biorefinery have all been well studied and investigated from a singular process perspective. Other studies have looked at the production of multiple biofuels in a biorefinery system while employing OFMSW as a feedstock. In understanding the process requirements and dynamics, it is possible to construct a system that employs OFMSW, where different fractions of the waste (either separated or after enzymatic hydrolysis) are diverted to different processes. This could result in the integration of bioplastic production processes coupled with biofuel processes.

Table 2: Proposed biorefinery scenarios for the primary production of bioplastics

Scenario	Feedstock	Technology	Products	Reference
1	Organic fraction of municipal solid waste	Fermentation, dark fermentation	PHA, ethanol, hydrogen	Ebrahimian et al.[28]
2	Food waste	Fermentation, alcoholic fermentation	PHA, ethanol	Kiran and Liu[39]
3	Food waste	Fermentation, alcoholic fermentation	PHA, ethanol	Alamanou et al.[40]
4	Garden refuse	Anaerobic digestion, fermentation	PHA, methane	Perin et al.[41]

PHA, polyhydroxyalkanoate

Some potential scenarios are outlined in Table 2, based on modified studies that have been surveyed. In all these studies, the production of PHA was not considered, although PHA production could easily replace one or more other processes requiring a carbon source. For instance, Ebrahimian et al.[28] reported the production of acetone, biobutanol, ethanol and hydrogen from OFMSW. The processes responsible for acetone and biobutanol could be removed and replaced with PHA production, because both processes require a carbon source. It would also be necessary to employ a microbial strain capable of metabolising the specific carbon source. Based on preliminary data from the system, it might also be necessary to balance the processes with sufficient organic material to provide the desirable yields. A life cycle assessment of bioplastics in South Africa was conducted by Harding et al.[42] They found that bioplastics such as polyhydroxybutyrate (PHB) were superior in all life cycle categories among all plastic alternatives, such as polypropylene (PP) and polyethylene. Furthermore, PP production was found to release 80% more CO_2 compared to PHB, while ozone depletion was almost 50 times lower with PHB production. In the South African context, this is a clear indication that bioplastic will play an integral role in combating climate change. The integration of such a biorefinery in South African municipalities could significantly reduce the amount of waste that ends up in landfills, thus contributing to landfill space savings and the reduction of GHG emission from both landfills and processes employing conventional fuels. The South African Research Chairs Initiative (SARChI) Waste and Climate Change Group at the University of KwaZulu-Natal is poised to address many of these questions. The first stage will be the assessment of a laboratory-scale bioplastic biorefinery, taking into account life cycle and techno-economic analysis. The process will then be analysed using the Waste Resource Optimization Scenario Evaluation (WROSE™) model to assess its impacts through the evaluation of several key indicators, including GHG emissions; potential for waste diversion from landfills and related savings; technical and economic feasibility for scale up; job-creation potential; social acceptability; health risks associated with the jobs created; and institutional indicators for implementation. These data could provide critical insight into the feasibility of bioplastic biorefineries as a waste management tool.

Conclusions

Plastic pollution is a major environmental problem around the world, and impacts on almost all ecosystems. South Africa alone accounts for about 10 million tonnes of plastic waste, with an associated cost of ZAR885 billion, taking into account clean up, disposal costs and the impact on certain livelihoods. South Africa is also facing several challenges on the organic waste disposal front owing to the diminished capacity of many municipal landfills. Furthermore, the disposal of organic waste to landfills poses many problems, including the release of GHG that plays a pivotal role in climate change. For this reason, by coupling these two problems of plastic and organic waste together, it may be possible to produce a more environmentally friendly plastic using organic waste as a feedstock. Several studies conducted around the world have indicated the feasibility of this process. In order to construct this process to be environmentally and economically viable, a biorefinery system might be the best option, so that complete valorisation of the feedstock occurs, thereby producing PHA and multiple biofuels such as biomethane and biohydrogen. These fuels have the potential to offset the current carbon footprint trajectory, thus acting as a stabilisation wedge for climate change.

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Competing interests

We have no competing interests to declare.

Authors' contributions

Both authors were responsible for the conceptualisation of the paper. P.M. was responsible for the writing process.

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Considerations on bio-hydrogen production from organic waste in South African municipalities: A review

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Organic waste disposal contributes to 3.8% of GHG emissions to the atmosphere, yet 68.8% of this putrescible waste fraction is still disposed of, untreated, to landfills in South Africa. The implementation of a ban on disposal of organic waste to landfills at provincial level opens up the need to research best technology pathways and waste minimisation strategies to valorise and promote the circularity of diverted waste streams. The SARChI Chair in Waste and Climate Change has developed the WROSE™ (Waste Resource Optimization Scenario Evaluation) model to assist municipalities in selecting the most appropriate waste management solutions. A research gap has been identified in the lack of information on full-scale applications of two-stage anaerobic digestion (2-stage AD) for combined bio-hydrogen and bio-methane production from organic waste. In this review, we explore drivers and barriers to the implementation of 2-stage AD in South Africa and propose possible scenarios using the WROSE™ model for its insertion into an Integrated Waste Management System at municipal level. A literature analysis suggests that 2-stage AD is a potentially viable solution to recover the inherent value of organic waste and promote circularity using bio-hydrogen and bio-methane. However, the currently available organic fraction in the municipal solid waste streams is not a suitable feedstock, as it requires high levels of pre-treatment. Suitable scenarios using the WROSE™ model are proposed for South African municipalities, paving the way for future research towards the scale-up of this technology.

Significance:

- Organic waste is not managed adequately in South Africa, contributing to greenhouse gas emissions without recovering the intrinsic value of the material.
- 2-stage AD is a potentially viable solution to recover the inherent value of organic waste and promote circularity using bio-hydrogen and bio-methane. Several barriers must be overcome before carrying out the technology at full-scale.
- A 2-stage AD scenario can be implemented at full-scale into an Integrated Waste Management System using appropriate decision-making tools such as WROSE™.

Introduction

In a world that has always prioritised the extraction of new materials, our resources and energy demand have skyrocketed because of overpopulation and improved living standards in developing countries. Consequently, the contribution from anthropogenic greenhouse gas (GHG) emissions to climate change has increased greatly.[1] Therefore, the new circular economy concept is gaining ground to tackle this issue. This idea considers a novel approach synthesised by the 4 Rs: reduce, reuse, recycle and recover.[2]

Africa has immense potential for recovering materials from waste, which is now mostly dumped or burned outside of proper waste management facilities.[3,4] However, African countries focus predominantly on passive and inexpensive treatment methods such as landfilling, which do not recover the added value inherent in waste materials but do contribute to environmental pollution. While only 4% of the yearly African organic waste production (71 million tonnes) is recovered, incrementing recycling rates to 25% would yield over USD243 million in additional monetary value, originating from the by-products of proper treatment.[5] Landfill disposal has commonly been the preferred method due to very affordable gate fees (in most cases fees are USD10–15 per tonne of waste in South Africa – up to 10 times lower than in Europe) and, in the past, abundance of space.[6] However, landfills are rapidly filling up, raising the need for an effective diversion of organic fractions such as food waste, garden refuse, the organic fraction of municipal solid waste (OFMSW), and agricultural waste. Another downside of landfilling of organic waste is the substantial impact on human health and the environment, including the uncontrolled GHG emissions to the atmosphere, due to the high biodegradability of organic waste.[7,8]

The South African government is working on the gradual diversion of solid waste from landfills.[9] Moreover, South African provinces, starting from the Western Cape, are progressively implementing organics-to-landfill bans to increase landfills' lifespans, reduce carbon emissions and valorise the economic potential of waste.[10] The new regulatory acts, along with the new law on extended producer responsibility[11], are raising the need to find an alternative treatment option for this putrescible waste stream.

Biological methods such as composting achieve proper stabilisation of organic matter, but they do not facilitate energy production or the recovery of valuable material, given the low commercial potential of compost.[12] On the other hand, anaerobic digestion (AD) partially sacrifices the stabilisation of biodegradable matter to recover a biogas mostly made of methane and carbon dioxide that can be burned to produce electricity or to fuel gas systems.[13] Moreover, if AD is performed in a two-stage configuration (2-stage AD), hydrogen gas could also be recovered after the first stage, thus increasing the energy recovery of the system and reducing the impact of organic waste treatment in terms of GHGs.[13]

Anaerobic biodigesters have successfully been implemented across rural South Africa on a micro-scale level, mainly using agricultural waste, animal manure and even sewage waste as feedstocks.[14] However, there is a lack of studies on their implementation in urban and peri-urban areas at a larger scale, where different feedstocks, such as OFMSW, food waste and garden refuse, are available.[15] Moreover, biological hydrogen production from such waste fractions has been investigated worldwide[16] as well as in South Africa[17], but mainly in a standalone configuration called dark fermentation, and not to optimise the successive production of hydrogen and methane. In contrast, 2-stage AD still needs to be improved and advanced from lab-scale to micro-scale and, possibly, full-scale, to make it applicable both at the household and municipal level. For this purpose, we investigated the drivers for and barriers to the implementation of such technology and explore the possibility of introducing a 2-stage AD scenario in an Integrated Waste Management System in South African municipalities using the Waste Resource Optimization Scenario Evaluation (WROSE™) model, which is an essential tool to assist municipalities in selecting the most appropriate and sustainable treatment method for organic waste management.[18,19]

2-stage AD for bio-hydrogen and bio-methane in South Africa

Recovering the inherent value of organic waste would be the ideal realisation of the circular economy concept, in which every material becomes a resource at the end of its life cycle. However, this approach requires adopting the most appropriate treatment methods, such as AD, to fulfil and maximise such a goal.

AD is a biological process that occurs spontaneously in natural environments devoid of oxygen, such as soil, sediments and ruminants' stomachs, and the waste body of landfills. A series of anaerobic bacteria degrade and convert organic matter into a biogas mostly made of methane and carbon dioxide.[13]

Conventional AD is a well-established process that allows for the recovery of energy from biogas. However, recovery efficiency can be further increased if the process is performed in two stages to prevent the degradation of hydrogen during acetogenesis.[13] In this new configuration, the first reactor hosts the first two phases (hydrolysis and acidogenesis) in a process called dark fermentation (as it occurs in the absence of light), while the second stage consists of a combined acetogenesis-methanogenesis on the digestate that emerges from the first stage. As shown in Figure 1, the second reactor might be preceded by a buffer tank that can be used to remove matter recalcitrant to hydrolysis, increase control on operational pH and organic load, or even dilute inhibiting compounds.[20]

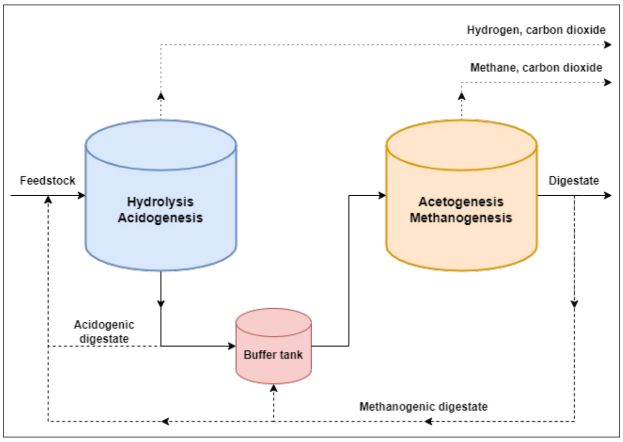


Figure 1: Configuration of a standard 2-stage anaerobic digestion system (solid lines: main liquid flow; dashed lines: recirculation flows; dotted lines: gaseous flows).

The first stage hosts both hydrolytic microorganisms and fermentative species. Hydrolytic bacteria (*Bacteroidetes* and *Firmicutes* phyla[21]) secrete extracellular enzymes that break down complex organic matter into simpler molecules, generating monosaccharides, amino acids and fatty acids from carbohydrates, proteins and fats, respectively. Those smaller compounds are then degraded into volatile fatty acids (VFAs), ethanol and low molecular weight alcohols, gaseous hydrogen and carbon dioxide by microorganisms such as *Clostridium* sp., *Enterobacter* sp., *Escherichia coli* and *Bacillus* sp. (mesophilic), thermophilic *Clostridium* (*C. thermocellum*) and *Thermoanaerobacterium* sp. and extremely thermophilic *Caldicellulosiruptor* sp. and *Thermotoga* sp.[22]

Hydrolytic species prefer a pH of 6–8 but are more adaptable to different environmental conditions than are acidogenic microorganisms, which thrive at a pH of 5.5–6.5.[20] Consequently, as the goal of 2-stage AD is to maximise both hydrogen and methane production, the optimal pH for the first stage is in the 5.5–6 range, thus preventing hydrogen consumption by methanogenic bacteria, which are inhibited at acidic pH.[23,24]

In the second stage, methanogenesis is preceded by acidogenesis, the transformation of VFAs into acetic acid and hydrogen operated by propionate-oxidisers such as *Syntrophus* and *Syntrophomonas* sp., *Pelotomaculum* sp., *Smithllela* sp., and *Syntrophobacter* sp.[21] These acetate-producing bacteria perform reactions that are not thermodynamically favoured, and therefore they have to rely on the hydrogenotrophic methanogens to consume the hydrogen immediately. This syntrophic partnership is essential to keep the H_2 partial pressure sufficiently low ($<10^{-4}$-10^{-5} atm) to guarantee favourable conditions for acetogenesis.[25] A second methanogenic pathway, called acetoclastic methanogenesis, consists of the transformation of acetic acid into methane and carbon dioxide and accounts for about 70% of the global methane production.[26] Unlike hydrogen-producing bacteria, methanogens cannot sporulate to withstand extreme environmental conditions and are limited to a pH range of 6.2-7.8, with best performances at pH 7-7.2.[20,24] Typical bacterial species responsible for methanogenesis are *Desulfobacterium* sp., *Methanoculleus* sp., *Methanospirillum* sp. and *Methanococcus* sp. (mesophilic), *Methanothermobacter* sp. and *Methanosarcina* sp. (thermophilic), and *Methanothermus* sp. and *Methanothermococcus* sp. (extremely thermophilic).[22]

Control of operational pH is paramount to maximise biogas yields and maintain the stability of the process, especially in the first stage, given the production and accumulation of acidic compounds. While chemicals can be used as buffering agents to avoid excessive acidification and prevent bacterial inhibition from VFAs build-up, their continued use is not sustainable from an economic standpoint. Therefore, recirculation of methanogenic digestate into the acidogenic reactor has been investigated, and has proved to be a feasible method to provide sufficient residual ammonia and bicarbonate to preserve the stability of the first stage, while reducing the cost of pH buffering.[24] Because an excess of ammonia can lead to bacterial inhibition, it is essential to keep the VFAs/alkalinity ratio in the 0.3-0.5 range.[27] As a consequence, the optimal recirculation ratio has been investigated. Depending on the feedstock, optimal values for the ratio are between 0.3 and 0.65, which leads to an increase in biogas production of up to 75%.[28-30] Recirculation of digestate can also be performed in the same reactor to increase the hydraulic retention time and enhance the removal of volatile solids (VS) and biogas production.[20]

Hydrolysis is usually the rate-limiting step of anaerobic digestion due to the recalcitrant compounds that make up lignocellulosic feedstocks.[31,32] Therefore, a 2-stage configuration can be carried out using two different operational temperatures: a thermophilic (50–60 °C) first stage that enhances the breaking down of refractory molecules, and a mesophilic (30–40 °C) second stage that maintains advantageous conditions for methanogenesis while reducing energy consumption.[20,24] When using a lignocellulosic substrate, the first stage is usually operated in a continuous stirred-tank reactor that can facilitate mixing, while the second stage can be carried out in different reactors, such as a continuous stirred-tank reactors, upflow anaerobic sludge blanket reactors (high loading rates, low retention times), anaerobic fluidised bed reactors (efficient, with high recycle rate but high energy costs) or expanded granular sludge bed reactors (modified anaerobic fluidised bed systems, with a lower upflow velocity and partial bed fluidisation).[20,33]

Energy expenditures are a significant operational cost for an anaerobic digestion system. In comparison with a single-stage reactor, a 2-stage configuration can potentially result in a twofold energy generation from biogas.[34] However, using two reactors increases the electricity and heating costs, thus hindering the system's energy balance. A recent study highlighted that, although the 2-stage configuration recovered up to 12.25 kJ/g-VS from biomethane production, its energy balance remained negative at -2.16 kJ/g-VS, despite being an improvement from the -3.41 kJ/g-VS achieved by the single-stage reactor.[34] Therefore, combining the energy recovery from both hydrogen and methane can potentially help obtain a net energy gain and needs further investigation.

Figure 2 highlights the role of a standard 2-stage AD system in transforming organic waste into valuable by-products that can be reintroduced into a circular economy or used to produce electricity and heat. However, because the demand for household heating is not widespread across South Africa, the combined heat and power unit could be replaced with a simpler combustion engine or gas turbine for electricity production in order to reduce costs.

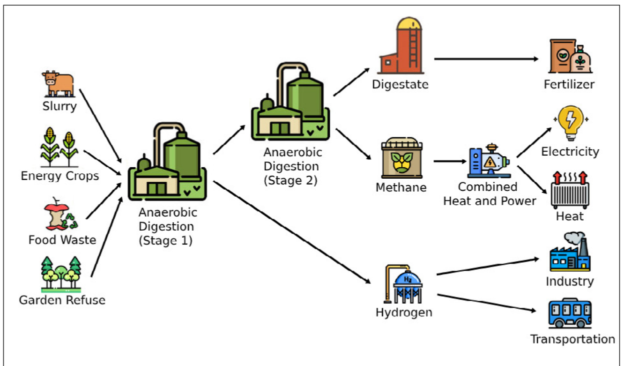


Figure 2: Representation of a 2-stage anaerobic digestion system, from feedstock to final use of by-products.

When a 2-stage AD system is fed with organic waste such as slurry, energy crops, food waste and garden refuse, this new configuration becomes a perfect realisation of the idea of a circular economy, as all the possible outputs can find some application in the economy as secondary materials (Table 1).

Table 1: Potential uses of by-products of 2-stage anaerobic digestion

By-product	Use	Reference
Digestate	Agricultural fertiliser	Tshikalange et al.[35]
CO_2	Food and drink industry (carbonated drinks, packaging and transportation, farming and slaughtering) Fuel and chemical industry (including oil recovery and fracking) Bioenergy production (bio-algal photo-fermentation)	Aresta[36] Zhang et al.[37]
CH_4	Chemical industry, fuel and energy production	Gogela et al.[38] International Energy Agency[39]
H_2	Chemical industry, transportation	Sharma et al.[40]

AD digestate has been successfully used as a cheaper and environmentally friendly alternative to inorganic fertilisers without affecting the quality and quantity of the final agricultural product, especially if the feedstock is source-separated organic waste.[35,41] In fact, the residual sludge coming from an AD process that partially stabilised the organic matter, with a VS reduction of between 60% and 90%, is a fluid with a low total solid content (3-15%) which contains macronutrients (N, P, K, Ca, S and Mg) and micronutrients (B, Cl, Mn, Fe, Zn, Cu, Mo and Ni) needed for plant growth.[42]

Carbon dioxide (CO_2) has extensive application in different sectors, such as the food and drink industry, fuel and chemical industry, and bioenergy production.[36,37] It is usually produced as a by-product of several industrial processes (methane steam reforming, fertiliser synthesis) but can be captured, utilised and sequestered from atmospheric emissions in order to limit its global warming potential. In fact, CO_2 is the main component of anthropogenic greenhouse gas emissions, and therefore the leading cause of climate change.[43]

The same consideration applies for methane, as its global warming potential over 100 years is 28–36 times higher than that of CO_2[44], even if its concentrations in the atmosphere are significantly lower (410 ppm for CO_2 versus 1.866 ppm for CH_4)[43]. However, combustion of methane generates more energy per unit mass (55.7 kJ/g) than any other solid fuel, as a consequence of its high hydrogen content[45], while also originating less CO_2. Therefore, methane is routinely used in many chemical industrial processes to produce fuel and electricity, primarily through steam generators and gas turbines.[38,39]

On the other hand, hydrogen is a non-toxic gas that can generate more heat per mass (142 kJ/g) than any other fuel[46], without generating any polluting emissions because the only by-product of its combustion is water vapour[47]. H_2 is generally produced from fossil fuels, most commonly through steam methane reforming, thus cancelling all the advantages of its clean combustion.[48] New renewable production methods have been investigated, and water electrolysis supplied with solar and wind power is a promising alternative, but is heavily reliant on weather conditions.[48] In contrast, producing hydrogen and methane through 2-stage AD using a constantly available feedstock such as OFMSW would ensure a clean, reliable and sustainable production that would also valorise the energy potential of organic waste.[49]

Availability and suitability of organic waste as feedstock for 2-stage AD

In South Africa, organic waste is most commonly landfilled, contributing to GHG emissions without recovering the intrinsic value of the material.[15] However, drivers such as the consistent increase in waste production could induce municipalities to endorse alternative treatment methods.[5]

The generation of municipal solid waste (MSW) is strictly connected to several demographic and monetary drivers, such as population growth, urbanisation, economic development, global trade, expansion of middle class and modified consumption habits.[7] Despite the declining population growth in South Africa, which dropped from 2.3% in 2013 to 1.0% in 2021, the population number continues to increase, surpassing 60 million people for the first time in 2021.[15,50] South Africa is experiencing a shift from a rural to a more urbanised population, especially in provinces such as KwaZulu-Natal.[50] The largest cities have doubled growth rates compared to smaller towns and contribute to a vast majority (over 80%) of the national gross value added.[50] Therefore, the number of people moving to urban areas will grow with time, leading to an increased MSW generation due to the enhanced lifestyle and the augmented accessibility to store-bought goods.[15] It has been projected that, in African countries, the growth in the production of MSW, estimated at 30% in the 2012-2025 timeframe, will not even out before 2100, therefore posing critical challenges in terms of waste management.[5] Furthermore, recent studies foresee that, in South Africa, the collection rate for MSW will increase to 66-75% in 2025 from 43-55% in 2012, posing an ulterior challenge in terms of proper management of the additional waste produced and collected.[3]

According to the South Africa State of Waste Report[15], in 2017, organic waste made up 56.3% of the total general waste in the country, for an estimated amount of about 30.5 million tonnes, of which 68.8% was landfilled. However, this fraction mainly consists of by-products of agricultural and industrial processing (sugar and sawmills, paper and pulp industry), while there is a lack of specific data for the OFMSW. Nonetheless, the totality of MSW, which made up 8.9% (4.8 million tonnes) of the national waste production, was still sent to landfill in 2017, therefore raising a need for a separate treatment of its putrescible fraction – the main contributor to the production of harmful leachates and the emission of GHGs from landfills.[51]

In South African municipalities, garden refuse is generally collected separately from municipal waste and then landfilled or, in some cases, composted to reduce the quantity of waste disposed of in a landfill.[52] It has been estimated that, in 2017, this fraction accounted for about 30% of MSW generated in South Africa.[15] The diversion of garden waste from landfills could unlock different beneficial effects, such as monetary savings (reduction of leachate production that will require treatment; landfill airspace savings and extension of the landfill lifespan) and reduction of GHG emissions in the atmosphere.[15]

These arguments are even more compelling when discussing the other major organic fraction currently landfilled in South Africa: food waste. South Africa produces about 31 million tonnes of food every year, but about one third is lost mainly during supply.[53-55] However, food wastage is not experienced only in the supply chain but also at a household level.[56] A study of the domestic waste habits in Rustenburg, in the North West Province, found that food waste production is strictly related to income levels. While food waste accounts for 13% and 17% of total waste production in middle-income and high-income households, respectively, a higher percentage (27%) is observed in low-income households, possibly because of inadequate refrigeration and proper storage facilities.[53,57]

Several characterisation studies investigating food waste production in major South African municipalities confirm that the amounts fluctuate within a 3–33% range.[58,59] Such food wastage has considerable financial repercussions. It has been calculated that, in 2012, food loss and waste directly amounted to ZAR61.5 billion (2.1% of South Africa's GDP), while the cost related to food wasted by households was worth ZAR21.2 billion (0.8% of national GDP).[53,60] In addition, indirect costs, such as diesel and electricity costs utilised in the food processing and supply chain, were estimated at about ZAR1 billion.[53]

Besides the economic aspects, proper management of food residues would also be beneficial from an environmental standpoint. There are two levels of emissions that are strictly associated with food waste: direct emissions from disposal of organic waste into landfills and indirect emissions linked to every step of the food production and supply chain. Recent studies show that, globally, the yearly direct emissions from food loss have more than tripled in the 1961–2011 period, mainly as a consequence of the contribution of developing countries, where people have switched to a diet richer in fresh food, while food waste related emissions from developed regions have contracted from half to a quarter of the global contributions.[61] In the UK, it has been calculated that food wastage at the household level accounts for about 3% of national GHG emissions.[53]

In South Africa, there is a lack of data on direct and indirect emissions, which still require better understanding and adequate quantification, particularly at the municipal level.[51,62,63] However, the South African Department of Forestry, Fisheries and the Environment has recently published the 2017 National GHG Inventory Report[64] to help quantify the actual emissions related to each sector. While the coal-fuelled energy sector is still responsible for the vast majority (80.1%) of South Africa's carbon footprint, the waste sector accounts for 3.8% (21 249 Gg CO_2e) of the national GHG emissions (excluding 'FOLU – Forestry and Other Land Use'), with disposal of solid waste contributing over four-fifths (81.7%) of the total emissions related to waste management.[64] Even though total national emissions decreased by 2.8% between 2015 and 2017, the contribution from the waste sector increased by 4.4% – an increase which was mainly driven by the disposal of solid waste.[64] Therefore, it is essential to develop a sustainable alternative to landfilling of putrescible waste, which is the main waste responsible for GHG landfill emissions, to reverse the trend while producing by-products that can promote circularity of the secondary materials in the economy.[62] AD, especially in its 2-stage configuration, can solve this problem, but several gaps still need to be addressed.

Barriers to the implementation of 2-stage AD in South Africa

A wide variety of organic materials can be used as a feedstock for AD, but most are not suitable for mono-digestion and require co-digestion to guarantee the right conditions for the bacterial species involved in AD.[65-67] For instance, it has been determined that the municipal-based lignocellulosic biomasses available in the eThekwini Municipality are the organic fraction of municipal solid waste, food waste, garden waste, and, potentially, energy crops cultivated on the topsoil of closed landfills according to a technique called phytocapping.[68] Similar feedstocks have been used worldwide to produce hydrogen and methane at a laboratory scale (Table 2).

Table 2: Municipal-based lignocellulosic waste used as a feedstock in lab-scale 2-stage anaerobic digestion

Feedstock	Hydrogen yield	Methane yield	Reference
Food waste + garden waste	46.2 ± 0.9 mL H_2/g VS	682 mL CH_4/g VS	Abreu et al.[16]
Food waste	8.6 ± 4.8 mL H_2/g VS/day	428.3 ± 30.9 mL CH_4/g VS/day	Baldi et al.[13]
Organic fraction municipal solid waste (OFMSW)	29.8 mL H_2/g VS	619 mL CH_4/g VS	Lavagnolo et al.[69]
Garden waste (grass)	52 mL H_2/kg VS	517 mL CH_4/kg VS	Liczbiński and Borowski[49]
Garden waste (leaves)	23 mL H_2/kg VS	421 mL CH_4/kg VS	Liczbiński and Borowski[49]

However, most of these studies focused on the co-digestion of solids with liquid feedstocks, such as sewage sludge, that could act as an inoculum. Additionally, there is only a handful of studies that considered co-digesting two different solid waste streams, and most of them focused on a conventional single-stage AD.[16,65-67,70] Therefore, there is a clear need to determine the best operational conditions to perform 2-stage AD using lignocellulosic feedstocks that differ in nature and which can offset their differences in terms of nutrients and guarantee a more stable and efficient digestion. For the same purpose, the pre-treatment of lignocellulosic waste, necessary to enhance solids' biodegradability and biogas yields, needs to be further investigated.[65,66]

Table 3: Case studies of industrial-scale waste-to-energy anaerobic digestion plants in South Africa fed with the organic fraction of municipal solid waste (OFMSW)

Name and location	Feedstock	Configuration	Outputs	Reference
Bio2Watt (Bronkhorstspruit, Gauteng)	Cattle manure, mixed organic waste	Thermophilic (50–52 °C) primary digester, mesophilic (39 °C) secondary digester, combined heat and power	4.6 Mw_e, 3 MW_{th}	Oelofse et al.[4]
GCX Africa (Grabouw, Western Cape)	Fruit and vegetable waste, other food waste	Digester (2700 m^3), combined heat and power	527 kW_e, 550 kW_{th} used to generate 500 kg/h of 10 bar_g steam	Gogela et al.[38]
New Horizons (Athlone, Western Cape)	Mechanically separated OFMSW (200–300 t/day), pure organic waste (70 t/day)	Material recovery facility, single-stage digester, gas processing	Compressed natural gas (>95% CH_4, 760 Nm^3/h), liquid CO_2 (18 t/day), organic fertiliser (100 t/day)	Fountain Green Energy[71] Gogela et al.[38]

Subsequently, the potential for up-scaling 2-stage AD must be assessed, following the successful example of industrial plants that already produce biogas in South Africa using OFMSW (Table 3).

In addition to the technology gaps, several barriers must be overcome before successfully applying 2-stage AD in South Africa. For instance, 2-stage AD requires a clean feedstock that can only be achieved by implementing a separate collection of the OFMSW.[69] Moreover, there is a need to change the perception of alternative waste treatment methods from more high-priced to more cost-effective than landfilling when environmental benefits are considered. Finally, there are limited opportunities for a market for secondary materials.[4,5] However, the political will to back up hydrogen projects through South Africa's Hydrogen Society Roadmap[72], which has been extended until 2031, can drive investments and demand for hydrogen. Another political driver is the implementation of organics-to-landfill bans at both national and provincial levels.[9,10] In addition, 2-stage AD can benefit from several socio-economic drivers, such as the potential for poverty alleviation and social development of disadvantaged people, through job creation, entrepreneurial opportunities, and women empowerment.[4,5]

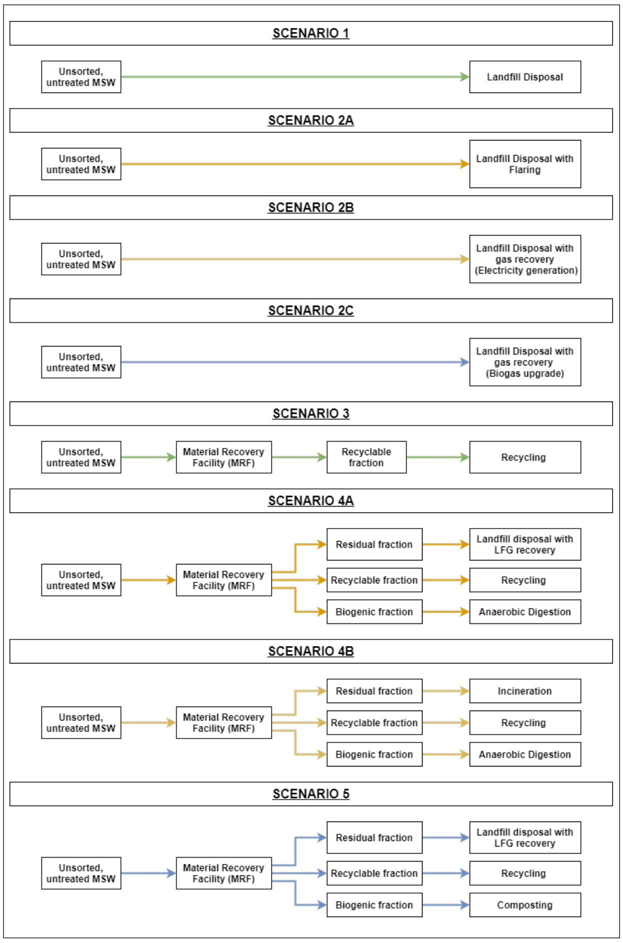
Considerations on the insertion of 2-stage AD in an Integrated Waste Management System

The scaling-up of 2-stage AD is a necessary but insufficient step to prepare its insertion in an Integrated Waste Management System. The technology must be investigated under a life cycle assessment, environmental impact assessment, or sustainable/environmental technology assessment approach to recognise all the flows and impacts related to the system.[73] Additionally, selection and quantification of the most appropriate indicators is required to perform a proper assessment of 2-stage AD.[19,74]

In this context, several waste-management models can provide decision-makers, such as industrial companies or municipal officials, with the tools to make informed decisions on the most suitable technology. For instance, the Waste Reduction Model (WARM) was developed by the US Environmental Protection Agency (US-EPA) to determine the implications of baseline and alternative waste management scenarios in terms of GHG emissions and energy and monetary savings.[75] Similarly, WRATE is a UK-based life cycle assessment model that focuses primarily on the environmental impacts of waste management strategies.[76]

Unfortunately, these models target environmental and technological aspects without including social and institutional indicators. Moreover, they rely on GHG emission factors suited to industrialised countries, and therefore they are not entirely reliable and applicable in developing nations. Other models developed specifically for South Africa, like SASCOST[77], are focused on highlighting the advantages deriving from the implementation of source-separation of waste, a preferable option that does not represent the current situation of waste management in most of the country[15].

Consequently, the SARChI Chair in Waste and Climate Change at the University of KwaZulu-Natal developed the Waste Resource Optimization and Scenario Evaluation (WROSE™) model.[18] The initial goal of WROSE™ was to compare several treatment methods, such as landfill disposal (with or without gas recovery), recycling and composting, with the current baseline scenario and quantify their GHG emissions, energy use, techno-economic feasibility, and monetary and landfill airspace savings, which would predict the extension of the lifespan of a landfill when each alternative scenario was applied. In order to make accurate calculations, WROSE™ needs a proper waste stream characterisation that precedes the determination of GHG emissions. Such outputs are obtained by modifying US-EPA/IPCC emission factors to consider both direct emissions and emissions/savings related to transportation, digestate application, and energy production from biogas.[18] Since 2010, the model has been progressively developed and made more accurate by expanding its dataset with more case studies and then including social (job creation potential, health risks, public participation) and institutional indicators (environmental and energy legislation, financial and administrative regulation, licence required), while also broadening the range of examined scenarios (Figure 3) in order to make it more relevant for the South African context.[19,74]

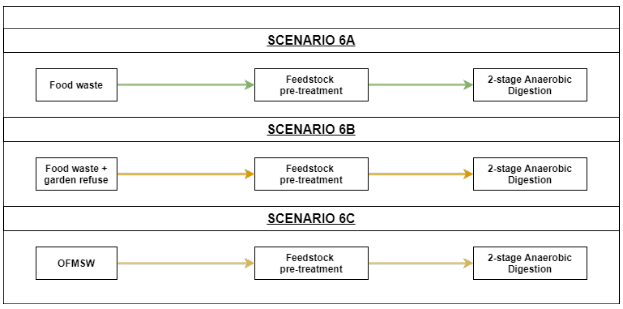


MSW, municipal solid waste; LFG, landfill gas recovery

Figure 3: WROSE™ waste management scenarios (adapted and modified from Trois and Jagath[18]).

Social and institutional indicators are particularly appropriate to elevate the WROSE™ model as one of the most powerful decision-making tools for South African municipalities to provide a solution that is both environmentally sound and highly impactful on people's lives. For example, it has been estimated that, while landfilling creates about 1 job/kt managed, recycling of waste would create 6–13 jobs/kt in Africa.[4]

Nonetheless, the WROSE™ model still needs to be further enhanced by developing accurate South African based emission factors and including 2-stage AD in its technology portfolio. One of the critical aspects is that the organic fraction separated in a material recovery facility is not suitable for 2-stage AD but only for stabilisation due to its impurities.[78] Hence, new scenarios (Figure 4) cannot be derived directly from the closest existing scenarios (4A–4B) because they need to consider the few clean organic waste fractions available in South Africa: food waste, garden refuse and OFMSW.



OFMSW, organic fraction of municipal solid waste

Figure 4: Proposed new scenarios for inclusion in WROSE™.

Future research must focus on defining detailed material and energy flows to determine the fate of each waste fraction and facilitate the integration of these scenarios in an Integrated Waste Management System. Each scenario should be investigated by testing the following set of identified indicators, comparing 2-stage AD with conventional AD[18,74]:

- GHG emission reduction (determined using both IPCC emission factors[79], in line with the nationally determined contributions of South Africa, and scenario-specific South African emission factors determined using the WROSE model[62,80])
- Technical feasibility (available feedstocks, development of pre-treatments tailored to each feedstock, bio-hydrogen and bio-methane potential, scaling-up of 2-stage AD)
- Economic feasibility (proper localisation of plant, investment costs, market profitability of by-products and potential short- and long-term savings)
- Diversion from landfill (extension of lifespan, monetary and airspace savings)
- Job creation potential (tonnes of waste or MW of electricity per job)
- Health risks (direct and indirect risk factors)
- Public acceptance and social perception (participation in source separation of waste, involvement in environmental impact assessment processes)
- Institutional indicators (environmental and energy legislation, financial and administrative regulation)

In particular, it is paramount to investigate the techno-economic feasibility and environmental impact of 2-stage AD in the context of a South African municipality.

With the inclusion of these new scenarios in WROSE™, the model will become paramount in advising municipalities on the feasibility of the new technology, paving the way for a potential insertion in an Integrated Waste Management System.

Conclusions and recommendations for future research

Landfill disposal of organic waste, still a common practice in South Africa, is associated with several deleterious impacts and many lost opportunities. Mismanagement of biodegradable waste contributes to carbon emissions and climate change, while its proper valorisation would guarantee energy and materials recovery according to the circular economy principle and create social and economic opportunities. For these reasons, 2-stage AD for the combined production of bio-hydrogen and bio-methane has been identified as a promising treatment method to achieve these goals. However, the technology needs to be researched and enhanced to address several barriers before the upscaling of 2-stage AD. Moreover, its insertion in an Integrated Waste Management System can be facilitated by determining material and energy flows and evaluating the new technology through a specific set of techno-economic, environmental, social and institutional indicators. To this end, the insertion of new 2-stage AD scenarios in the WROSE™ model would provide South African municipalities with a powerful tool to determine the environmental, economic, and social benefits of the new technology while minimising the impacts of a new plant.

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Competing interests

We have no competing interests to declare.

Authors' contributions

A.D.: Conceptualisation; literature review; methodology; data collection; writing – the initial draft; writing – revisions. C.T.: Conceptualisation; methodology; writing – revisions; student supervision; project leadership.

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