

UNIVERSITY OF KWAZULU-NATAL

**Developing a Black Soldier Fly supply chain that beneficiates
organic wastes: A Durban case study**

By

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ABSTRACT

As a result of the global population continuing to expand, the generation of waste is rapidly increasing. The global urban population generated 300,000 tonnes of waste a day in 1990. By 2000, this had increased to three million tonnes of waste a day, and is expected to double by 2025.

The increasing volume of waste creates a number of problems including, but not limited to, the exploitation of natural resources and the expenses incurred handling the waste. The majority of waste generated is disposed of in landfills. Landfills are a major contributor to current environmental problems. Organic waste within landfills contributes to greenhouse gas emissions and toxic leachate in the soil and groundwater. There is commonly a build-up of flammable gases within landfills that pose health, safety and environmental risks.

The Black Soldier Fly (BSF) is a wasp-like insect that has been identified as a potential consumer of organic waste that would otherwise be sent to landfills. The Black Soldier Fly Larvae (BSFL) are avid consumers of bio-degradable organic waste. Fully grown BSFL are rich in protein and fatty acids that provide opportunities for the production of various by-products.

The purpose of this study is to assess the one commercial BSFL rearing site with operational documentation publicly available. The aim is to assess the on-site operations and develop a functional supply chain. The objectives of the study are to identify the stakeholders involved, understand the operations and logistical activity on-site and to identify key factors and variables within the operation.

The study used a single case study approach to analyse documented data in a qualitative context. During the data analysis, each part of the operation was investigated and in summarising the findings, a diagram was presented to fulfil each objective. Each diagram was combined to create a functional supply chain for the BSFL operation. The supply chain outlines the key stakeholders, on-site processes and variables.

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GLOSSERY OF TERMS

ABP	Animal By-products Regulation
BSF	Black soldier fly
BSFL	Black soldier fly larva
CJD	Creutzfeldt Jakob Disease
DAFF	Department of Agriculture, Forestry and Fisheries
DEFRA	Department for Environment, Food & Rural Affairs
EDI	Electronic data interchange
ERP	Enterprise resource planning
EU	European Union
FAO	Food and Agricultural Organization
FIFO	First in, first out
HACCP	Hazard analysis critical control points
HVAC	Heating, ventilation and air conditioning
IBM	International Business Machines
kW	kilowatt
LED	Light-emitting diode
MSW	Municipal solid waste
MW	Megawatt
NPK	Nitrogen, Phosphorus, Potassium
PPE	Personal protective equipment

PRG	Pollution Research Group
SCM	Supply chain management
SCR	Supply chain resilience
SDGs	Sustainable Development Goals
UD	Urine diversion
WWTW	Wastewater treatment works
ZAR	South African Rand

CHAPTER 1: INTRODUCTION

1.1 Introduction

The population of the world is growing, albeit at a slower rate than in recent history. It is still set to increase to 9.7 billion by the year 2050 (United Nations Department of Economic and Social Affairs, 2019, p. 5). Compared to the global population of 7.8 billion reached in the middle of 2020 (Gu, Andreev, & Dupre, 2021, p. 604), there will be a projected 2 billion more people living on earth in the next 28 years. Of these, 1.05 billion or 52%, will live in sub-Saharan African countries (United Nations Department of Economic and Social Affairs, 2019, p. 6).

Along with the increasing population, there is a rapid rate of urbanisation; in 2018, 66% of the South African population resided in urban areas (United Nations Department of Economic and Social Affairs, 2019, p. 22). This is above the global average of 55% of the population living in urban areas (United Nations Department of Economic and Social Affairs, 2019, p. 5). By 2050 South Africa is predicted to have 80% of the population permanently settled in urban areas. This equates to 58 million people living in urban areas out of a projected total national population of 72.5 million (United Nations Department of Economic and Social Affairs, 2019, p. 15)

Population growth and increased urbanisation have a clear and direct effect on an increase in waste generation. As more people develop a higher standard of living with more consumption, their output of waste increases (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, pp. 18-20; Onyango, 2018, p. 60). This is supported by global waste data: in 2012, 1.3 billion tonnes of waste were produced globally, but moving forward to 2016, 2.0 billion tonnes of waste were generated. By 2030, the global annual generation of waste is expected to reach 2.6 billion tonnes and by 2050, 3.40 billion tonnes (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 18).

In 1900, globally, 220 million people (13% of the population) lived in urban areas, however by the year 2000, 2.9 billion people (49% of the population) were living in urban areas and in 2018, 4.2 billion people (55% of the population) resided in urban areas (United Nations Department of Economic and Social Affairs, 2019, p. 21). In this same period, municipal solid waste generation increased tenfold from 0.3 million tonnes to 3 million tonnes of waste per day in 2000; this trend is expected to continue and by 2025 it will be double that of the year 2000 (Hoorweg, Bhada-Tata, & Kennedy, 2013, p. 616).

Sub-Saharan Africa produced 174 million tonnes of waste in 2016. This is estimated to increase to 269 million tonnes by 2030 and 516 million tonnes by 2050 (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 28).

Global and national development have brought about an area of major concern; with such large populations expecting and experiencing a higher standard of living, more waste is being produced than ever before, and this amount is only going to rise. This raises the question of what is being done to deal with the increasing amount of waste produced.

1.2 Motivation for this study

South Africa faces similar waste management problems to the rest of the world, exacerbated by a high population growth rate, rapid urbanisation and increasing proportions of low and middle-income populations. These will be the largest sources of the increase in waste generation. In 2017, approximately 108 million tonnes of waste were produced. Seventy-nine percent was sent to landfills and 21% was recovered through various recycling schemes (GreenCape, 2020, p. 8; Department: Environmental Affairs, 2018, p. 19). The waste that was recycled was mainly in the form of plastic, paper, glass, tyres, metals and organic waste (GreenCape, 2020, p. 8; Department: Environmental Affairs, 2018, p. 19).

The use of landfills as a management tool to deal with waste is extremely hazardous to the environment. Not only do they negatively affect the environment (El-Fadel, Findikakis, & Leckie, 1997, p. 17; Department: Environmental Affairs, 2018, p. 62), but they also occupy large and valuable tracts of land. This decreases the value of surrounding areas and presents health hazards for communities in adjoining areas (Smolen, Moore, & Conway, 1992, pp. 293-294; Department: Environmental Affairs, 2018, p. 62).

From a sustainability perspective, landfills contain a significant volume of waste that has considerable potential to be dealt with using alternative, sustainable methods. The most common and established methods include recycling, composting and incineration (Bhada-Tata & Hoornweg, 2012, p. 5; Department: Environmental Affairs, 2018, p. 63). These methods have been established with various degrees of success around the world, and here too in South Africa. However, researchers continue to find new methods to deal with various forms of waste that are currently ending up in landfills. One such development has involved *Hermetia stratiomyidae*, more commonly known as the Black Soldier Fly (BSF).

The BSF is a wasp-like insect originally indigenous to the Americas. The BSF can survive in temperate regions (Ghughuskar, 2012, p. 130) but has a lack of hardiness in cold environments (Wang & Shelomi, 2017, p. 2). BSFs are not considered pests (Weththasinghe, Hansen, Mydland, & Øverland, 2022, p. 939). The adult flies only consume water and are not known to accumulate toxins, approach humans, bite or sting, act as vectors or disseminate any diseases (Wang & Shelomi, 2017, p. 12).

The main point of interest concerning the BSF is its larvae. The Black Soldier Fly Larvae (BSFL) feed on biodegradable organic waste. The BSFL convert the waste into protein and lipids in the form of a grown, mature BSFL. This results in the BSFL being a valuable and viable source of protein that can be used in animal feed, aquaculture and even potentially human nutrition. Furthermore, these products can be produced sustainably (Park, 2016, p. 2; Purkayastha & Sarkar, 2021, p. 3).

The use of organic waste in this type of waste management system is believed to be more beneficial than other means, such as composting and incineration, as this is a more direct means of closing a sustainability cycle. Directly feeding a feed source bypasses the process of composting that is used to fertilise the soil to grow feed for animals.

The additional benefit of this method, besides diverting organic waste from landfills, is the valuable outputs that are created by rearing BSFL. The by-products of this process address a different challenge that is being faced in the form of how to continue to feed the growing population.

As the global population grows, an estimated increase of 50 per cent in edible crop yield will be required by 2050 to meet the forecasted food demand (Searchinger, Waite, Hanson, & Ranganathan, 2019, p. 8; Sethi, Cassou, Bedregal, & Constantino, 2021, p. 5). Additionally, as the income in the developing world increases, the demand for resource-intensive produce, such as vegetables, meat and dairy, is predicted to rise by approximately 70 per cent (Searchinger, Waite, Hanson, & Ranganathan, 2019, p. 66). Globally, it is estimated that an additional 593 million hectares of farmland will be required by 2050 to produce enough crop yield to meet the demand (Searchinger, Waite, Hanson, & Ranganathan, 2019, p. 150). The world faces a significant challenge in providing food for the 800 million people who are currently malnourished whilst also meeting the future demand (Perez-Escamilla, 2017, p. 513; Searchinger, Waite, Hanson, & Ranganathan, 2019, p. 1) .

It is for these two key reasons that this study aims to look at a current attempt to commercialise the production of BSFL from biodegradable organic food waste and human faeces.

The current field of research around BSFL has been focussed predominantly on small-scale individual aspects within the concept, such as BSFL breeding conditions, the BSFL lifecycle and the conversion rate of various feed sources by the BSFL (Purkayastha & Sarkar, 2021, p. 21; Park, 2016, p. 7). While these are important aspects, the next step in creating a successful large-scale process and upscaling all stages has not been successfully researched and published. This provides the gap that this study focuses on. By studying attempts to achieve large-scale production, insight is gained into the next key challenges that this concept needs to overcome.

The focal point of the study was the pilot test site operated by The Bio-Cycle research group in partnership with the eThekweni Municipality and the Pollution Research Group (PRG) of the School of Chemical Engineering at the University of Kwa-Zulu Natal. This site is focussed on processing organic waste using BSFL, and on a large scale.

The purpose of this study is to identify various factors that are affecting the economic and operational viability of the entire supply chain required for a mass BSFL production process and the sustainability of BSFL as a source of protein for agricultural and aquaculture purposes. A viable supply chain can be used as a guide for future development and implementation.

The function of a supply chain and the benefits it provides are key. An optimal and sustainable supply chain is critical to meet demand, lower costs, produce more efficiently and maintain a competitive edge (Horvath, 2001, p. 207). Some of the functions that make up a supply chain include product development, sourcing, production, logistics and sales (Skjoett-Larsen, 2000, p. 379). An effective supply chain aims to create financial and productivity benefits whilst considering profitability, efficiency and customer satisfaction (Lockamy & Smith, 1997, p. 144). For this reason the contribution of a potentially viable supply chain will provide significant value to the BSFL concept.

1.3 Problem statement

The exciting potential that BSF have lies not only in providing an environmentally friendly means of disposing of organic waste but also in producing a sustainable source of protein-rich feed which can serve agricultural and aquacultural feed demands. The concept is in its early stage of development globally but currently there is a body of scientific research and literature that focuses on many individual key aspects within the overall concept. There are many

variables and complexities that have been successfully studied individually and in controlled labs on a small scale. However, further research on large-scale studies combining many individual aspects from the body of knowledge was lacking, especially from a commercial standpoint. For viable BSF operations to be established, a sustainable supply chain must be designed if the concept is to be commercially successful.

This study seeks to contribute to the development of BSFs as a waste management system by devising a viable supply chain that will serve as a framework for further development through the identification of key stakeholders, the logistical and operational processes and the factors affecting efficiency and commercial viability.

There are several existing and potential stakeholders that can be involved in this process but an overall supply chain that promotes integration and collaboration is required. A clearly defined end-to-end supply chain framework can provide a holistic view of the process and facilitate further research.

1.4 Research questions

- Who are the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?
- What are the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*)?
- What are the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?

1.5 Research objectives

- To identify the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.
- To identify the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*).
- To determine the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.

1.6 Research contribution

The BSF technology provides a solution to many of the current issues being faced in South Africa and globally. The dual ability of BSF to divert organic waste from landfills and produce a commercially valuable and viable, sustainable feed source in the form of BSFL is key in its attractiveness.

This study contributes to the development of the concept by identifying the key factors of the process within the supply chain and the factors that are currently hindering the sustainability and viability of this technology. It provides a better understanding of the supply chain and the challenges that BSF commercial projects are encountering.

This study adds further value by highlighting key points and exposing areas which need further research and understanding to ensure a more successful supply chain. This is required mainly in the development of more detailed process modelling, engineering and optimisation.

Through the development and advancement of BSF technology, this study will contribute to a potential solution that will contribute to nine of the 17 Sustainable Development Goals (SDGs). The SDGs are a set of 17 interlinked goals set out by the United Nations (UN) in 2015 to achieve a better and more sustainable future for all (General Assembly of the United Nations, 2015, p. 6). The aim is to achieve the 17 goals by the year 2030 and this is measured by a set of 169 targets. The 9 goals that BSF technology can contribute toward are presented in Figure 1.1.



SUSTAINABLE DEVELOPMENT GOALS



Figure 1.1 List of nine goals the BSF can contribute towards from the SDGs

Source: (General Assembly of the United Nations, 2015, p. 3)

Ultimately, the study seeks to provide a clearly defined supply chain framework that may be used to encourage a proliferation of commercial ventures utilising BSFs to provide environmental and commercial benefits.

1.7 Conceptual framework

The conceptual framework for this study is illustrated in Figure 1.2. The framework illustrates the supply chain elements, from the range of inputs, through the BSF operation, to the possible outputs.

The process starts with the various waste streams that can feed into the operation; it could either be just one stream or a blend of multiple waste streams. From the available waste streams, the next steps lead to the processes of receiving the waste either by collection or delivery.

The waste received then feeds into the main operations onsite. The first step is for the waste to be sorted. This could entail a range of activities depending on each stream source. It may have to be separated from non-organic waste or be unpacked and mixed into one combined mixture. Once prepared to a usable state it is then spread across the feeding bays, ready for the BSFL to be introduced.

The BSFL can either be sourced from a breeder, if available and accessible, or the site will need to breed its BSFL. Whichever option is suitable, the BSFL will need to be brought in and added to the prepared waste. Following this, the feeding and growing of BSFL will take place.

Once the BSFL reach maturity they will then be harvested. This means separating them from any remaining waste and cleaning them and putting them through a rotary drier. Through the separating, cleaning and drying stage, residue that does not proceed to the pressing and suitable larvae stage is collected and termed frass, which may be used as a good fertiliser.

The output processing begins with the pressing of the BSFL to obtain oils that can be used in biodiesel. Thereafter, the pressed BSFL are then suitable as a protein-rich animal feed. These outputs can then be packaged, marketed and sold through distributors and/or other third parties, or directly to end-users of these products.

The large broader geographic space refers to the larger area in which the operations take place and is influenced by the country and region it is in, and the climate and surrounding land use characteristics. The local geographic area refers to the site location that is selected for the operations of growing and processing. Many site-specific factors affect the performance of the BSFL, so this local area selection is a key aspect.

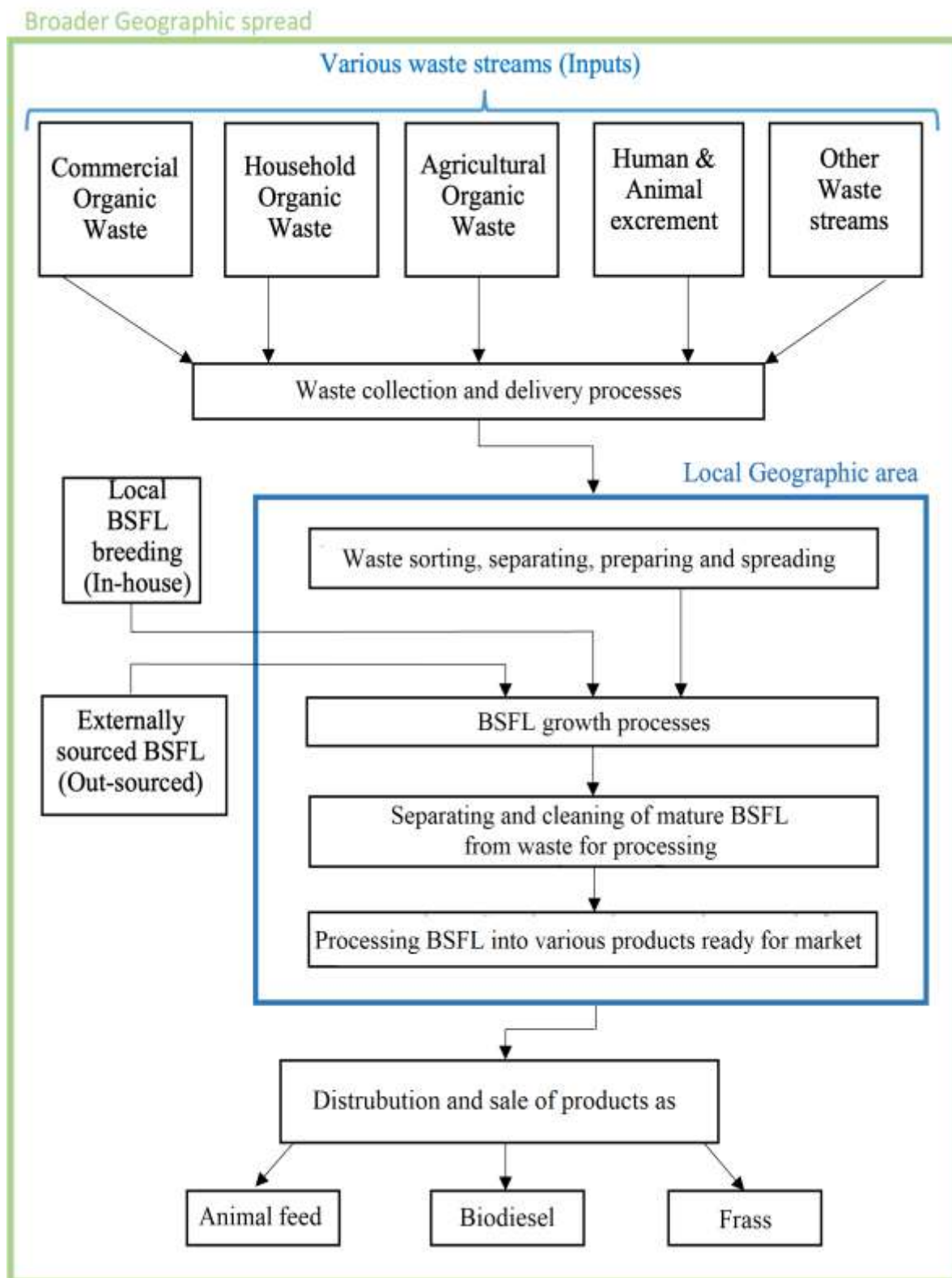


Figure 1.2 Conceptual framework of an organic waste BSF beneficiation supply chain

Source: Author's Creation

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The quantity of municipal waste generated across the globe is increasing at a rapid rate (Bhada-Tata & Hoornweg, 2012, p. 8). Almost all cities are struggling to manage the increasing volume of waste and meet waste reduction targets. Up-to-date information surrounding how waste is discarded, recovered, or recycled is limited (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 48). Most countries do not collect or publish explicit waste disposal data. This is a challenge in conducting global-scale studies or for those in the developing regions. Low and middle-income countries depend on landfills and dumping as a method of waste disposal (Hoornweg, Bhada-Tata, & Kennedy, 2013, p. 615). Considering that developing nations are the largest contributors to the growth in waste generation, landfills are of significant concern. Landfills are known to have a negative impact on their immediate environment as well as local economic and health concerns. However, they have remained popular due to their simplicity in setting up and running and their low operational costs (Hoornweg, Bhada-Tata, & Kennedy, 2014, p. 118). In South Africa, the municipal solid waste (MSW) industry still primarily consists of unsorted waste collection and landfilling. These services are not holistically managed, with individual municipalities or individual private service providers having the market share. Currently, less than 10% of the total waste generated in South Africa is recycled. The growing South African urban population has resulted in a rapid increase in the generation of MSW and has put significant pressure on the existing facilities and services (Department: Forestry, Environment and Fisheries, 2020, pp. 12-26)

BSFs provide an effective alternative to landfilling organic waste and are among the most feasible biological means of dealing with organic waste in South Africa. Although currently the production and use of BSLs for waste management is undertaken on a small scale, the process has a large potential in the waste management sector as well as in the animal feed and fertiliser market (Purkayastha & Sarkar, 2021, p. 22). BSFs provide a solution within the circular economy (Figure 2.1) by not only reducing the volume of waste and associated risks but by producing commercially valuable by-products. BSFs can effectively convert low-quality organic material into high-quality protein and nutrients for use as animal feed, nitrogen-rich frass for fertiliser and accumulate lipids which can be converted to biodiesel (Figure 2.1).

Costs of Pre- and Post-Consumer Food Waste

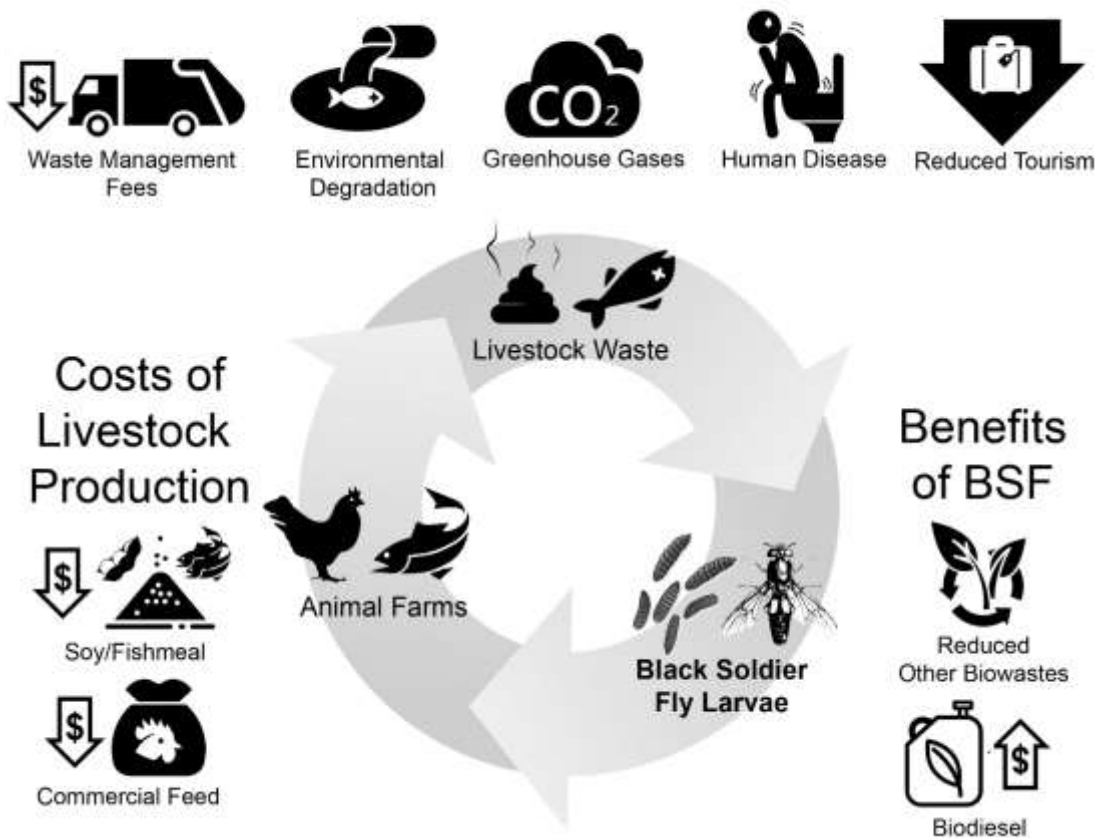


Figure 2.1 The circular economy of BSF

Source: (Purkayastha & Sarkar, 2021, p. 5)

This chapter will be an extensive review of the literature surrounding MSW management and the current measures available to deal with waste, alternative waste management measures and a discussion around BSFs. The content is compiled from secondary data and highlights the areas where this study can contribute.

2.2 Municipal waste

The definition of municipal waste incorporates substances and objects which are intended or required by law to be disposed of or are being recovered. Municipal waste includes domestic waste, commercial, office, small business and trade waste, garden and green waste, waste collected from street sweepings and litter containers. MSW excludes waste from water treatment works and any radioactive materials, as well as from construction and demolition sites (OECD, 2017, p. 1).

2.2.1 Municipal waste in a global context

Presented below are the findings from the most recent studies regarding municipal waste on a global scale. Although, the figures presented in these studies can be inconsistent due to differing methodologies, limited and different sources of data, conflicting definitions of waste classifications, incomplete data or omission of measurement units or different periods of reporting (Bhada-Tata & Hoornweg, 2012, p. 32), across all the studies the volume of global waste generation is increasing (FAO, 2011, p. 4; Hoornweg, Bhada-Tata, & Kennedy, 2013, p. 615; Hoornweg, Bhada-Tata, & Kennedy, 2014, p. 118; Porter, Reay, Higgins, & Bomberg, 2016, p. 5; Alexander, et al., 2017). Globally, almost all cities are struggling to meet waste reduction targets (Chan, 2016, p. 1).

The findings on MSW trends vary between studies, due to the various assumptions that are required to be made to conduct studies on a global scale.

Hoornweg *et al.* (2013; 2014) reported an increase from 0.1 billion tonnes of MSW produced per year, in 1900, to 1 billion tonnes of MSW produced per year, in 2000, and have projected the MSW production to double to 2 billion tonnes in 2025 and 4 billion tonnes by 2100.

A review of global municipal solid waste (MSW) was conducted by the World Bank's Urban Development and Local Government Unit of the Sustainable Development Network (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 52). The report states that the approximate global annual MSW produced in 2016 was 2 billion tonnes, by 2030, is expected to generate 2.6 billion tonnes and, by 2050, is expected to reach 3.4 billion tonnes (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 52).

With economic development, Chen *et al.* (2020) found that the total global MSW generation continues to increase but at a declining rate. Global MSW generation has increased from 0.6 billion tonnes in 1965 to 2 billion tonnes in 2015 and is predicted to reach 3.5 billion tonnes by

2050. The study has projected that the percentage of global organic waste production will decline by 8%, while the percentage of other types of waste, especially paper, will increase from 2015 to 2050 (Chen, Bodirsky, Krueger, Mishra, & Popp, 2020, p. 74021).

A key component of municipal waste is food (organic) waste. Food waste refers to food lost by deterioration, waste or removal from the supply chain (Kibler, Reinhart, Hawkins, Motlagh, & Wright, 2018, pp. 52-62). The increasing volume of food wasted poses many social, economic and environmental threats to humans globally.

A global study by the Food and Agricultural Organization of the United Nations (FAO), states that in 2010 the total volume of food wastage was estimated to be 1.3 billion tonnes (FAO, 2011, p. 4). Porter et al. (2016) reported that between 1961 and 2011 the annual volume of food waste increased from 0.5 billion tonnes to 1.6 billion tonnes. The regional contribution within this global average has changed over the period. In 1961, developed countries generated 48% of the global food waste volume but their share was reduced to 24% in 2011 (Porter, Reay, Higgins, & Bomberg, 2016, p. 722). Furthermore, in a study by Alexander *et al.* (2017) issues surrounding the sustainability of over-consumption and food disposal were addressed. The study found that, on a global scale, 8% of plant-based produce and 19% of animal-based products are lost through over-consumption and food disposal by customers (Alexander, et al., 2017, p. 192).

2.2.2 Municipal waste in a South African context

The MSW industry in South Africa principally consists of pavement or private waste collection and municipal landfilling and is managed by individual municipalities or private service providers. Commercial and industrial waste is managed by the private sector. South Africa produced approximately 0.11 billion tonnes of MSW in 2017 (Department of Environmental Affairs, 2018, p. 122). In 2017, approximately, 0.1 billion tonnes were landfilled, which resulted in less than a 10% recycling rate. Of the estimated total waste, approximately 0.06 billion tonnes were considered general waste and 0.05 billion tonnes were ‘unclassified’ waste. The Department of Environmental Affairs (2018) reported that there has been a 3.26% annual increase between 1997 and 2010, a 3.95% annual increase between 2006 and 2010 and a 1.57% annual increase between 2002 and 2010, in the general waste generation in South Africa.

The growing South African population, particularly in urban areas, has resulted in a significant increase in MSW generation and has put significant pressure on the existing facilities and services (Mabalane, Oboirien, Sadiku, & Masukume, 2021, p. 1168). In 2017, 59% of

households have municipal organised pavement collection, 2% utilise communal containers, 34% use communal dumps and 5% dispose of waste illegally (Niyobuhungiro & Schenck, 2022, p. 322). The most significant challenge faced by municipalities in South Africa is the shortfall in revenue collection. This leads to cutbacks in the essential maintenance and municipal services which increases the risk of service failure and health and environmental hazards (Teklehaimanot, Kamika, Coetzee, & Momba, 2015, p. 385).

The implementation of appropriate waste management systems will reduce the accumulation of MSW within cities due to population growth and economic development (Mabalane, Oboirien, Sadiku, & Masukume, 2021, p. 1168). South African municipalities spend millions of Rands (eg. Cape Town ~ ZAR 350 million and Johannesburg ~ZAR 58 million) annually removing waste that has been illegally dumped (Niyobuhungiro & Schenck, 2022, p. 323).

2.2.3 Contributing factors to the generation of municipal waste

Municipal waste is closely linked to urbanisation, economic wealth, living standard, and consumption of goods and services. Improvements in these factors tend to result in a relative increase in the amount of waste generated (Bhada-Tata & Hoornweg, 2012, p. 8; Hoornweg, Bhada-Tata, & Kennedy, 2013, p. 615; Hoornweg, Bhada-Tata, & Kennedy, 2014, p. 118).

2.2.3.1 Population growth and urbanisation

The effect of rapid population growth on waste production is predictable. The more people living on earth and consuming goods, the more waste is produced. The global population increased from 2.5 to 7.7 billion between 1950 and 2019 (Figure 2.2). Additionally, the global urban population has increased at a more significant rate from 0.7 to 4.2 billion between 1950 and 2019. The global population is estimated to increase to 9.7 billion by 2050 and 10.9 billion by 2100 (Figure 2.2) with an estimated 18% and 22% increase in urban population by 2050 and 2100, respectively (The World Bank, 2016, p. 63).

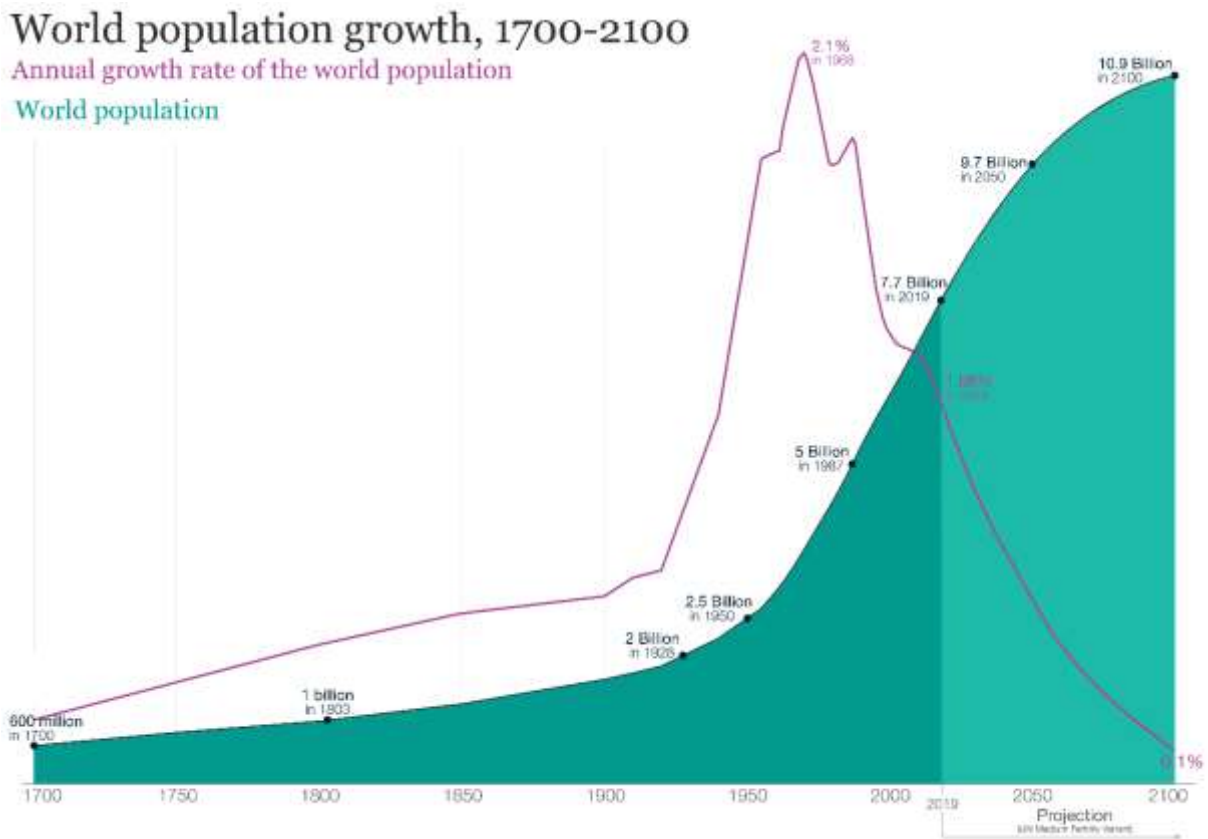


Figure 2.2 The estimated world population and growth rate from 1700 to 2100

Source: (United Nations Department of Economic and Social Affairs/Population Division, 2017, p. 4)

Urban residents generate double the waste compared to rural residents (Bhada-Tata & Hoornweg, 2012, p. 111), thus the more people residing in these areas the more prominent the increase in waste will become. The result is small, densely populated areas producing the majority of the MSW within the country, which falls under the local government or municipality’s responsibility to handle, remove and dispose of.

The exponential growth of the population and subsequent demand for commodities results in a challenge for governments to provide adequate investment and maintain infrastructure development to handle the volume of waste. Improving the public health of a growing population and the local and global environmental conditions in which to live will require significantly increasing investment and programs to address rising waste generation and adapt the existing service (World Bank, 2021, p. 63).

South Africa experienced rapid population growth, especially between 1985 and 2005. The national population has increased from 36 million in 1990 to 49 million in 2000 and to 50

million in 2020. It is projected that the population will increase to 52 million by 2030. The growth rate and urban migration are not uniform across the country. The population is concentrated in urban centres in the Western Cape, Gauteng and KwaZulu-Natal. This presents a problem as a high population influx puts pressure on municipal resources. In some cases, the increase in population can result in infrastructural and municipal services development, however, in the majority of cases, a lack of effective management strategies could hurt implementation. (Teklehaimanot, Kamika, Coetzee, & Momba, 2015, p. 985). Many waste management challenges have yet to be overcome and the relevant Sustainable Development Goals (SDGs) are not on track to reach the required targets (General Assembly of the United Nations, 2015, p. 1).

2.2.3.2 Economic factors

Economic influence relates to the income level of the local population, and more specifically the disposable income. As disposable income and standard of living increase, consumption and waste generation will likely increase (Bhada-Tata & Hoornweg, 2012, p. 8). Both high- and low-income countries are observing an increase in MSW, with developing and developed nations seeing a 3% and 4.5% annual increase in MSW respectively. In 2015, approximately 1.3 billion tons (~75%) of MSW are produced by urban areas (Yadav & Samadder, 2017, p. 1) and 0.7 billion tonnes (~46%) of MSW is produced by the high-income class (Bhada-Tata & Hoornweg, 2012, p. 11) As populations become wealthier, their consumption of foods and objects increase thus creating more waste.

Many Asian and African countries, with either already high populations or rapidly growing populations, are identified to be the leading contributors to the expected growth in waste generation (Munawar & Fellner, 2013, p. 7; Lebreton & Andrady, 2019, p. 5). Although currently, developing countries tend to produce less waste than developed countries, globalisation, urbanisation and the distribution of wealth globally are increasing the consumption and waste production in developing countries. Globalisation promotes investment in the developing countries and subsequently increases the wealth of the population and thus leading to an increase in consumption (Bhada-Tata & Hoornweg, 2012, p. 8; Yadav & Samadder, 2017, p. 9124).

In developed countries, infrastructure and waste management systems tend to be established and in operation. Additionally, more specific systems such as recycling schemes have been deployed and alternative, sustainable methods of handling, minimising and disposing of waste

have been researched and implemented (Bhada-Tata & Hoornweg, 2012, p. 5). As a result, current and increasing volumes of waste can be managed effectively. Most developing nations do not have advanced systems and as a result, depend on potentially environmentally hazardous methods of waste management and disposal.

Economic development is particularly important in South Africa due to the history of social engineering and distorted spatial development. Economic development provides employment, income security and material well-being in previously marginalised areas and communities (Turok & Borel-Saladin, 2014, p. 676). The total Disposable Personal Income in South Africa increased from ZAR 720 million in 1960 to ZAR 3.5 billion in 2021. The increasing economic development and standard of living across the country have not only resulted in an increase in revenue for public investment and municipal service but also in increased waste generation (Nkosi, Muzenda, Zvimba, & Pilusa, 2013, p. 2). Rodseth *et al.* (2020) presented figures for domestic waste generation for high, middle and low-income individuals (Figure 2.3). From the various sources presented, the trend of an increase in waste generation with an increase in income is evident for South Africa.

Region	Domestic waste generation (kg/capita/day)			Source
	Low income	Middle income	High income	
South Africa ^a	0.41	0.74	1.29	Department of Environmental Affairs and Tourism ¹⁷
South Africa ^b	0.2–0.7	0.7–1.9	1.5–3.0	Department of Agriculture, Conservation and Environment, North West Provincial Government ¹⁸
Johannesburg	0.38	0.66	0.99	Gauteng Department of Agriculture and Rural Development ¹⁹
Limpopo ^c	0.32	0.4	0.7	Ogola et al. ²⁰

Figure 2.3 Per capita domestic waste generation rates in South Africa

Source: (Rodseth, Notten, & Von Blottnitz, 2020, p. 3)

2.2.4 Organic waste

A significant portion of MSW consists of waste of biological origin and scientists have reported that the accumulation of organic waste, globally, is reaching critical thresholds. Organic waste

has many conflicting classifications resulting in inconsistent reporting. The report by the World Bank on global waste defines organic waste to include food scraps, garden and green waste, wood and paper processing residues (Bhada-Tata & Hoornweg, 2012, p. 8). Organic waste is required to be managed effectively to avoid contamination of natural resources, reduce the risk to human health and limit the environmental impact. It is estimated that the average global organic waste generation is 0.77 kg/person/day (Khalid, Arshad, Anjum, Mahmood, & Dawson, 2011, p. 1) and rapidly increasing as the production of plant-based produce increases.

The extent to which organic waste contributes to the total MSW in a region varies and is affected by several factors, with the most significant relating to the income of the local population (Bhada-Tata & Hoornweg, 2012, pp. 16-17). On average the organic waste contribution of low-income is approximately 64% of total waste, while in high-income areas it is estimated to be 28% (Bhada-Tata & Hoornweg, 2012, p. 19). It is theorised, that the higher percentage of organic waste in low-income regions is due to the consumption being predominantly food-orientated, while in high-income areas the consumption is skewed towards material goods.

There is limited data regarding food waste as a proportion of MSW in South Africa, at a national or municipal level. There is one known published study (Oelofse & Nahman, 2013, p. 81) and one report (Department of Environmental Affairs, 2018, p. 22) available on the proportions or volumes of food waste on a national scale for South Africa. Oelofse and Nahman (2013) provided a preliminary estimate that of the 177kg/capita/annum of food waste generated in South Africa, waste at the consumption stage, which can be expected to contribute to organic MSW, constituted 7kg/capita/annum. The Department of Environmental Affairs, in 2017, estimated that the percentage of food waste that constitutes MSW was estimated to be approximately 10.8% of the municipal waste generated, in South Africa (Department: Environmental Affairs, 2018, p. 29). In a study by Silbernagl (2011), the percentage of food waste in urban and rural landfills within Cape Town was estimated to be between 3.4% to 4.4% and 8% to 24%, respectively (Silbernagl, 2011, p. 138).

A limited number of household-level waste studies have been undertaken across South Africa and the results are presented below. From a 1999 study in Cape Town, it was found that food waste comprised 8.2% and 4.8% of household waste generated by low- and high-income households, respectively (Department of Environmental Affairs and Tourism, 1999, p. 58). An updated study was undertaken in 2008 that determined that 12.5% of the household waste comprised food waste. This study did not make any differentiation between income groups (Gibb Engineering & Science, 2008, pp. 1-36). In Johannesburg, two studies were undertaken.

The first determined that, on average, food waste constituted 19.42%, 10.63% and 7.31% of total household waste in low-, middle- and high-income households, respectively (Jarrod Ball and Associates, 2001, p. 12). The second presented 27% and 17% for low- and high-income households (Silbernagl, 2011, p. 138).

2.3 Municipal waste management through landfills

Landfills are the predominant means of dealing with MSW globally (Munawar & Fellner, 2013, p. 7; Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 42). Governments and municipalities are generally responsible for dealing with MSW and thus cost is a key factor in the decision-making process. Landfills are a cost-effective and relatively simple operation, resulting in their particular popularity in developing countries (Munawar & Fellner, 2013, p. 7).

2.3.1 Description

A landfill is described as disposal, compression and embankment at appropriate sites (Vaverková, 2019, p. 2) by the organised piling of waste (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 41; Townsend, et al., 2015, p. 6). Landfills are either constructed as an overground mound or, more commonly, in a large hole which is filled over time. Traditionally, to limit the harmful effects of landfills on the surrounding environment

Landfills are covered over the top. However, due to the hazardous nature of landfills being reported more frequently in scientific literature and the press, it is becoming a more common practice to line the floor under a mound before the waste gets placed (Crowley, Staines, Collins, Bracken, & Bruen, 2003, p. 33). Landfills may be covered by using various combinations of materials. Soil and plastic sheets are a common selection. The covering of landfills should occur daily after the day's waste collection has been compacted as efficiently as possible. The waste is compacted to reduce bulkiness and conserve airspace (Munawar & Fellner, 2013, p. 20; Peter, Nagendra, & Nambi, 2019, p. 161).

2.3.2 Prevalence

Approximately 37% of MSW generated globally is disposed of by landfills with only 8% of this disposed of in sanitary landfills (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 20). Three conditions must be met for a landfill to be classified as sanitary. These include hydrogeological isolation using a liner, collection of leachate and emitted gasses from the site

and the daily covering of the waste. Sanitary landfills are almost exclusively found in high- and middle-income regions with low-income regions relying on open landfills or informal dumpsites. Kaza et al. (2018) estimated that 93%, 54% and 39% of total global waste is disposed of in landfills in low-, middle- and high-income regions, respectively.

It is estimated that in South Africa, 90% and 62% of waste was landfilled in 2011 and 2017 respectively (Department of Environmental Affairs, 2018, p. 96). Table 2.1 presents a breakdown of waste management in 2017. The significant reduction in waste in landfills demonstrates effective strides in waste management on a national scale.

Waste Type	Generation (tonnes)	Recycling/recovered (%)	Landfilled (%)
Municipal	4821430	0.00	100.00
Commercial and Industrial	3550505	10.00	90.00
Organic	30499455	31.10	68.80
Construction	Unknown	90.00	10.00
Paper	4482992	58.00	42.00
Plastic	2211225	43.70	56.30
Glass	1113362	78.40	21.60
Metals	2492636	75.00	25.00
Tyres	4035929	100.00	0.00
Other	729615	9.10	90.80

Table 2.1 General waste by management option in 2017

Source: Adapted from (Department of Environmental Affairs, 2018, p. 96) (Department of Environmental Affairs, 2018)

Although the proportion of MSW to landfills has reduced, when the population that each landfill site is serving across the country is considered, the country remains constrained in terms of effective waste management. On average each landfill site serves 68 000 people (Table 2.2) and using the waste generated per capita figures estimated by Oelofse and Nahman (2013) for South Africa, each landfill on average receives 12 million tonnes of waste a year.

Table 2.2 The landfill sites, population and average servicing capita per site across the provinces of South Africa

Province	Landfill Sites (2018)	Population (2016) Millions	Average Servicing capita/site
Eastern Cape	120	7	58 000
Free State	78	2.8	36 000
Gauteng	169	13.4	80 000
Limpopo	48	5.8	120 000
Mpumalanga	98	4.4	45 000
North West	71	3.7	52 000
KwaZulu-Natal	48	11.1	230 000
Northern Cape	94	1.2	13 000
Total	726	49.4	68 000

Source: (Department of Environmental Affairs, 2018, p. 96)

2.3.3 The effects of landfills

Landfilling for the disposal of MSW, in both developed and developing nations, remains the generally accepted method however, landfills pose significant health and environmental risks, especially as the volume of waste globally is projected to increase.

The process of decomposition of organic matter takes place in two phases: the aerobic phase (with oxygen) and a longer anaerobic phase (without oxygen), with various breakdown products resulting from these processes (Table 2.3).

Table 2.3 The products of aerobic and anaerobic decomposition of organic matter

Element within organic matter	Aerobic Decomposition (Oxidation)	Anaerobic Decomposition (Reduction)
Carbon (C)	CO ₂ - Carbon dioxide	CH ₄ - Methane
Nitrogen (N)	NO ₃ ⁻ - Nitrate	NH ₃ - Ammonia
Sulphur (S)	SO ₄ ²⁻ -- Sulphate	H ₂ S- Hydrogen Sulphide

Source: Adapted from (Crowley, Staines, Collins, Bracken, & Bruen, 2003, p. 28) (Crowley, Staines, Collins, Bracken, & Bruen, 2003)

Initially, the exposure of organic waste contained within landfilled MSW to oxygen over time causes aerobic decomposition by micro-organisms that most critically convert oxygen to carbon dioxide. As the oxygen becomes depleted, the second phase of decomposition commences in an anaerobic state. Microorganisms adapted to these conditions produce methane. (El-Fadel, Findikakis, & Leckie, 1997, pp. 2-3; Crowley, Staines, Collins, Bracken, & Bruen, 2003, p. 28).

2.3.3.1 Air pollution and odorous gasses

Landfill gas is classified as one of the most significant anthropogenic sources of both carbon dioxide and methane. The decomposition of waste within landfill sites constantly produces both these gasses. The degree to which the organic matter has decomposed is dependent on the time exposed to oxygen during handling, dumping and before being covered (El-Fadel, Findikakis, & Leckie, 1997, pp. 2-3). The waste can also be exposed to oxygen through small air pockets when the waste has not been compacted completely (Munawar & Fellner, 2013, p. 20).

Methane is a more potent greenhouse gas than carbon dioxide with 25 times greater greenhouse effect (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 42). The period of time that organic matter is subjected to anaerobic decomposition is of significant concern as landfills become a significant source of greenhouse gas emissions. (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 42). In Africa, an estimated 7% of the continent's total greenhouse gas emissions are generated from open landfills (Diener, Studt Solano, Roa Gutiérrez, Zurbrügg, & Tockner, 2011, p. 159). The continued inhalation of methane, nitrogen dioxide and sulphur dioxide can have detrimental effects on human and animal health. Exposure to methane can cause a loss of coordination, nausea, and vomiting. Exposure to nitrogen and sulphur dioxide can result in increased susceptibility to respiratory infections, nose and throat irritations, asthma, bronchoconstriction, and dyspnoea (Njoku, Edokpayi, & Odiyo, 2019, p. 2125).

Ammonia and hydrogen sulphide are responsible for most of the unpleasant odours around landfills. The strength and smell vary and depend on the landfill site, the composition of waste, the stage of decomposition, and the climatic conditions. The highest concentrations of odorous gases at landfill sites are often reported during summer, due to the increase in the decomposition of waste and a higher release of ammonia. Limited wind, High humidity and atmospheric pressure with limited wind increase the concentration of odorous gasses in the vicinity of the landfill (Lim, Cha, Kong, & Baek, 2018, p. 194). Landfill odour complaints are one of the

leading citizen complaints to municipal offices across South Africa. A build-up in the concentration of gasses and the spreading of odours can be avoided through venting and a daily cover (El-Fadel, Findikakis, & Leckie, 1997, pp. 11-12; Munawar & Fellner, 2013, p. 20).

The gasses produced by landfills can have significant effects on ecosystems. The lateral movement of gas through the soil profile into the area beyond the landfill boundaries can cause the displacement of oxygen from the soil structure. The reduction in oxygen can cause decay in soil health, micro-faunal populations, and burrowing animals. Additionally, the resulting anaerobic conditions in the root zone, caused by the migrated landfill gas, cause the vegetation to be damaged (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 46).

2.3.3.2 Fire and explosion hazards

Landfill sites pose high fire and explosion risks because of the colourless and highly flammable nature of methane and hydrogen sulphide (El-Fadel, Findikakis, & Leckie, 1997, pp. 10-11). Methane and hydrogen sulphide can form gas pockets underground, which have been known to ignite or explode upon disturbance or ignition. Additionally, these gasses can vent and filter some distance underground, depending on the nature of the sub-surface, and cause gas pockets or gas leaks in areas surrounding the landfill (El-Fadel, Findikakis, & Leckie, 1997, p. 11).

Underground fires pose another hazard, through the ignition of gas pockets, fires can be started. Underground fires can lead to chimney-like cracks or vents in the landfill being formed, allowing the fire to be able to draw in oxygen to sustain itself (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 45). Fires can also ignite on the surface through the presence of flammable gasses. The fire can be sustained for long periods by fuelling off the combustible waste and the gasses being emitted. Not only are they a challenge to contain and extinguish, but can produce heavy smoke which can potentially contain toxic fumes (El-Fadel, Findikakis, & Leckie, 1997, pp. 10-11)

2.3.3.3 Acid rain and water pollution

Acid rain refers to any form of precipitation containing sulfuric or nitric acid absorbed within the atmosphere. Various gasses released from landfill sites contribute to an increase in acid rain which in turn affects the acidification of soils and the environment. Acid rain affects vegetation causing a reduction in photosynthesis, a loss of stomatal control and changes in synthetic pathways within plants (Iravani & Ravari, 2020, p. 12083).

Leachate is a toxic liquid formed as a result of various liquids filtering through the landfill, removing soluble compounds (nitrate, sulphate, ammonia and sulphuric acid) from the decomposing waste as infiltrates. Additionally, other toxins present in the landfill can dissolve into the leachate (El-Fadel, Findikakis, & Leckie, 1997, pp. 8-9). There are various sources for the liquids, which are mainly in the form of water, such as precipitation, irrigation and runoff. Alternatively, they can come from the internal moisture content of the waste, liquids produced in the decomposition of waste and underground water intrusion, however, these are less significant.

The leachate that is produced can be toxic. The toxins that it contains, and the degree to which it contains them, are all site-specific and are affected by the type of waste and the stage of decomposition of the landfill. The leachate poses a significant risk to the surface- and groundwater through contamination (Newton, 2017, p. 1). Contamination of groundwater occurs when the leachate filters down through the landfill, either seeping down to the bottom and into the ground, or by meeting an impermeable layer of waste or bottom cover and seeping out to the side and through the edge. The contamination of surface water can occur through baseflow from contaminated groundwater stores or through runoff over the landfill site. Surface- and groundwater contamination poses a significant environmental risk through the rapid movement of water through a catchment and the extensive-time period for recovery (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 46).

During times of heavy rainfall, the raised water levels and saturated soils can cause a landfill to flood and potentially transport the solid waste away from the landfill site as well as spread chemical contaminants into local water supplies and soil profiles beyond the landfill boundaries.

2.3.3.4 Ecological damage

The selection of a site for the construction of a landfill can be controversial. Like all engineering projects, the construction of a landfill has the potential to harm the existing ecology of the area through landscape alteration, and loss of biodiversity and habitats. The soils underlying a landfill undergo the highest level of disturbance to structure and chemical properties (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 42). The most significant damage is caused by the removal of topsoil. The topsoil is vital to ecological functioning and the disturbance to the vital soil properties and soil degradation is irreversible.

The soil, therefore, has a reduced ability to support plant growth (Iravanian & Ravari, 2020, p. 12083).

During construction, there is a significant impact on the soils and vegetation of the site. The utilisation of heavy machinery can cause the removal of topsoil as well as the compaction to the soil profile. The vegetation is removed or damaged and the existing habitat is disturbed. Unlike the soil, damage to vegetation can be remediated and various case studies have demonstrated that closed landfills can support a diverse ecosystem (Iravanian & Ravari, 2020, p. 12083).

Although the natural biodiversity is displaced by landfills, local species can be replaced by other animals that feed on refuse, such as various exotic bird species and other animals such as rodents. Such “exotic biodiversity hubs” can threaten indigenous species in a wider area. There is a risk that both exotic and indigenous animals can be harmed by consuming disposed plastics and toxic products and becoming entangled within the refuse (Arnold, 2021, p. 2).

2.3.3.5 Land settlement

Land settlement, also known as subsidence, is the shifting of waste within the landfill mainly due to decomposition (Newton, 2017, p. 1). The volume of waste decreases as it rots, causing it to fall into newly formed voids, thereby lowering the overall landfill height (Aplet & David Conn, 1977, p. 4). Other causes of land settlement include waste dissolution into leachate, the compaction of waste, subsurface fires, mechanical compression from the thickness and self-weight of the waste, and compaction from construction and structures (El-Fadel, Findikakis, & Leckie, 1997, p. 12).

Land settlement can hinder remediation activities and operations on closed sites. Due to the continuing decomposition of waste, the landscape is constantly changing, putting infrastructure at risk. Constant maintenance is required on remediation and closed landfill sites (Munawar & Fellner, 2013, pp. 19-20). The rate of land settlement varies and is dependent on the contents and environmental factors surrounding the landfill site.

2.3.3.6 Social impacts on local communities

In addition to various environmental impacts, landfills can have adverse effects on the surrounding communities (Smolen, Moore, & Conway, 1992, p. 293). Landfills are constructed

to be managed and therefore are generally situated in or near urban or residential areas (Hite, Chern, Hitzhusen, & Randall, 2001, p. 186).

Local landfills have an adverse economic impact on surrounding residential real estate (Smolen, Moore, & Conway, 1992, p. 293; Hite, Chern, Hitzhusen, & Randall, 2001, p. 200). Various factors have been identified to harm surrounding property value, such as flies, odour, aesthetic unattractiveness, poor air quality, noise and the potential contamination of local water supplies (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 47). The degree to which the landfill factors affect the surrounding area is dependent on the environmental conditions, landfill size and the type of waste (Smolen, Moore, & Conway, 1992, p. 287). It has been reported that odour and aesthetic unattractiveness rank as the leading factors affecting surrounding areas of landfills (Reichert, Small, & Mohanty, 1991, p. 310). The economic impacts of a landfill can still be felt when the landfill is closed and is non-operational. This is due to the waste still being present and the abovementioned effects still relevant. The adverse economic implication on real estate within proximity of a closed landfill may be partially mitigated by rejuvenation of the area (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 49). In addition to the adverse effects of the physical landfill, the presence of waste pickers working and sleeping rough within the surrounding areas can have a detrimental socio-economic impact on the area.

Landfills can have significant health implications on the local communities (Danthurebandara, Van Passel, Nelen, Tielemans, & Van Acker, 2012, p. 47). The negative health effects of poor air quality in the vicinity of a landfill are described in detail in Section 2.3.3.1. In addition to the detrimental effects on community health due to the contamination of air, water resources and soils can cause further complications. Consuming or bathing in contaminated water, whether from the surface- or groundwater can expose the population to toxic chemicals or even heavy metals.

Additionally, if communities are growing subsistence crops in contaminated soils, or irrigating using contaminated water, these chemicals and heavy metals can be introduced into the body through the consumption of this product. Although there is limited medical science surrounding the health implications of landfills, there have been several studies that report higher numbers of specific health-related issues around landfills than in areas further away. The common areas of concern tend to include congenital malformation, birth weight, pre-mature birth, childhood growth, cancer, liver function and symptoms of illness such as skin problems, sleepiness and

headaches (Crowley, Staines, Collins, Bracken, & Bruen, 2003, p. 33; Vrijheid, 2010, p. 102; Palmiotto, et al., 2014, p. 18).

The presence and operation of a landfill can provide employment opportunities and promote local business. An effective waste management system is an expensive endeavour with every phase requiring a workforce. The construction and operation of landfills can provide job opportunities and better living for the local community.

2.4 Alternative municipal waste management methods

With the growing awareness around the issue of waste management, there are various early methodologies being developed that aim to improve, reduce, divert, reuse and repurpose waste generated (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100). There is a selection that has become more widely utilised and as a result, has become recognised as an effective alternative to landfills.

South Africa is experiencing significant challenges regarding the operating of landfills and the availability of capital and space for the commissioning of new landfills. Waste disposed of within landfills is no longer economically productive, thus, diverting waste from landfills and developing a secondary resources economy around is imperative for socio-economic and environmental sustainability (Department: Forestry, Environment and Fisheries, 2020, p. 34).

2.4.1 Recycling

Recycling is the most well-known and prevalent alternative to landfilling (Bhada-Tata & Hoornweg, 2012, p. 5). The World Bank has reported that globally 13.5% of waste is recovered through recycling in 2017 (Figure 2.4). The rate of recycling is greater in high-income countries averaging approximately 25% (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100).

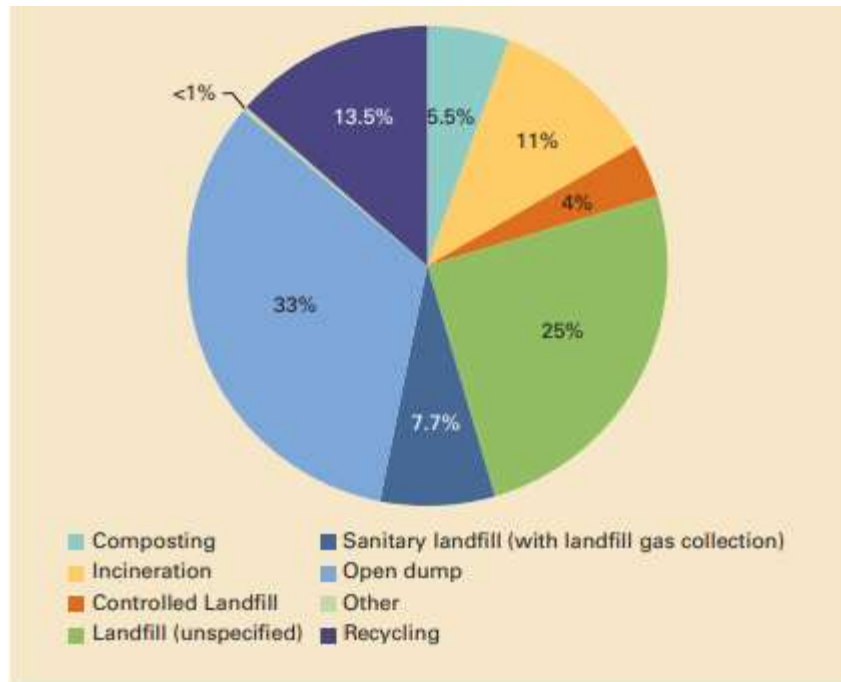


Figure 2.4 Proportion of global waste treatment and disposal methods

Source: (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100)

Recycling provides an environmentally friendly and financially and operationally viable option for waste management and thus receives a majority of the attention, financing, and support. Several products (glass, metal and paper) can be more cost-effective to recycle than to manufacture (OECD, 2017, p. 1) and relieve pressure on raw natural resources utilised in manufacturing processes.

The process of recycling has taken place in South Africa since the mid-1980s and was driven by shifts in social and economic paradigms. In 2017, the rate of recycling in South Africa was estimated to be 10% of total MSW (Department of Environmental Affairs, 2018, p. 8). The current national legislative framework provides a significant challenge for both the private and public sectors to be compliant and competitive in the market and thus waste continues to be landfilled (Godfrey & Oelofse, 2017, p. 57).

Informal waste pickers have been the driving force behind South Africa's recycling economy. With an absence of waste separation at source at both a municipal and national level and gatekeeping by municipalities, waste pickers have been key to accessing resources (through buy-back schemes) that the private sector has been unable to access. The South African informal waste sector is responsible for collecting approximately 90% of the post-consumer materials recovered for recycling. This informal industry puts South Africa's recycling rate in

line with many developed countries and on average saves each municipality an estimated R500 000 annually (Godfrey & Oelofse, 2017, p. 57).

2.4.2 Composting

Composting is a means of repurposing biodegradable waste. It has been traditionally used in rural areas but has more recently been adopted for urban areas on a large scale. Composting offers a valuable product as well as the ability to re-purpose waste more sustainably. The major challenge of large-scale composting is the process of waste separation into biodegradable and non-biodegradable contents. The biodegradable material (kitchen or garden waste) must be separated, and impurities can be significantly detrimental to the composting process.

The World Bank has reported that globally 5.5% of waste was composted in 2017 (Figure 2.4). The process of composting is greater in high-income countries averaging approximately 10% of the total MSW (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100).

In South Africa, it is reported that the limited number of composting sites throughout the country receive approximately one-fifth of the total municipality's waste in the form of green waste. Of this volume, 10-15% is composted (Ekelund & Nyström, 2007, p. 30). MSW South Africa has developed a National Organic Waste Composting Strategy (NOWCS) as a campaign to address the country's waste objectives. The goal of the campaign is to "divert organic biodegradable waste from landfills and to composting sites" as certified by the Department of Environmental Affairs (Department of Environmental Affairs, 2013, p. 12).

2.4.3 Incineration

The incineration of MSW provides not only a means to reduce the volume of waste entering landfills but as a potential alternative source of energy (Makarichi, Jutidamrongphan, & Techato, 2018). Incineration is another possible alternative which sees the organic waste is used as a fuel to burn and undergoes a reduction in volume. Additionally, the burnt waste then has limited effects once it is disposed of at landfills. Incineration is primarily used in high-income, high-capacity, and land-constrained countries.

Globally, there are approximately 1179 modern incinerator plants (Makarichi, Jutidamrongphan, & Techato, 2018, p. 814) treating 11% of the total global MSW (Figure 2.4) with 22% of MSW in high-income countries being incinerated in 2017 (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100). In European countries, incineration has proven to reduce

the volume of deposited MSW by approximately 90% (Makarichi, Jutidamrongphan, & Techato, 2018, p. 814).

In Africa, modern incineration has limited application due to the exorbitant running costs, ongoing operation and maintenance and the heterogeneous and unsorted waste streams (Makarichi, Jutidamrongphan, & Techato, 2018, p. 814). Theoretically, South Africa has the highest potential to produce energy through incineration in Africa (Adeleke, Akinlabi, Jen, & Dunmade, 2021, p. 1551) with an estimated 30 000-Gigawatt hours (Makarichi, Jutidamrongphan, & Techato, 2018, p. 814).

In more sophisticated systems, the incinerator captures energy from the combustion of the waste to use as an alternative source of energy for domestic or industrial use. Incineration does, however, produce greenhouse gases and the incinerated waste is disposed of in a landfill but constitutes a smaller volume.

2.4.4 Anaerobic digestion

Anaerobic digesters use bacteria and micro-organisms in a closed air system to break down the waste while simultaneously producing methane gas as a by-product. Methane is captured and used as an alternative source of energy. Anaerobic decomposition occurs naturally in a landfill as outlined in Section 2.3.3.1 and emits various gases directly and in an unregulated matter into the atmosphere. Utilising anaerobic digestion facilities allows the process to be controlled, captures the produced gasses to ensure that it is more environmentally friendly, and the gasses can be diverted for commercial use.

Globally, anaerobic digestion is more prominent in high-income countries as a reflection of the construction and running costs of a facility (Figure 2.5). Significant projects in Brazil (lower-middle income classification) reflect largely in the elevated percentage compared to other income classes. Although the composition of MSW in most low-income countries is more suited to anaerobic digestion currently 0.3% and 10% of MSW are treated in lower-middle-income and lower-middle-income countries, respectively (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100).

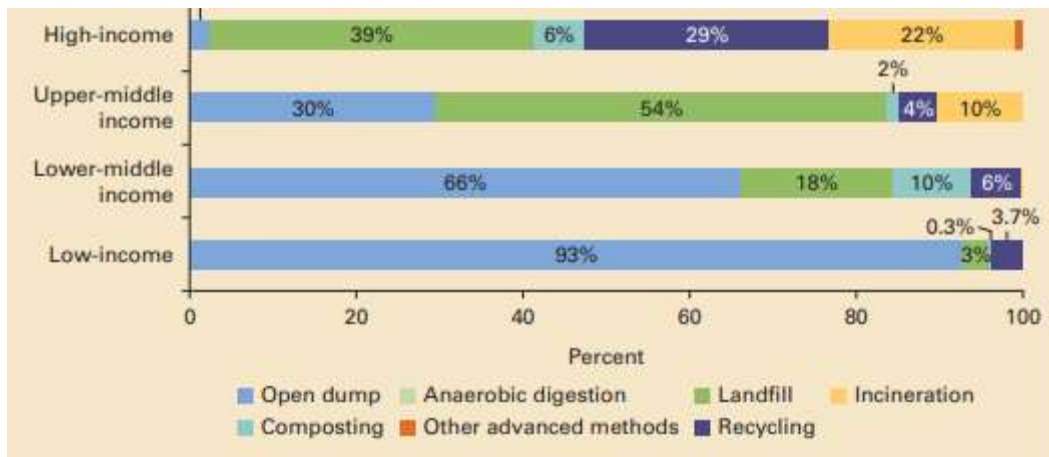


Figure 2.5 Disposal methods by income

Source: (Kaza, Yao, Bhada-Tata, & Van Woerden, 2018, p. 100)

Anaerobic digestion could be beneficial in South Africa to tackle the waste management crisis and supplement the power sector. South Africa generates waste that is rich in organic composition and through anaerobic digestion, a high inherent energy value can be recovered. The infrastructure necessary for controlled anaerobic digestion is expensive and therefore South Africa, and other developing countries, have not fully captured the benefit or operated at full potential (Adeleke, Akinlabi, Jen, & Dunmade, 2021, p. 1551).

There is little literature or statistics regarding anaerobic digestion in South Africa. One study suggested that 25% of the MSW produced in Johannesburg is organic, and of this organic waste, 40% is available for anaerobic digestion (Adeleke, Akinlabi, Jen, & Dunmade, 2021, p. 1551). Otherwise, anaerobic digestion projects are dotted around the country (Table 2.4). These projects tend to be a private agreement between a commercial waste producer and a small-scale energy producer. These projects seem to follow no formal framework or reporting.

Table 2.4 Anaerobic digestion projects in South Africa

Project/Developer(s)	Location	Substrate	Power Output
Alrode brewery Humphries Boerdery piggery	Bela-Bela	400 tonnes of organic waste per day	Not available
Bio2watt Prospection brewery	Pretoria	Animal manure	4.6 MW

BiogasSA Morgan Springs Abattoir	Springs	Slaughter and organic waste	0.4 MW
Biotherm SA PetroSA	Mossel Bay	Refinery wastewater	4.2 MW
CAE Uilenkraal dairy farm	Darling Uilenkraal	Bovine manure	600 kW
CAE University of Fort Hare	Alice, Eastern Cape	4000 m ³ of dairy and piggery manure Athlone	Two 132 kVA Generator
Elgin Fruit and juices Ibhayi brewery	Grabouw	Above 5 tonnes of fruit waste per day	500 kW
Farm secure	Klipheuwel (Zandam) Mossel	Above 5 tonnes of manure per day	600-700 kW
FarmSecure Carbon	Bonnievale	Above 5 tonnes of bovine manure per day	Not available
FarmSecure manure	Darling GrootPost	Bovine manure	Not available
Ibert	Bredasdorp	4 tonnes abattoir waste per day	100 kW
Ibert	Queenstown	42 tonnes of mixed waste from a piggery per day	Not available
Ibert EnviroServ	Cavalter	20 tonnes abattoir waste per day	500 kW
iBert Jacobsdale	Jan Kempdorp	5.5 tonnes abattoir waste per day	135 kW150 kW
Ibert Robertson	Riverdale	4 tonnes abattoir waste per day	100 kW150 kW
Rhodes Food group Selectra	Stellenbosch Franschhoek	Sewage, silage, manure, agricultural waste	0.5 - 1 MW
Veolia water Technologies/Distell	Stellenbosch	1000 m ³ wastewater per day	Not available

WEC Northern Wastewater Treatment Works	Johannesburg	Sewage sludge	MW
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Source: (Adeleke, Akinlabi, Jen, & Dunmade, 2021, p. 1551)

2.4.5 Biological treatments

A potential method with growing interest for dealing with heterogenous MSW is utilising a biological treatment (Garg, 2014, p. 217) such as vermicomposting, faecal sludge treatment by aquatic worms or waste digestion by invertebrates (Diener, Studt Solano, Roa Gutiérrez, Zurbrügg, & Tockner, 2011, p. 359). Biological treatment consists of either re-aeration of waste to allow organisms existing within the waste to increase the rates of decomposition or the introduction of species, such as worms or fly larvae to assist with decomposition. Fly larvae are particularly effective in decomposing diverse waste in favourable conditions and have the potential to address the challenges relating to inadequate waste management in developing countries (Salam, et al., 2021, p. 101934). The larvae are successful in reducing the volume of animal manure, faecal sludge, municipal waste, food waste and plant residues (Čičková, Newton, Lacy, & Kozánek, 2015, p. 70).

Larvae present a unique opportunity in that biodiesel can be derived from the lipids, and/or proteins constituting their biomass (Giroto & Cossu, 2019, p. 100454) and can be utilised for animal feed (Čičková, Newton, Lacy, & Kozánek, 2015, p. 70) and the frass for soil fertiliser (Purkayastha & Sarkar, 2021, p. 15).

Various fly species have been studied for waste management. In general, house fly larvae have a preference for animal manure, BSFL a variety of decaying organic matter, and blowfly and flesh fly larvae for meat-dominant waste (Čičková, Newton, Lacy, & Kozánek, 2015, p. 70).

The use of BSF (*Hermetia illucens*) in organic waste management has gained the attention of the industrial sectors and entrepreneurs in developing countries. The approach holds huge potential as a self-sustained and cost-effective method for treating organic and heterogeneous waste while producing a host of useful by-products (Singh & Kumari, 2019, p. 109569). Large-scale (200 tonnes per day) pilot facilities have been built in Canada, China, Holland, South Africa and the United States (Diener, Lalander, Zurbrügg, & Vinnerås, 2015, p. 6).

2.5 The Black Soldier Fly

Several biological organisms could provide a means of minimising waste in landfills. To minimise MSW with a high organic waste content, especially in South Africa, BSFs provide a very effective biological solution. In addition to a preference for organic waste, BSFs can convert low-quality organic material into high-quality proteins for animal feed (Weththasinghe, Hansen, Mydland, & Øverland, 2022, p. 940), nitrogen-rich frass for fertiliser and accumulate lipids which can be converted to biodiesel (Wang & Shelomi, 2017, p. 91).

2.5.1 Description

The BSF is a wasp-like insect originally indigenous to the Americas. The BSF can survive in temperate regions (Ghughuskar, 2012, p. 130) but has a lack of hardiness in cold environments (Wang & Shelomi, 2017, p. 91). BSFs are not considered pests (Weththasinghe, Hansen, Mydland, & Øverland, 2022, p. 940) because the adult flies only consume water, do not accumulate toxins, approach humans, bite or sting, nor vector or disseminate any diseases (Wang & Shelomi, 2017, p. 91).

The typical adult BSF is approximately 16 mm long with two wings (Park, 2016, p. 3). The abdomen of the male tends to be bronze in colour whilst the female has a red hue (Figure 2.6).

Their legs are black with light yellow forelegs and have black, straight antennae (Hawkinson, 2005; Park, 2016, p. 3; Ghughuskar, 2012, p. 130). BSFs lack any chewing part within their mouth structure and are only able to suck liquid supplements.



Figure 2.6 Image of a mature male (left) and female (right) BSFL

Source: (Generalovic, et al., 2021, p. 2)

2.5.2 Life cycle

There are five major stages of BSF life: egg, larvae, prepupae, pupae, and fly (Figure 2.7) (Purkayastha & Sarkar, 2021, p. 21).

The BSF lifecycle begins with a larva in an egg. The larvae take approximately 4-5 days to hatch from being laid (Ghughuskar, 2012, p. 131). BSFL migrate to sources of organic waste after hatching (Park, 2016, p. 5) where they feed for 2-4 weeks. The feeding period depends on the availability of food and environmental conditions (Purkayastha & Sarkar, 2021, p. 22). As the larvae feed and reach maturity they develop into prepupae. During this stage, the prepupae commence feeding, empty their gut and migrate to a dry place (Barraza, Lopez, Quan, Wat, & Wolbert, 2016, p. 2; Purkayastha & Sarkar, 2021, p. 22). Once pupation begins, the larvae become immobile. During pupation, the larvae moult six times before their exoskeletons harden and darken. Pupation can take approximately two weeks; thereafter an adult BSF emerges (Barraza, Lopez, Quan, Wat, & Wolbert, 2016, p. 2). An adult BSF has an average life span of approximately 8–20 days (Purkayastha & Sarkar, 2021, p. 22) where its sole purpose is to reproduce.



Figure 2.7 The typical lifecycle of BSF

Source: (Purkayastha & Sarkar, 2021, p. 22)

The BSF reproduce at an exponential rate (Diclaro & Kaufman, 2015, p. 2). BSF generally mate within two days of emergence. BSF females are monogamous and mating can occur in the air and on the ground with one male BSF (Purkayastha & Sarkar, 2021, p. 22). Females lay eggs within the following two days in a dry environment near or sometimes on organic waste that will provide a food source for the larvae once hatched (Park, 2016, p. 4). It takes approximately 25 minutes for a female to lay between 350 and 1000 eggs. The fertilized eggs hatch after four days (Purkayastha & Sarkar, 2021, p. 22)

2.5.3 Factors affecting the lifecycle

The environmental conditions have a significant effect on the metabolism of BSF. BSF and BSFL are affected by the ambient temperature, relative humidity and intensity of sunlight. BSF and BSFL can survive and reproduce in environments with moderate rainfall, mild to warm summers and cool winters. Mating is regulated by light intensity while the lifespan and laying

of eggs are dependent on the humidity and temperature (Tomberlin, Adler, & Myers, 2009, p. 932)

2.5.3.1 Mating

During the mating stage, a significant hindrance is seasonal changes in the duration and intensity of sunlight and low temperatures. Mating notably reduces during the winter months. Relative humidity has a significant effect on both the length of life and the mating process of the BSF. Park (2016) reported that a relative humidity of below 25% was not conducive to mating while Ghughuskar (2012) reported that a relative humidity of between 30% and 90% was optimal for both a full life cycle and successful mating. The BSF require direct sunlight to mate. Although BSFs can survive outside the tropical the reproduction rate is lower. Studies found that 85% of mating took place in the morning when sunlight was $110 \mu\text{mol m}^2 \cdot \text{s}^{-1}$ (Park, 2016, p. 7). Increasing the sunlight above this threshold decreased mating activities. To replicate this light indoors requires a specific artificial light. A 500-watt, $135 \mu\text{mol m}^2 \cdot \text{s}^{-1}$ quartz-iodine lamp (Park, 2016, p. 7) or a LED (LED ratio UV: B: G = 1: 1: 3) light (Hoc, Noël, Carpentier, Francis, & Caparros Megido, 2019) can provide adequate light to stimulate the eyes of the BSF and ensured reproduction and eggs fertility.

2.5.3.2 Eggs

BSF lay eggs inside crevices in or near an organic food source where the hatchlings can crawl into the food source with ease. The most conducive conditions for egg-laying have been reported when the moisture content of the waste is between 60% and 70% and the relative humidity is higher than 60% (Purkayastha & Sarkar, 2021, p. 22). At lower humidity, there is an increased chance of water loss through the egg membrane leading to its desiccation. Hatching occurs after 3 to 6 days from laying when the temperature is within an optimal range of 28 °C to 30 °C. Eggs do not tend to hatch when the ambient temperature is below 12 °C and the BSFL has a significant change in early mortality when the temperature was between 16 °C to 19 °C (Holmes, Vanlaerhoven, & Tomberlin, 2012, p. 973).

2.5.3.3 Black Soldier Fly Larvae

The growth of BSFL is dependent on temperature, humidity, feed composition and population density. There are varying reports regarding the optimal temperature range for larvae in the pre-pupal and pupal phases. Tomberlin *et al.* (2009) reported that larvae could survive in

temperatures not exceeding 36 °C whilst Chia et al (2018) reported that larvae in pre-pupal and pupal phases can survive at temperatures between 12 °C to 37 °C and 10 °C and 44 °C, respectively. The optimum temperature range that has been reported for BSFL growth is between 25 °C and 30 °C. The BSFL can survive in more adverse conditions by undergoing a form of hibernation until conditions become more favourable (Park, 2016, p. 6). With an increase in relative humidity, the mortality rate of BSFL decreases. The number of larvae per unit area is a determining factor in the rate of growth and the size of BSFL. A larval density of 1.2 larvae/cm² has been suggested as the optimum density with 5 larvae/cm².

2.5.3.4 Black Solider Fly

BSFs and BSFLs can tolerate a range of temperatures with the optimal temperature range for a mature BSF, cited in literature, between 15-47 °C (Diener, Studt Solano, Roa Gutiérrez, Zurbrügg, & Tockner, 2011, p. 360). There is no consensus on the optimal temperature for BSF with Diener *et al.* (2011), Ghughuskar (2012), Park (2016) and Chia *et al.* (2018) citing 32 °C, 27 °C, 28 °C and 30 °C, respectively. The success of both BSFL hatching, BSF emergence and adult BSF lifespan increases with an increase in relative humidity (Figure 2.8) (Holmes, Vanlaerhoven, & Tomberlin, 2012, p. 973).

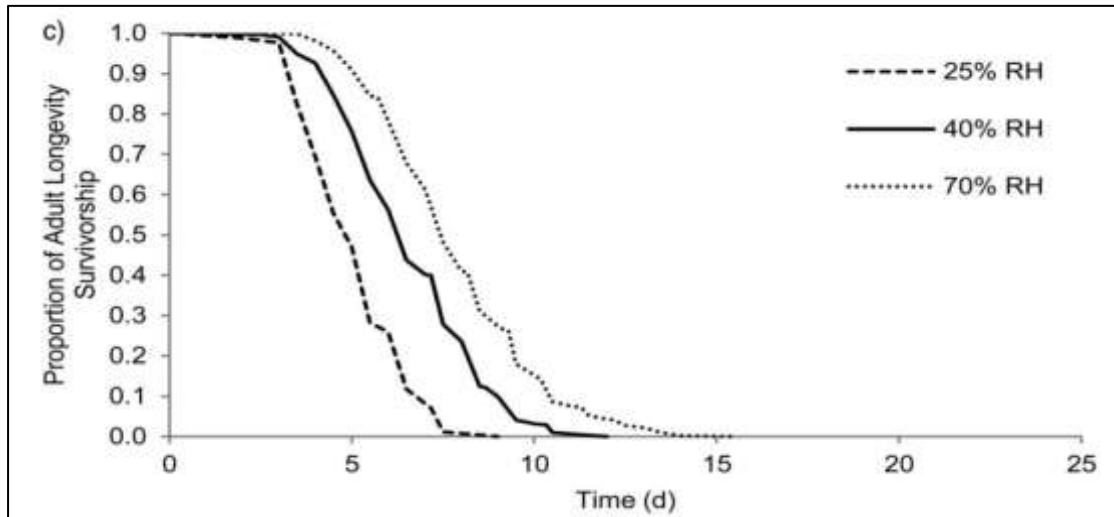


Figure 2.8 The effect of relative humidity on adult BSF longevity

Source: (Holmes, Vanlaerhoven, & Tomberlin, 2012, p. 973)

2.5.4 Diet and conversion rates

The adult BSF does not have a digestive system and no functioning mouthparts. Adult BSF can suck up liquids but rely on the large stores of fat and protein within their bodies from the larval

phase for energy (Ghughuskar, 2012, p. 132; Park, 2016, p. 8). The BSFL has a preference for organic waste but is reported to consume a wide range of organic materials.

BSFL consume organic waste at a rapid rate and convert the waste into valuable nutrients. The conversion rate of waste into valuable biomass is dependent on the type of waste, with different substrates being converted quicker than others (Newton, Sheppard, Watson, Burtle, & Dove, 2005, p. 9; Purkayastha & Sarkar, 2021, p. 22). BSFL convert waste into their body mass. Before the renewed interest in BSFL for waste management and commercial purposes, it was thought that manure was the preferential food choice of BSFL.

The conversion rates of multiple types of manure have been studied and outlined in Table 2.5. It has more recently been discovered that BSFL effectively consume and convert various types of organic waste, not just manure. Although when fed various types of manure the BSFL tend to gain a higher mass over less time, when fed faecal sludge or food waste a higher proportion of the waste is biodegraded (Table 2.5).

Table 2.5 Biodegradation and larval development data of BSF

Type of waste fed	Material biodegradation (%)	Duration of larval development (days)	Weight of Prepupae/pupae (mg/ pupa)
Faecal sludge/food remains (3:7)	95.2	14	295
Faecal sludge/food remains (1:1)	88.2	16	263
Faecal sludge/food remains (7:3)	88.0	14	299
Poultry feed	84.8	16	251
Food waste	81.8	16	101
Soybean residue curd	72.4	19	97
Faecal sludge/Brewer's waste	69.7	15	261
Diary manure/soybean residue (1:4)	68.3	21	123
Municipal organic waste	68.0		84
Faecal sludge/banana peeling	67.1	18	197
Faecal sludge: Market	66.6	18	39
Faecal sludge/Brewer's waste	63.6	15	270
Primary sludge waste	63.3	20	137
Faecal sludge/banana peeling	63.1	20	238
Faecal sludge/Brewer's waste	63.1	15	196

Faecal sludge	61.5	22	170
Abattoir waste/fruit and waste (1:1)	61.1	17	252
Dog food	60.5	18	252
Poultry manure	60.0	19	164
Market waste	59.4	18	59.9
Diary manure/soybean residue (2:3)	56.6	21	117
Faecal sludge/banana peeling (1:1)	56.1	24	253
Food waste	55.3	19	212
Pig manure/dog food/human	55.1		
Chicken manure curd	55.0	18	98
Mushroom root waste	54.8	26	120
Faecal sludge (3:7)	54.7	27	18.1
Human faeces (lump (7:3) feeding)	54.6	30	241
Human faeces (incremental (4:1))	54.2	28	199
Diary manure/chicken manure	53.4	19	86
Brewer's waste	52.4	16	78
Diary manure: Chicken (2:3)	52.1	20	92
Faecal sludge	50.3	16	70
Undigested sludge waste	49.2	48	145
Diary manure/chicken manure	49.1	21	81
Maize straw curd	48.4	19	48
Diary manure cake	48.0	16	99
Human faeces (3:2)	47.7	19	245
Fruit and vegetable	46.7	45	218
Diary manure/soybean residue (3:2)	46.5	21	112
Abattoir waste (1.4:1.2:1)	46.3	17	248
Poultry manure (7:3)	46.0	11	114
Banana peels	44.7	16	55
Diary manure/chicken manure	44.3	21	73
Diary manure	43.2	22	53
Brewery by-product waste	42.5	32	113
Chicken feed	41.8	17	48
Brewer's waste	38.7	15	45
Pig manure	37.7	144	69
Cassava peel waste	37.0	54	10

Cow manure feeding)	36.8	214	74
Chicken manure	36.7	144	56
Swine manure cake	33.0	17	83
Diary manure/soybean residue (4:1)	32.4	23	89
Coffee pulp	30.0	13	147
Diary manure the	25.8	24	63
Pig manure curd	13.7	17	24
Digested sludge (3:7)	13.2		70

Source: Adapted from (Purkayastha & Sarkar, 2021, p. 22)

2.5.5 Economic value of BSF and BSFL

BSFs and BSFL have several commercial benefits when used in the treatment of MSW. These include the production of protein-rich animal feed, nitrogen-rich frass for fertiliser, and oils for biodiesel production but the most significant is the reduction in landfill management operating costs.

2.5.5.1 Animal feed

Traditionally, soybean and fish meal (a commercial product made from wild-caught fish and associated bycatch) are commonly utilised as animal feed due to their high protein content. Both these products are under stress as soybean production for animal feed is in direct competition with human consumption and the sustainability of wild-caught fish is questionable (Purkayastha & Sarkar, 2021, p. 22). Processed BSFL can be utilised as a protein component within the animal feed. The cultivation of BSFL requires less land area and water than the production of soybean and fish meal. As BSFL consume waste they are considered to be more economically viable to produce.

The BSFL have a high protein and micronutrient content. Depending on the composition of the waste the BSFL consumes, the protein and fat content varies (Table 2.6). On average, the dried BSFL contains approximately 40-42% protein and 30-35% fat (Ghughuskar, 2012, p. 133; Mutafela, 2015, p. 9; van Huis, et al., 2013, p. 94), and the amino acid profile is similar to soybean. The dried BSFL provide a promising option for increasing the protein content in the feed, providing greater supplementation opportunities in animal feed for both agriculture and aquaculture with an estimated 16% cost-benefit and 25% return on investment (Purkayastha & Sarkar, 2021, p. 22).

Table 2.6 Protein and fat composition of BSFL biomass when fed different types of waste

Type of waste fed to BSFL	Protein (%)	Fat (%)
Food waste	58.0	15.0
Coconut endosperm waste	43.7	31.8
Digestate	43.6	33.1
Vegetable waste	43.2	28.0
Kitchen waste	43.1	40.7
Chicken feed	43.0	27.2
Poultry manure	42.2	21.8
Restaurant waste	42.0	35.0
Pig manure	41.3	31.0
Banana peels	41.2	33.6
Food waste	41.1	30.1
Chicken manure	40.5	41.0
Kitchen waste	39.9	37.1
Brewer's waste	39.0	24.0
Faecal sludge	37.7	25.9
Brewer's spent grain	36.1	35.9
Pig manure	34.9	38.0
Poultry manure	33.0	34.3

Source: Adapted from (Purkayastha & Sarkar, 2021, p. 22)

2.5.5.2 Fertiliser

The residue from the BSFL (frass) has a high nutrient content, particularly of nitrogen, and can be used as a fertiliser. The levels of nitrogen, phosphorous and potassium (NPK) vary and are dependent on the waste inputs (Table 2.7). The overall emission of greenhouse gases from the production of BSFL is significantly lower than that of traditional fertilisers and BSFL removes heavy metal concentrations from waste streams which reduces the costs of environmental remediation of both the waste site and the agricultural land. There are, however, limited studies focused on the application of BSFL residue as a component of fertiliser and the subsequent crop yield.

Table 2.7 Nutrient composition of BSFL when fed different types of waste

Type of waste fed to BSFL	Organic matter (%)	Nitrogen (%)	Phosphorus (%)	Potassium (%)
Food waste	88.7	31.2	11.4	8.4
Golden needle mushroom root	76.0	2.7	2.1	1.3
Chinese cabbage seeds Rapeseed	65.7	52.9		
Chicken manure	64.0	2.7	5.0	3.8
Cow manure	59.9	6.3	9.6	19.5
Pig manure	58.0	10.0	27.0	13.9
Chicken manure	51.0	8.1	16.4	21.2
Sewage sludge	47.0	19.9	11.1	5.1
Coffee husk	31.1	1.3	0.5	2.8

Source: Adapted from (Purkayastha & Sarkar, 2021, p. 22)

2.5.5.3 Biodiesel

Biodiesel is at the forefront of the alternative fuel discussion. The most explored option is utilising edible oils for biodiesel production. This however has invited debate about food and water security. The oil extracted from the pressing of the larvae is a viable source of biodiesel (van Huis, et al., 2013, p. 10) The biodiesel production from BSFL has the engineering advantages of self-separation from organic waste, high-fat content and rapid proliferation (Park, et al., 2022, p. 14). Additionally, compared to current crops used for biodiesel, BSFL has a quicker turnover time and requires less land for production (Kim, et al., 2021, p. 161). The fat fraction of BSFL is a potential source of international standard biodiesel with an estimated yield of 93% (Jung, et al., 2022, p. 121700) to 95% (Purkayastha & Sarkar, 2021, p. 23). 1§presents the cetane number and flashpoint temperature of biodiesel produced from BSFL-fed various waste types. The cetane number is an indicator of the ignitibility of diesel fuels and the minimum acceptable number is 40. The flashpoint temperature is the lowest temperature at which a liquid will produce sufficient vapour to produce a flammable mixture in the air. For diesel to meet commercial standards the flashpoint must lie within the range of 125- and 180-degrees Fahrenheit.

Table 2.8 Fuel quality of produced biodiesel from BSFL

Waste fed to BSFL	Cetane number	Density (kg/m ³)	Viscosity (mm ² /s)	Flashpoint (°F)
Restaurant waste	58	860	4.9	128
Rice straw and Restaurant waste	55	895	5.9	123
Organic waste	53	885	5.8	123
Fermented wheat bran	50	875	5.2	121
Fermented wheat bran	50	872	5.2	121
Restaurant kitchen waste	49	875	4.6	143

Source: Adapted from (Purkayastha & Sarkar, 2021, p. 22)

2.5.6 Viability of BSFL production

The viability of the BSF concept depends on the ability to develop a system that can effectively and efficiently produce BSFL on a large scale. There is great interest in the potential of BSFL for waste management as they process a diverse range of waste streams and can significantly reduce waste mass. The literature demonstrates that there is potential for BSFLs to meet the rising demand for protein and there is much optimism around bioconversion. However, there is still a fundamental need for research into the economic practicalities of a large-scale system (Suckling, Druckman, Small, Cecelja, & Bussemaker, 2021, p. 128711).

Currently, the most promising design is in a small-scale system. A small-scale self-harvesting system exploits the BSFL genetic behaviour of exiting the waste before pupation and this facilitates the harvesting of the BSFL (Mutafela, 2015, p. 9). The design incorporates an elevated ramp that is installed in the container the feeding BSFL are kept in. The pre-pupal larvae exit the feed by moving up the ramp and falling into a separate bucket through a hole at the end of the ramp. This simplifies the challenge of having to separate the mature BSFL from the remaining organic waste. The critical areas that currently need to be addressed are the mass breeding of BSF and BSFL and developing an effective and sustainable feeding system, leading to more efficient harvesting and processing of the BSFL (Suckling, Druckman, Small, Cecelja, & Bussemaker, 2021, p. 128711).

2.5.7 BSFL market

The global black soldier fly market is predicted to increase by an estimated 33% by 2030 and reach a market value of US\$ 3.4 billion (Wood, 2021, p. 1). As wild fish stocks deplete and there is growing concern over deforestation linked to soybean production, alternate sources of protein, especially insect-derived protein, will become a bigger player in the global market (Sonesson, Davis, & Ziegler, 2010, pp. 1-10).

Mass-reared BSFs have economic viability due to the capability to feed on organic waste, the ability to contribute to a circular economy and provide an alternative source of protein for both livestock and pet feed (Jucker, Lupi, Moore, & Leonardi, 2020, p. 362). The potential growth in the BSF market will arise from increased demand for pet food and meat production, the continuous development in the aquaculture industry and government investment in insect meal for livestock feed. Along with animal feed, there is a growing market potential for organic fertiliser and biodiesel. In 2019, animal feed and in 2020 organic fertilisers comprised the largest BSF market share, demonstrating the current volatility in the BSF market (Wood, 2020, p. 1).

The major market share of BSFL for animal feed in 2019 is mainly attributed to the increasing consumption of meat, increased investment in the BSF industry, a significant number of start-up businesses, a growing aquaculture industry and government approvals for the use of BSFL as a component of animal and pet food (Wood, 2020, p. 1). Whilst the increased market share in 2020 has been attributed to a paradigm shift towards organic produce consumption as well as an increase in small-scale hobby farmers during the Covid-19 pandemic. Globally, the high demand for protein-rich animal feed, organic fertilisers and the large potential sources of organic waste available are further encouraging the development of mass rearing of BSFs (Meticulous Research, 2021, pp. 1-12).

2.5.8 BSFL private sector

The BSF industry has significant investment potential given the solutions it provides to several environmental issues (Meticulous Research, 2021, pp. 1-12). Although currently a niche sector, private investors can expect increasing financial interest in the sector as the concept transitions into mainstream industry. Partnering with companies and municipalities to process their organic waste, enables the private sector to escalate environmental and climate efforts while producing commercially valuable products (Aris, 2021, p. 1).

There are multiple private companies operating in the BSF market. Table 2.9 presents the major companies operating in the BSF market. These companies are privately-owned, and thus, their revenue figures and business operations and processes are not available in the public domain (Meticulous Research, 2021, pp. 1-12).

Table 2.9 List of the most prominent BSF companies, their year of funding, location, business model and company presence

Company	Founding	Location	Business Model	Company Presence
AgriProtein	2008	South Africa	Converting food waste into protein for animal, pet, and aquaculture feed and natural oil for cosmetics	North America, Europe, Middle East and Africa, Asia-Pacific, and Latin America
Protix B.V.	2009	Holland	Manufacturing and supply of BSF, cricket, mealworm, and locus products for animal feed and human consumption	Europe, North America, and Asia-Pacific
EnviroFlight Corporation	2009	United States	Developing BSF-based ingredients for poultry, aquaculture, pets, and fertilizer	North America, Latin America, Europe, and Asia-Pacific
BioflyTech	2012	Spain	Artificial breeding and intensive production of BSF biomass for protein products for fish, farm animals and pets.	Europe and the Middle East
Entofood Sdn Bhd	2012	Malaysia	Production of BSF protein for animal feed and organic fertilizer	Asia-Pacific
Nutrition Technologies Group	2014	Malaysia	Manufactures and supplies BSF proteins, oils, and frass for the aquaculture, agriculture, and animal feed industries	Asia-Pacific and Europe

F4F SpA	2014	Chile	Recovery of organic waste and the production of BSF animal feed and protein flour.	Latin America
SFLY Comgraf SAS	2015	France	Producing, manufacturing, and providing chitin and chitosan from BSF	Europe and Asia-Pacific
Hexafly	2016	Ireland	Producing plant nutrition, pet food, animal nutrition and human personal care from BSF	Europe
InnovaFeed	2016	France	Production and marketing of products for animal feed and aquaculture industry from BSFs	Europe, North America, Asia-Pacific, and Latin America

Source: Adapted from (Meticulous Research, 2021, pp. 1-12)

2.5.9 BSFL regulations

Most countries or unions require raw and/or final products that directly or indirectly feed into the human food chain to be tested, approved, and licensed.

In the United States, the Association of American Feed Control Officers approves the use of BSFL raised solely on feed-grade materials for use in aquaculture feeding salmonoid fishes. While this is very specific and does not include BSFL raised on faecal and organic waste, it does provide recognition in the industry of the benefits of BSFL as an alternate feedstock to fishmeal (Wang & Shelomi, 2017, p. 91).

In the European Union (EU), the regulations for the use of animal by-products and food waste for animal feed are stricter than in most countries. This is currently enforced through Regulation (EC) 1069/2009 and by Regulation (EU) 2019/1009 (the “New EU Fertilising Products Regulation”) from July 16, 2022. The strict regulations are a direct result of the Bovine Spongiform Encephalopathy outbreak which occurred in Europe in the 1990s causing Creutzfeldt Jakob Disease (CJD) (Stamer, 2015, p. 678).

The current regulations have been reviewed by the European Food Safety Authority and the new regulations account for animal feed and fertilisers produced from insects reared on human and hazardous waste (Byrne, 2021, p. 1). The new regulations allow for these animal feeds and fertilisers to be sold and used commercially, however, the raw materials, processes and final

products must undergo rigorous testing and licensing process. No products have currently been fully approved (Huygens, Saveyn, Tonini, Eder, & Delgado Sancho, 2019, pp. 6-9). The application of biosolids to agricultural land is regulated by the Animal By-products Regulation (ABP) directive and the Sewage Sludge Directive 86/278/EEC (European Environment Agency, 1986, pp. 1-12), which are integrated into both the old and new regulations. This directive allows sewage that falls within specific conditions, deemed as safe, to be applied directly to agricultural land as well as any residue from organic or human waste to be integrated into organic fertilisers (Whiteoak & Petsinaris, 2020, p. 1).

In the UK, the Department for Environment, Food & Rural Affairs (DEFRA) and Local Authority Trading Standards regulate the products and processes used to produce animal feed. Raw components and the final product must meet the requirements of the Feed Hygiene Regulation 183/2005 (European Union, 2005, pp. 1-32) and apply a Hazard Analysis Critical Control Points (HACCP) system (Food Standards Agency, 2017, pp. 1-30). These requirements apply whether the raw products are processed commercially or sent direct to farms. DAFRA regulated the manufacturing, testing, importing, and exporting of fertilisers in the UK (Department for Environmental, Food and Rural Affairs, 2020, p. 5). The raw products of fertilisers do not have to be tested; however, the final product has to meet the requirements of the domestic fertiliser legislation and be tested by a UK-approved laboratory. There are currently no specifications for neither animal feed nor fertiliser produced using insects reared on human or hazardous waste (European Union, 2005, pp. 1-32).

In South Africa, animal feed and agricultural fertilisers were regulated by the Department of Agriculture, Forestry and Fisheries (DAFF), now the Department of Agriculture, Land Reform and Rural Development (DALRRD). The Fertilizers, Farm Feeds, Agricultural Remedies and Stock Remedies Act 36 Of 1947 regulates the production, distribution, import and export, sale and use of animal feed and fertilisers and has been amended several times since its first commencement (Department of Agriculture, Forestry and Fisheries, 1947, p. 2). However, the legislation and regulations to use the BSFL as a component of animal feed and for the frass as fertiliser vary. In order for BSFL to be commercially used as animal feed it is mandatory that the product is licensed by DALRRD and for the frass to be used in fertiliser its registration is recommended (Department of Agriculture, Forestry and Fisheries, 2015, p. 2).

The mandatory licencing process for animal feed is more complicated than the recommended licencing of frass to be used in a fertiliser (Animal Feed Manufacturers Association, 2015, pp. 1-5). Both the BSFL and the frass are considered raw products used in the production of feed

and fertiliser (Department of Agriculture, Forestry and Fisheries, 1947, p. 2). In order to utilise the BSFL within animal feed, it is necessary to license the product as it indirectly feeds into human food chains. The licencing for animal feed is intensive and requires that the feed production methodology be stable, meet quality standards and be continuously monitored for safety (Department of Agriculture, Forestry and Fisheries, 2015, p. 2). The law does not prohibit the use of human or hazardous waste for rearing the larvae for either animal feed or fertiliser. The only requirement is to demonstrate that the final blended product is safe and stable (Department of Agriculture, Forestry and Fisheries, 1947, p. 2).

Although the raw product for fertiliser does not need to be licensed, the process of licensing the final product becomes significantly easier if the raw product is licensed (South African Government, 2022, p. 1). The fertiliser produced from the frass would require statistical pot trials for licencing (Gärttling, Kirchner, & Schulz, 2020, p. 8). These trials compared the potential protein of the frass fertiliser with other traditional organic fertilisers as well as demonstrated compliance with Act 36 (Department of Agriculture, Forestry and Fisheries, 1947, p. 2). In most developing countries legislation and policies regarding the use of insect-processed animal protein do not exist, in these cases the FAO recommends that global good agricultural practices take precedence over local legislations (FAO, 2017, p. 4).

In South Africa, the guidelines for biodiesel production are outlines in the South African Biofuels Regulatory Framework (Department of Mineral Resources and Energy, 2019, p. 116). The framework issues guidance on the production of biodiesel from grain crops. There is no current guidance on biodiesel derived from insects.

2.5.10 BSF limitations

BSFL is an emerging waste management alternative that has the potential to produce commercially viable by-products. BSFL can economically and ecologically contribute to an effective circular economy. However, BSFL waste treatment is still in its infancy. Regarding the technological development, limitations reside firstly in the artificial breeding process of BSFs. The optimisation of the artificial environment and lighting to enhance artificial breeding is challenging with limited scientific studies available for reference. The second resides at the source of waste. Technology to collect and separate waste on a large scale, especially in developing countries, is absent. The system is dependent on a consistent input of waste as food for the BSF. If this cannot be guaranteed, the performance of the system is uncertain. There has been limited cost-benefit analysis undertaken. Thus, the technology may not be economically

attractive to investors and the commercial benefit from BSFL is not widely published. Risks to the system have not been extensively studied. Therefore, the effect and risk of contamination and/or other biohazards on the BSF itself and the by-products is not well understood (Purkayastha & Sarkar, 2021, p. 22).

Due to the infancy of BSF technology, there is no legal infrastructure surrounding it. There is very little scientific research regarding the effects of animals consuming feed consisting entirely or in part of BSFL. Due to the high levels of uncertainties, many nations currently prohibit the use of insects grown on waste as animal feed, especially animals farmed for human consumption.

The protein and fat content produced by the BSFL is highly dependent on the constituents of the waste (Renna, Schiavona, Gai, & Dabbou, 2017, p. 5). This makes regulation and legalising such a framework challenging as both input and output factors are consistently variable (Schiavone, et al., 2017, p. 2). Pathogens are a significant concern with any products entering the human food chain (Mutafela, 2015, p. 9). Although, BSFL products have low potential pathogenicity when produced from appropriate organic waste, as a new product it must undergo rigorous testing and approval procedures (Mutafela, 2015, p. 9) .

Within the scientific and commercial communities, there is no commonly agreed-upon way in which to measure, manage and research the BSFL (Schiavone, et al., 2017, p. 2). The surrounding methodology vague and differs study to study. With the growing interest in BSF for waste management one hopes that the volume of research and peer review papers increasing, and a common methodology will emerge.

The current limitation in production of BSFL lies within its small-scale applicability, challenges with upscaling and the timing within the lifecycle of the BSFL. As the BSFL begin to pupate they begin using the nutrients they have stored in their bodies and the nutritional value of the pupae is therefore less than pre-pupal larvae. In an optimised large-scale system, the larvae would ideally be collected at their most nutritionally rich point (Mutafela, 2015, p. 10; Newton, Sheppard, Watson, Burtle, & Dove, 2005, p. 4; Burtle, Newton, & Craig Sheppard, 2011, p. 3). Private companies have conducted research into the development of mass production systems as they anticipate that the production of BSFs is potentially financially viable. A South African company, Agriprotein, which specialise in BSF have done extensive work on the concept and reports that their Cape Town plant can process 100 tons of waste a day and produce 2,000 tons of MagMeal® (their BSFL protein) a year (Agriprotein, 2017, p. 1). However, at present, the supporting evidence is not yet available. With private companies conducting the majority of the

research and development, outside researchers are excluded and all the acquired information is then held confidentially. This represents a major constraint as it may limit the dissemination of the concept and hinders other researchers from working on the current challenges.

Currently, there is little knowledge of the market for the product as the focus remains on the development of the system and the products. As critical as this is, there is still the risk of developing a vulnerable system, as it is without a confirmed market for its products. For example, the level of demand, unspecified restrictions, unknown selling prices and certain other factors will affect the potential success of the system.

2.6 Supply chain theory

Supply chain management (SCM) is a strategic framework to effectively manage the flow of materials and information from manufacturing, through to distribution and point of sale (Lambert & Cooper, 2000). An optimised supply chain is critical to meet demand, lower costs, produce more efficiently and maintain a competitive edge (Horvath, 2001, p. 207). SCM includes product development, sourcing, production, procurement, logistics and sales (Skjoett-Larsen, 2000, p. 379).

2.6.1 The history of supply chain theory

The concept of supply chains has evolved systematically before appearing in literature (Tsay, Nahmias, & Agrawal, 1999, p. 301). Transport routes, organised labour and armies within ancient empires are signs of logistical development. Prior to the industrial revolutions in Europe and the United States and the improvement in shipping capabilities, supply chains were limited to the local region (Rodrigue, 2020, pp. 1-3). It is thought that the first supply chains emerged in the production of rum in the United States using sugarcane seeded in India but grown in the Caribbean (Galloway, 2005, pp. 11-12). This was one of the first documented evidence of organisation, land and human resources, material supply and property ownership.

In the 18th century, mass production and interchangeable parts originated through weaponry in the United States and ship pulley production in England (Hazarika, Dixit, & Davim, 2019, p. 14). Concepts of continuous workflows and specialisation had not developed. Mass production was introduced by Ford, in the 1920s, and included new ideas on producing at a large scale to reduce costs, increase efficiency and utilise supply chains irreversibly (Helper, 1991, p. 784). The increase in shipping and railroad capabilities in the 1940s improved the speed and availability of freight transport. Along with more efficient warehousing and loading processes,

cost-effective global trade was possible (Patararechachai, 1995, p. 114). During World War II military organisations required efficient supply chains locally and in Europe. This accelerated the consolidation of industrial engineering and operations research into supply chain engineering (Mangan & Lalwani, 2016, p. 7).

IBM developed the first computerised inventory management and forecasting system in 1967 (Packer, 1967, p. 668). Computerised data improved logistics management, forecasting, and inventory management. In conjunction with the development of barcoding, the pilot real-time warehouse management system was installed in 1975 (Morana, 2013, p. 66). The emergence of the personal computer in the 1980s immediately impacted SCM. The use of spreadsheets, optimisation models and algorithms improved processes and predictability throughout the supply chain (Lancioni, Smith, & Oliva, 2000, p. 50). Processes such as planning and resource management become available to visualise, save, and share. The rapid growth in the market share of the Japanese automotive industry between 1965 and 1989 created a paradigm shift within SCM. The Japanese lateral style of subcontracting and partnerships reduced costs and increased productivity at rates not achieved anywhere else globally (Dyer & Ouchi, 1993, p. 51). The competitive edge this lateral thinking provided was evident and thus began to gain traction within industry in the late 1990s. The term “Supply Chain Management” was introduced in 1983 (Cousins, Lawson, & Squire, 2006, p. 699).

Since the term, SCM was officially derived, six significant shifts have been observed in the evolution of SCM (Movahedi, Lavassani, & Kumar, 2009, p. 77).

1. Creation era

The creation era includes the requirement for large-scale changes and attention to the emerging Japanese management practices.

2. Integration era

This era was characterised by the increased focus on value-adding and cost-reducing through the integration of electronic data interchange (EDI) and enterprise resource planning (ERP) systems.

3. Globalization era

Attention was on increasing global systems of supplier relationships and the expansion of supply chains beyond national and continental boundaries.

4. Specialisation era (phase I): outsourced manufacturing and distribution

Companies began to focus on specialisation and outsourced non-core operations. Supply chains began to extend beyond the company walls and management was distributed across partnerships.

5. Specialisation era (phase II): supply-chain management as a service

Specialisation has advanced beyond logistics and into supply planning, collaboration, execution, and performance management.

6. SCM 2.0

With the continuous development of the internet, e-commerce and software capabilities, global supply chains continued to transform (Kayikci, 2019, p.7). The expansion of manufacturing in Asia and the emergence of AI and machine learning techniques have focussed supply chains towards data-driven, process-focussed and collaborative systems that strive for growth for all participants (Björkdahl, 2020, p.2). Collaborative platforms connect multiple buyers and suppliers with financial institutions and, automated supply-chain finance transactions are possible.

2.6.2 Evolving definitions of SCM

Several definitions of SCM have been established over time (Stock & Boyer, 2009, p. 692). The development of the definition of supply chain has expanded from a simple one-way logistics ideology towards a multi-lateral process focus considering the end-to-end process between procurement and the customer. Figure 2.9 presents some of the available definitions of modern SCM developed over the past three decades. Despite several available definitions, several themes are at the forefront including activities, benefits, and components.

SCM activities are most commonly composed of finances, services, information flows and the networks of relationships. The flow of information can be one-way, supplier to consumer, or two-way, where customer information is feedback into the process. Two-way flow encourages the movement of materials and information towards the end-product as well as demand from the marketplace influencing back to the raw-material processes (Handfield & Nichols Jr, 1999, pp. 1-10). SCM incorporates the process of managing the interface between key stakeholders, various supply chain members and enterprise functions (Walters & Lancaster, 2000, p. 160) An effective supply chain aims to create financial and productivity benefits whilst considering profitability, efficiency and customer satisfaction. Each member of the supply chain contributes to value-adding, logistics management and customer service (Lockamy & Smith, 1997, p. 144).

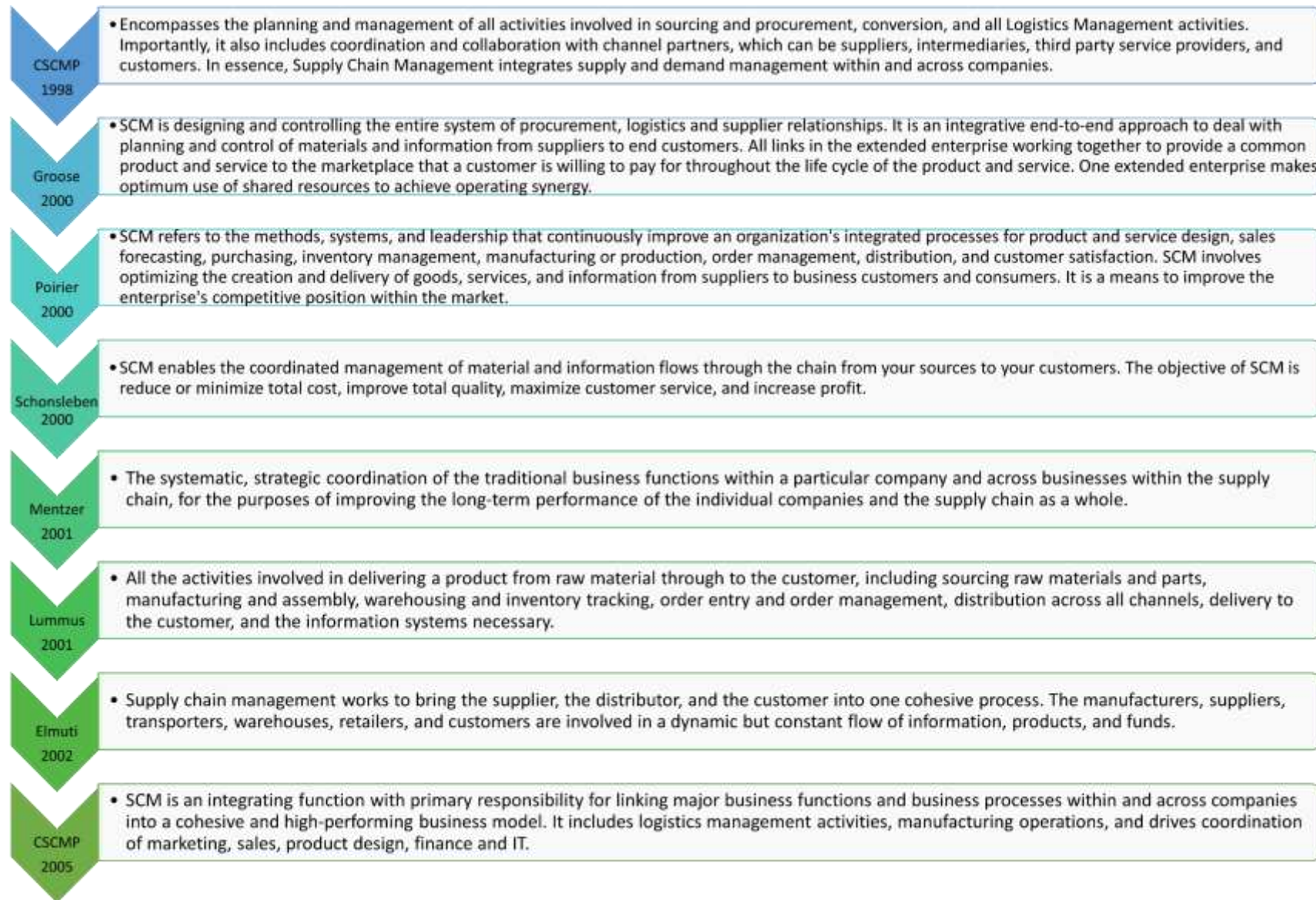


Figure 2.9 The evolution of the modern supply chain definition over time

Source: (Adapted from (Stock & Boyer, 2009, p. 692))

2.6.3 Aims and objectives of SCM

SCM is the backbone of modern commercial organisations. The primary aim of SCM is to ensure efficient running of a company and improve the chances of success (Chopra & Meindl, 2007, p. 267). Figure 2.10 presents eight of the most prominent objectives of SCM.

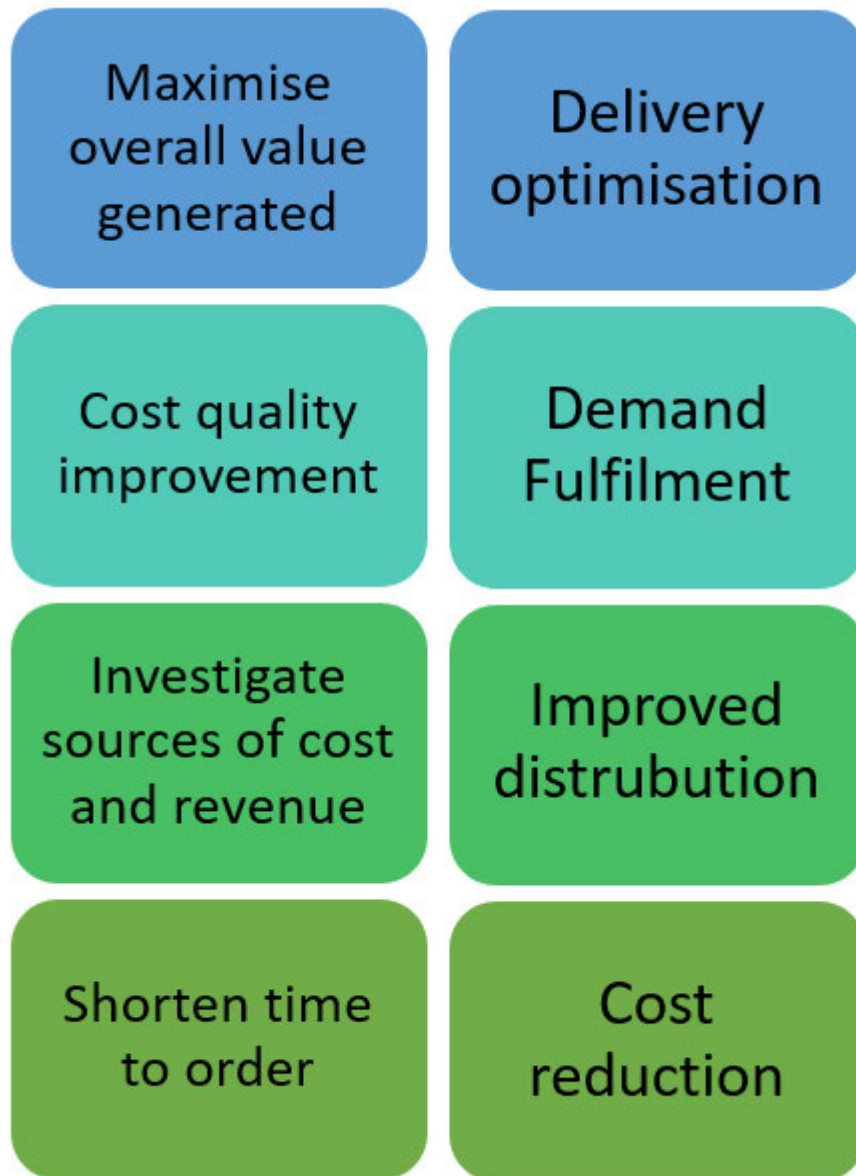


Figure 2.10 Eight prominent SCM objectives

Source: (Adapted from (Chopra & Meindl, 2007, p. 267))

2.9.4 Benefits of effective SCM

SCM has evolved from manual, logistics-focused processes to digital automation and coordination of all steps within the supply. Global supply chains that exist today are

increasingly complex and provide visibility of information, services and goods from procurement to manufacturing and delivery to the consumer. Optimising a supply chain is not a simple undertaking but offers the following benefits (Fawcett, Magnan, & McCarter, 2008, p. 36):

- A more agile business
- Better collaboration
- Better flow of materials, products and information
- Better visibility and data analytics
- Customer retention and experience
- Higher efficiency rate
- Improved quality control
- Improved risk mitigation
- Increases output
- Keeping up with demand
- Qualitative improvements
- Reduced inventory and overhead costs
- Shipping optimization
- Uninterrupted cash flow

2.6.5 Supply chain resilience

An important consideration of SCM is the resilience of the supply chain. SCR is defined as "the capacity of a supply chain to persist, adapt, or transform in the face of change" (Simchi-Levi, Wang, & Wei, 2018, p. 1478). A resilient supply chain is able to constantly adapt to external conditions and transform into a fundamentally new system. Three components of resilience exist persistence, adaption and transformation. Persistence is recovering following a disruption to the system, adaption is the system reaching a "new normal" and transformation is to analyse the current components and envision alternatives (Wieland, 2021, p. 60).

2.7 Conclusions

The current and projected increase in waste generation is well documented. Currently, the majority of the MSW generated is disposed of within landfills. Landfills not only pose a risk to the immediate environment but the surrounding communities. The potential air and water pollution can negatively impact the flora, fauna and soils surrounding the site and the health of nearby communities.

There are several alternative waste management systems available that could potentially address the diversion of waste away from landfills. Some of these methods have proven successful but the majority of successful cases have been reported from developed countries with existing infrastructure and investment. It is challenging from a financial perspective to match the cost-effectiveness of a landfill for developing countries.

When considering a circular economy, an effective alternative waste management system does not only deal with the waste at hand but creates by-products that hold potential financial value. The BSFL concept holds considerable promise and is an attractive option to contribute to addressing waste management. BSFL has proven to effectively consume heterogeneous sources of organic waste. BSFL convert various compositions of organic waste to high density proteins and lipids. In addition to being an effective waste management methodology, the BSFL can be used to as a protein component in animal feed and pressed for oil to use in the production of biodiesel, while the residue can be used to produce a nitrogen-rich organic fertiliser.

The concept of creating commercially valuable by-products from a waste management system, is proving attractive to the private sector. Perhaps the new-found interest will lead to financial backing which could rapidly increase the progress in the development and upscaling of alternative waste management methodologies, which would otherwise remain the financial responsibility of a science community and government structures.

The business operations and processes of successful private companies are not available in the public domain. Therefore, there is a significant gap in the publication of a standardised methodology for breeding and commercialising BSFL and the implementation of BSFL for waste management.

In order for the BSFL concept to advance, developments from a commercial viability standpoint need to be researched. One significant step that will contribute to that is to establish a functioning supply chain. This will allow more test sites and study trials to take place and commercial viability tests to be done. It will also allow market research and product development testing to take place as the next steps in the progression of the BSFL concept.

A large scale pilot BSFL research facility was established in South Africa, and as a result of this pilot study a close out report was produced compiling all findings and results from the combination of studies and testing conducted throughout the research period and this report has been published. It is from this single report that this study will aim to analyse and develop a supply chain that can be used as a framework for further research and for the commercialisation of BSF waste management systems.

CHAPTER 3: METHODOLOGY

3.1 Introduction

“Research is an endeavour / attempt to discover, develop and verify knowledge. It is an intellectual process that has developed over hundreds of years ever changing in purpose and form and always researching to truth.” (Pandey & Pandey, 2015, p. 10).

The following sections outline how the research at the Isipingo BSFL rearing site was undertaken. It defines the purpose of the research and states how the research questions were developed. Furthermore, it justifies the selected research strategy and design and discusses the research methodology used for data collection and analysis. Finally, it provides guidance on measures taken to maintain the credibility throughout.

3.2 Research purpose

Pandey and Pandey (2015) state that the purpose of research is to “discover answers to questions through the application of scientific procedure.”

In order to answer those questions, there a range of general objectives one would seek to achieve and they can be exploratory, explanatory or descriptive (Pandey & Pandey, 2015, p. 10; Saunders, Lewis, & Thornhill, 2016, p. 134). Exploratory research is conducted to gain or increase familiarity into a phenomenon in order to increase the range of knowledge and depth of insight about it. Explanatory research aims to explain the causal relationships amongst the variables, it explores the how and why a situation, case or condition is brought about. A descriptive research design portrays an exact profile of a persons, events or situations (Pandey & Pandey, 2015, p. 10; Saunders, Lewis, & Thornhill, 2016, p. 134)

This study was an exploratory study. This study set out to gain insight into the operations on site at the Isipingo WWTW. Through gaining an understanding of the operations onsite, all stakeholders, the processes used and the key variable factors that affect the process can be understood which will allow a supply chain to be developed.

3.3 Research questions and objectives

One of the most important and time-consuming tasks in a research study is developing the research questions. Two critical aspects to understand about the research questions is the substance (i.e., What does my study entail?) and form (What type of question am I asking i.e.,

who, what, where, why or how?) (Yin, 2014, p. 5). Yin (2014) provides a guide for relevant situations for different research questions and strategies (Table 3.1).

Table 3.1 Situations for various research strategies

Research strategy	Form of research question	Requires control of behavioural events	Focus on contemporary events
Experiment	how, why	Yes	Yes
Survey	who, what, where, how many, how much	No	Yes
Archival analysis	who, what, where, how many, how much	No	Yes/no
Historic analysis	how, why	No	No
Case study	how, why	No	Yes

Source: Adopted from Yin (2014)

Yin (2014) also goes on to state that in the case of an exploratory study, where the focus is on ‘what’ questions, any of the five of the research strategies is suitable as the aim is to develop a deeper understanding and further research.

As this is an exploratory study and the aim of the study is to understand what is occurring throughout the operational supply chain, the following research questions were developed.

- Who are the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?
- What are the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*)?
- What are the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?

From the abovementioned questions, the following research objectives were formulated:

- To identify the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.
- To identify the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*).

- To determine the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.

3.4 Research strategy

Research strategy is defined as the strategy that directs how an investigation will take place and how data will be collected and analysed (Saunders, Lewis, & Thornhill, 2016, p. 135). There are different types of research strategies, and they include experiments, surveys, archival analysis, historical analysis and cases studies (Yin, 2014, pp. 4-10; Saunders, Lewis, & Thornhill, 2016, p. 135).

In Table 3.1, Yin (2014) presents three conditions for selecting a research strategy. The research questions are addressed in Section 3.3. The remaining two conditions focus on the extent of control a researcher has on the behavioural aspects and the need to focus on contemporary events.

This study focusses on recent developments at the Isipingo WWTW. Therefore, it meets the criteria set out by Yin (2014) to be classified as a contemporary events. Additionally, there is no need to control behavioural activities on-site merely to gain insight into operational practises. Considering these three conditions, a case study is deemed to be the most suitable research strategy.

Yin (2014) defines a case study as “*an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between phenomenon and context are not clearly evident.*”

The BSFL site at the Isipingo WWTW is a unique case. This site is a PPP resulting in all results and findings being publicly available. At the completion of the site study a final closeout report was produced, combining all findings and results from the research conducted throughout the study by all research parties involved. This data is the only available data found focusing on a large scale operation from which a study can be conducted, resulting in a single site case study being the only suitable strategy (Grau & Alcock, 2019, pp. 1-68).

The report covers the processes of the overall pilot study, and the steps undertaken from initial assumptions in the operations, to the design and setup and testing of the original designs. The report then identified all issues discovered and all adjustments and additional aspects added to improve the site. It further expanded on market research and possible products and markets.

There are common misconceptions regarding case study research (Flyvbjerg, 2006, p. 224). Flyvbjerg (2006) stated that five of the most common misconceptions regarding case study research are:

- General, theoretical knowledge is more valuable than concrete, practical knowledge
- One cannot generalise on the basis of an individual case, therefore the single case study cannot contribute to scientific development
- The case study is most useful for generating hypotheses, that is, in the first stage of a total research process, while other methods are more suitable for hypotheses testing and theory building
- The case study contains a bias toward verification, that is, a tendency to confirm the researcher's preconceived notions.
- It is often difficult to summarise and develop general proposition and theories on the basis of specific case studies

Despite these misconceptions, case study research assists in gaining a deeper and more detailed understanding of this topic making it an appropriate and valuable research strategy (Yin, 2014, pp. 4-10). These misconceptions are noted and will be addressed throughout Chapter 3 and justifications will be provided.

3.5 Research design – Case study

A research design is defined as a logical blueprint that outlines the process of moving from the research questions through to producing a set of conclusions. This process can involve, a number of steps, including data collection and analysis.

Yin (2014) outlines five components for case study research design that were used to guide this research.

1. The study questions
2. Its propositions, if any
3. The unit(s) of analysis
4. The logic linking the data to the propositions
5. The criteria for interpreting the findings

3.5.1 The study questions

The research questions for this case study are set out and explained in Section 3.3. The purpose of the study questions are to assist in defining the form of the study (Yin, 2014, p. 21). The research questions for this case were created by the guidance from the literature review and aimed to gain understanding of the operations on-site at Isipingo WWTW. This was necessary to develop a supply chain. The three areas of interest are the stakeholders involved, the processes and logistics and the key variable factors that influence the operations.

3.5.2 The propositions

The propositions of the study are used to direct the focus on what needs to be studied while maintaining scope within the limitations of the study (Yin, 2014, p. 21). In the case of exploratory research, Yin (2014) states that propositions might not be suitable or available. Stating and defining the purpose of the study within the boundaries is required (Yin, 2014, p. 21).

The propositions of this study are as follows,

- The stakeholders involved in the whole BSF operation
- The operations and logistical processes to achieve a functional BSF operation
- The key factors and variables effecting efficiency within the BSF operations

3.5.3 The units of analysis

The definition for the unit(s) of analysis is determined by what is to be analysed or what is the “case”. This is depicted by the study topic but more importantly the questions that define the study (Yin, 2014, p. 21). The unit(s) of analysis need to have limits or boundaries that are a reflection of the unit defined. This can include geographic space, period of time and range of activities.

The unit of analysis for this study is defined at the BSF site operating at the Isipingo WWTW, with the aim to research the operations on-site and develop a functional supply chain for the BSF concept. The boundary for the unit of analysis is the activities and parties leading into the site, taking place on-site and outputs. And the time period is from mid-2017 and until late 2019.

3.5.4 Linking the data and propositions

Understanding the propositions and defining the appropriate data to address the proposition allows the correct data to be used and analysed to achieve the purpose of the study (Yin, 2014, pp. 21-22). In the case of this study, the data pertaining to each proposition is simply linked. There are five methods of data analysis to use in analysing the data and linking it to the three propositions (Shamoo & Resnik, 2009, p. 886).

The five data analysts methods for qualitative research are (1) content analysis, (2) narrative analysis, (3) discourse analysis, (4) framework analysis and (5) grounded theory (Shamoo & Resnik, 2009). For this study, due to the available data source, content analysis is the selected method.

3.5.5 The criteria for interpreting the findings

In research it is vital that data analysis is conducted to the highest possible quality. Yin (2014) presents four principles that outline quality research and they can be used to ensure standards are met:

- The analysis should indicate that all evidence was attended to
- The analysis should address all possible rival explanations
- The analysis should address the most significant aspects of the case study
- The researcher should use prior knowledge in the case study

To follow these principles available evidence is presented in the findings in Chapter 4. Alternative explanations are addressed in Chapter 2 and reviewed in Chapter 5. The study focuses on the key aspects of the study. And any prior knowledge gained in the review of literature in Chapter 2 is utilised.

3.6 Case selection

There are several circumstances whereby utilising a single case study is an acceptable research design. These are, but not limited to, a representation of (1) a critical case, (2) an extreme or unique case, (3) a typical or representative case, (4) a revolutionary case or (5) a longitudinal case (Yin, 2014, p. 39).

The case of the BSFL site at the Isipingo WWTW would not be considered as a typical or longitudinal case. There are no other such sites with publicly available operational data on which to conclude that the site is a typical representation nor are the findings able to be analysed

from multiple points in time. The case might be considered a critical or unique case as the findings would be able to extend the available knowledge and the case provides exclusive insight into the operations of a BSFL rearing site. The case would be best suited as a revolutionary case as the researcher has had the opportunity to observe and analysis operations and data previously inaccessible to the research community.

Single site case studies can be further categorised into holistic and embedded case studies. The Isipingo study would be considered an embedded case study (Yin, 2014, p. 39). This is due to the consistent unit of analysis application for multiple prepositions.

Due to the revolutionary nature of the case, the BSFL rearing operation at the Isipingo WWTW was selected for the single site case study. The case is revolutionary in terms of it being the only site to currently rear BSFL off both human and food waste and in that it has produced the only publicly available operational report (Grau & Alcock, 2019, pp. 1-68).

3.7 Research paradigm

Two broad categories of research exist, quantitative and qualitative. Quantitative research produces numeric results through repeatable methodology. Qualitative research tends to generate non-numerical data and focuses on understanding research questions as an idealistic approach. The use of qualitative findings is gaining increased attention across multiple disciplines (Pathak, Jena, & Kalra, 2013, p. 192). When undertaking qualitative research, the methods of sampling, data collection and analysis should be carefully considered as well as the validity and reliability of the research approach.

There are several approaches to qualitative research (Merriam, 2002, pp. 1-17).

Creswell (1998) and Merriam (2002) outline four common approaches:

- Phenomenology- focus on the essence of an experience
- Grounded theory- constructs a substantive theory
- Ethnography- focus on human society and culture
- Case studies- bounded, intense analysis of a phenomenon

Qualitative research methodology can be divided into three categories (1) observational studies, (2) interviews and (3) document analysis (Pathak, Jena, & Kalra, 2013, p. 192). The methodology is determined by the nature of the research questions, determining the data sources available and which sources will provide the most reliable information. It is necessary for

qualitative studies to be thoroughly designed and adhere to robust methodology in order to limit pre-conceived bias and produce high quality research (Merriam, 2002, pp. 1-17).

The integration of qualitative research methodology into a study allows for increased adaptability, subjectivity and an increased opportunity for collaboration. The methodology can be adapted in reaction to real-life experiences and allows for a more individualistic approach. Qualitative research inherently allows for greater collaboration resulting in more robust research approaches and conclusions. Qualitative research is, however, time and labour intensive and relationships and patterns can be challenging to identify (Carr, 1994, p. 718).

Document analysis is a straightforward, unintrusive and cost-effective research methodology. Working with published documents tends to limit the cost to the researcher and the need for extensive ethical consideration (Yin, 2014, p. 95). Furthermore, it is a non-reactive form of research and thus the conclusions drawn tend to be less bias and more robust. The required documentation could be privately protected and is not always accessible to the public or research community as well as documents that are available may not be specifically produced for research purposes and thus not contain sufficient information. Additionally, documents may not be complete, the authenticity debatable and could contain inherent bias (Cardno, 2018, p. 630).

3.8 Research location

This study focuses on a case study conducted at the Isipingo Waste Water Treatment Works, in Isipingo, KwaZulu Natal, South Africa

3.9 Data collection

A critical research decision is the choice of methodology for data collection. Primary and secondary data can be compiled during the data collection process. For a case study, primary data can be collected through interviews, direct observations, and participant observation. While secondary data is collected through documentation and archival records (Yin, 2014, p. 95).

Figure 3.1 presents the techniques of data collection suitable for a case study and the strengths and weaknesses of each technique.

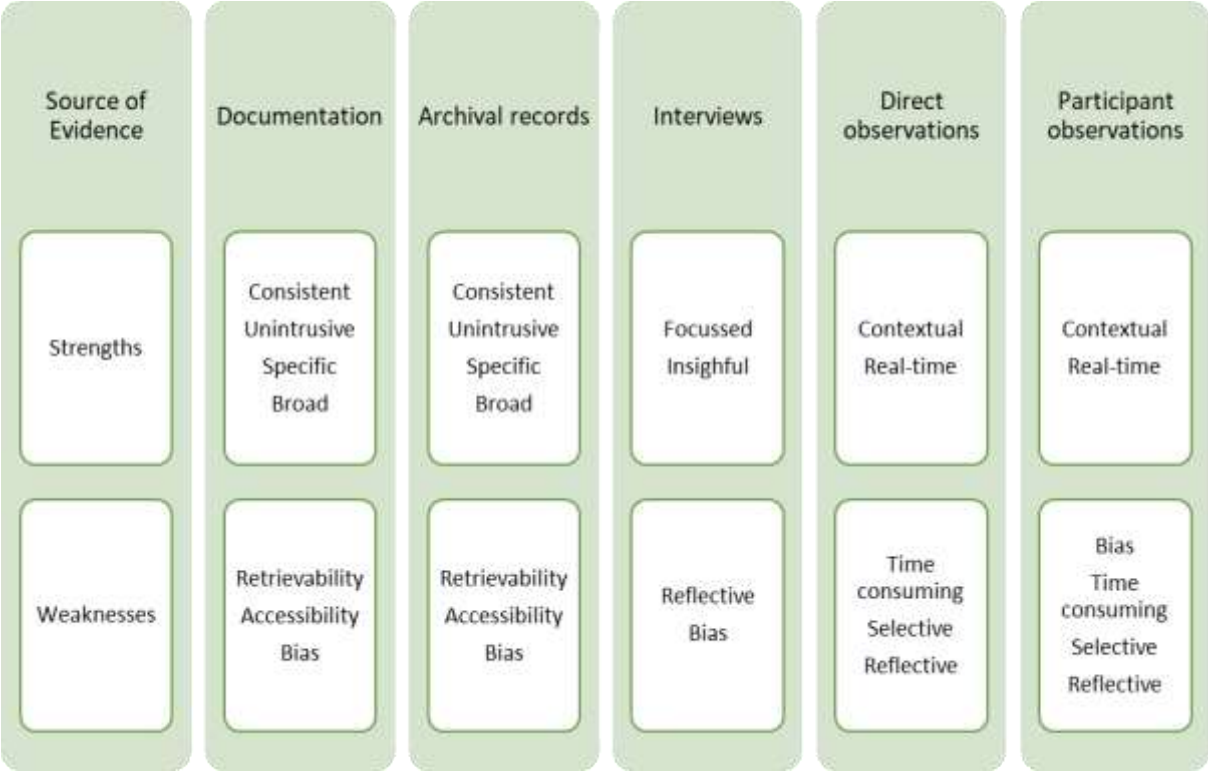


Figure 3.1 Suitable techniques for the collection of case study data

Source: Adopted from (Yin, 2014, p. 86).

Documents are useful, and in some cases critical, for revolutionary case studies (Bengtsson, 2016). For the purposes of this study, documentation analysis was selected as the most suitable and robust technique for collecting and analysing data. Document analysis is a straightforward, unobtrusive and cost-effective research methodology. Working with published documents tends to limit the cost to the researcher and the need for extensive ethical consideration (Yin, 2014, p. 86) (Yin, 2014).

Documents remain a consistent source of data that allow the researcher to review the data multiple times. Generally, the reviewed documents are not necessarily developed with the study in mind, and therefore present references and details with limited bias towards the study (Cardno, 2018, p. 627). Furthermore, it is a non-reactive form of research and thus the conclusions drawn tend to be more robust. The required documentation could be privately protected and is not always accessible to the public or research community as well as documents that are available may not be specifically produced for research purposes and thus not contain

sufficient information. Additionally, documents may not be complete, the authenticity debatable and could contain inherent bias (Cardno, 2018, p. 627).

The data collection procedure should include systematic searches for relevant documents. All available documentation should be considered and there is little excuse for not undertaking a thorough analysis of the documentary evidence accessible to the researcher. The research community has at times been critical of an over reliance on documentary evidence, however, regarding BSFL rearing sites and specifically the Isipingo BSFL rearing site, documentary evidence is the only available source of knowledge available to the researcher.

The document used for this study is the close out report from the Isipingo BSFL site and is a combination of the research undertaken throughout its operation. It was compiled by experts from all areas involved, including members from the Bio-Cycle research group, the eThekweni Municipality and the Pollution Research Group (PRG) of the School of Chemical Engineering at the University of Kwa-Zulu Natal (Grau & Alcock, 2019, pp. 1-68).

3.10 Data analysis

Data analysis is described by Shamoo and Resnik (2009) as “the process of systematically applying statistical and/or logical techniques to describe and illustrate, condense and recap, and evaluate data.” Furthermore, data analysis allows a researcher to separate the phenomenon of interest from the statistical noise that may be present within the data (Bengtsson, 2016, p. 10).

As stated in Section 3.7, this study is making use of qualitative data. Five techniques can be utilised for the analysis of qualitative data (Shamoo & Resnik, 2009, pp. 1-10).

1. Content analysis - the contextualising, categorising, summarising and presenting of secondary data
2. Narrative analysis - the reformulation of stories
3. Discourse analysis - the analysis of verbal and informal written text
4. Framework analysis - the identification and interpretation of a thematic framework
5. Grounded theory - the initial analysis of a single case to formulate a theory followed by the analysis of additional cases to contribute or disprove to the theory

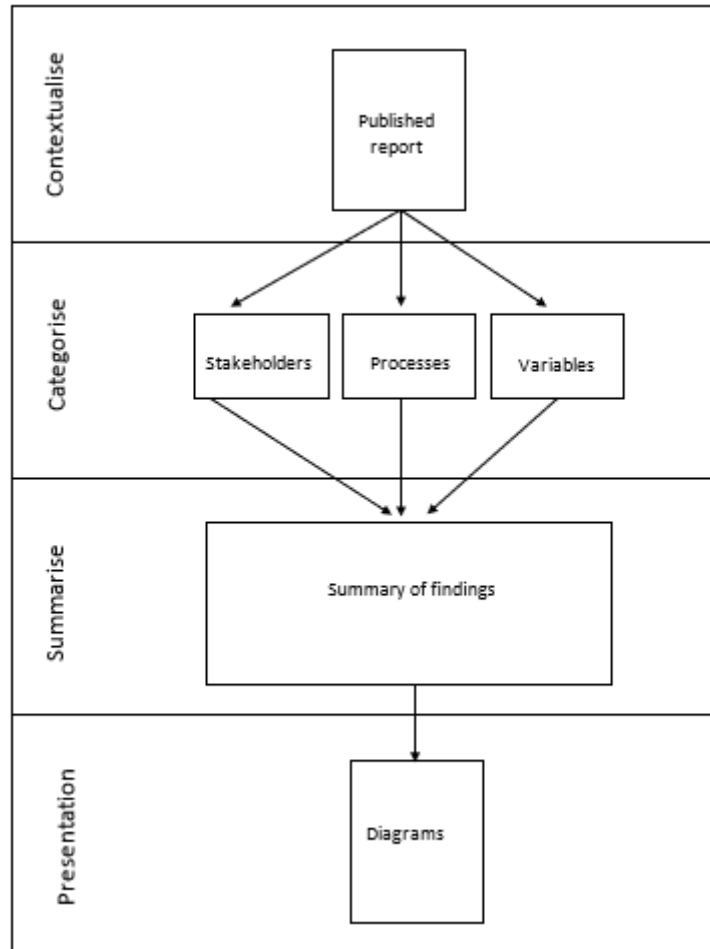


Figure 3.2 Data analysis contextual logic

Source: Author's creation

The qualitative data were analysed utilising the technique of content analysis. Findings were categorised, summarised and presented in the form of multiple frameworks of varying complexity (Figure 3.2).

3.10.1 Contextualisation of data

The first step in content analysis is for the researcher to familiarise themselves with the data. Once a holistic view of data is obtained, the researcher can deduce what constitutes the themes and conclusions can be drawn. The research questions and study aim should remain in mind during the contextualisation phase (Patton, 2002, pp. 30-32).

The process of contextualisation cannot be automated by other data analysis techniques, it requires the researcher to thoroughly examine the available content and contextualise it within the bound of their study (Bengtsson, 2016, p. 10).

The available single closing report from the BSFL rearing operation at the Isipingo WWTW was examined numerous times and was contextualised within international, national, local municipal and site context. This report was the final closing product compiled from all the studies and work conducted on site throughout the project's operations (Grau & Alcock, 2019, pp. 1-68).

3.10.2 Categorisation of data

During the categorisation of data, themes and categories are identified. During the categorization process, themes and categories are identified. The nature of these themes and categories should be that they differ externally but concur internally. Data should not fall in-between themes or categories however the themes and categories can link to one another (Krippendorff, 2004, p. 115).

There is no formal methodology for the categorisation of data from content analysis. Guidance is provided that each theme or category should be rooted in the data from which they are derived and ultimately contribute to achieving the aim of the study (Bengtsson, 2016, p. 10).

The data obtained regarding the Isipingo BSFL rearing site was categorised into three categories: namely, stakeholders, process and variables (Figure 3.3). The stakeholder category was divided into international, national and municipal stakeholder sub-categories. The processes were further categorised into multiple sub-categories outlining the range of processes taking place on the BSFL site. Variables were further discretised into four sub-categories inputs, environmental conditions, known variables and calculated variables (Grau & Alcock, 2019, pp. 1-68).

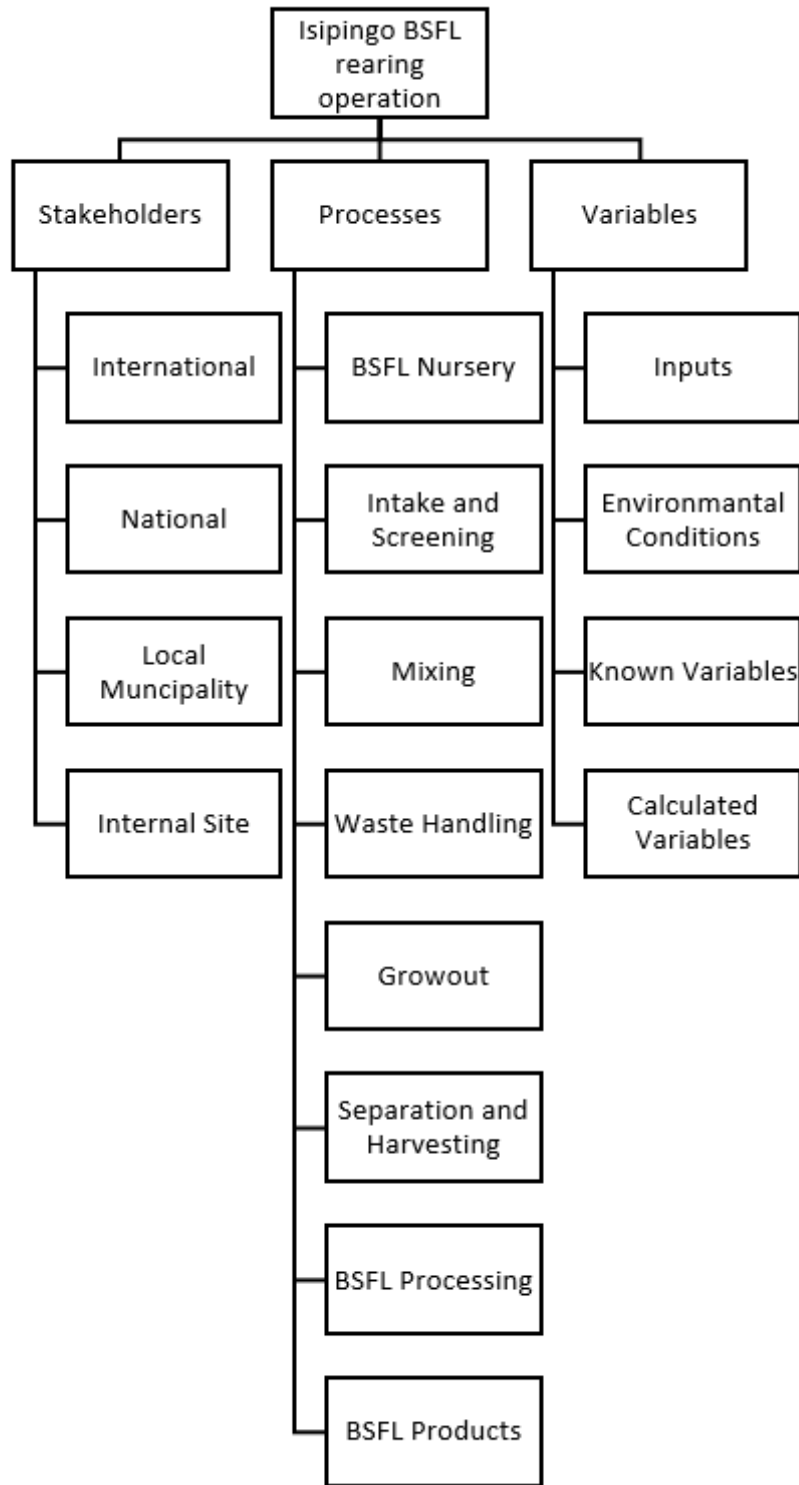


Figure 3.3 The categorisation of data from the BSFL rearing operation at the Isipingo WWTW

Source: Author's creation

3.10.3 Summarising of data

Once the categories and sub-categories are established, the data can be summarised into tangible outcomes. It is necessary to investigate the unique nature and distribution of each category. It is challenging to summarise qualitative data and therefore to ensure outputs that meet the aim of the study every effort must be made to limit any loss of valuable information when summarising (Bengtsson, 2016, p. 10).

For the BSFL rearing operation at Isipingo, how each of the categories and sub-categories interact, the interdependencies and controllable factors were summarised.

3.10.4 Presentation of data

There are two approaches to presenting the outcomes of a qualitative study. The first to report the key findings from each category and provide a generalised conclusion to summarise the findings (Burnard, Gill, Stewart, Treasure, & Chadwick, 2008, p. 430). The second is to represent the findings using a visual aid. The type of aid can vary based on the researcher preference and the most suitable means to demonstrate the findings in a clear and concise manner (Bengtsson, 2016, p. 10). A visual aid provides an opportunity for the researcher to provide an effective overview of the findings as well as demonstrate the overall context of the findings and the relationships between the categories.

In the case of the Isipingo BSFL rearing site, the findings were presented using two approaches. Multiple diagrams were developed to illustrate the stakeholders, processes and variables and the inter-relationships. Additionally, the findings were reported to allow for the visual presentation of findings to be fully understood.

3.11 Credibility of research findings

Credibility refers to the degree in which the researcher's synthesis and presentation of the data matches the perception of the source, whether it be documentary or participation (Bloomberg & Volpe, Presenting methodology and research approach, 2008, pp. 65-93). In order for a qualitative study to be considered credible, the description presentation of the data should be immediately recognisable by the participants of the study or the author of the secondary data (Bloomberg & Volpe, 2008, p. 231; Ponelis, 2015, p. 538). Additionally, to support the credibility of qualitative research, the research design should consider dependability, validity, and transferability (Cope, 2014, p. 3).

3.11.1 Dependability

The dependability of the findings refers to their constancy and replicability (Cope, 2014, p. 3). Dependability is reliant of the quality of the data collection and reporting methodology. Dependability can be illustrated when other studies concur with the findings or methodologies and when the research is undertaken in a systematic approach (Ponelis, 2015, p. 538). It is important to note that a researcher should obtain the same results when undertaking the same case study again, rather than attempting to replicate the results using another study (Yin, 2014, p. 149).

Yin (2014) provides guidance to ensure that a single case study remains dependable. The utilisation of robust case study protocol throughout the research design and data collect will ensure that the case study meet the criteria for dependability. This study made use of the recommendation of Yin (2014) in formulating a case study and proceeding with the data collection. The findings from this study would be replicable if it were to be undertaken again.

3.11.2 Validity

It is necessary for an exploratory case to demonstrate that both the case and the findings are valid. In terms of case studies, it is important to consider both construct validity and external validity (Stuart, McCutcheon, Handfield, McLachlin, & Samson, 2002, p. 422). Internal validity is not suitable for exploratory studies (Yin, 2014, p. 149).

3.11.2.1 Construct validity

Construct validity refers to the establishment of the correct operating measures regarding the concepts being studied. It is challenging to provide evidence of construct validity in case study research. Often it is criticised on the bounds that the researcher can fail to sufficiently develop operational and unbiased measures to collect data (Yin, 2014, p. 149).

Two measures a researcher can take to ensure the construct validity of their study is to establish a key chain of evidence during data collection and have key stakeholders review the draft findings after summarisation. In the case of the Isipingo BSFL rearing study, a chain of evidence was established from the outset and key stakeholders in the operation have reviewed and confirmed the initial findings (Yin, 2014, p. 149).

3.11.2.2 External validity

External validity is establishing the bounds in which the findings can be generalised beyond the case study. External validity is one of the biggest hurdles in case study research and is often criticised for providing a weak basis for generalisation. Yin (2014), however, outlines a research design measure to increase the external validity of a case study. The utilisation of publish theory, especially when using a single case study, will increase the external validity of a study.

The foundation of this study is on the synthesis of, mainly scientifically, published literature. This literature provides insight to the wider context and community beyond the bounds of the case study and allows the case study to be contextualised as part of a greater solution.

3.11.3 Transferability

The transferability of a study allows the findings to be applicable to similar situations. The transferability of findings largely rests in the methodology of data collection and summarisation. Findings should be systematically reported in order to ensure transferability (Cope, 2014, p. 3).

In order for a qualitative study to meet transferability criteria, the results need to have meaning to individuals who wish to apply the study in their own capacity. This study provided a series of supply chain diagrams pertaining to the Isipingo BSFL rearing site, however, these findings can be transferred to any exercise to establish a new BSFL rearing site.

3.12 Ethical considerations

In order to conduct this research Ethical clearance was obtained from the University of KwaZulu-Natal Ethics Committee.

Furthermore, this study only made use of data already in the public domain. This was in the form of secondary data in published reports and data which are referenced accordingly.

3.13 Limitations of the study

The main limitation of this study is the use of a single case study based at the Isipingo WWTW. This was single unique and significant study, but due to it being one single case, the results and output of the study will lack the ability to be generalised to the wider national and global scale and across all potential individual supply chains.

As a result, the supply chain will require further research to test and prove the functions of the supply chain and the effectiveness. Nonetheless, this study represents the first step in the process of designing and developing a supply chain for the beneficiation of organic wastes by BSFL.

3.14 Chapter summary

The questions which the study sought to answer were:

- Who are the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?
- What are the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*)?
- What are the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?

To address the research questions, a single case study was utilised. The research methodology to address these questions was presented in this chapter. In summary qualitative research in the form of a single case study was undertaken through document analysis. Although, case studies and particularly single case studies, have been subject to criticism in their credibility, they remain an essential research strategy for the ability to gain valuable insight in revolutionary cases. The researcher provided a robust explanation as to how the methodology and findings of this study meet the criteria for a credible case.

CHAPTER 4: FINDINGS

4.1 Introduction

Chapter 4 will address the findings found from this study, utilizing the research methods outlined in chapter 3 an analysis of the research study site report was conducted. The findings aim to answer the three research questions set out in Chapter 1.

- Who are the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?
- What are the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*)?
- What are the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?

The aim is that by answering these questions and getting an understanding of the operations on-site at the study and functional supply chain will be able to be developed.

The chapter begins with an overview of the background of the site which will allow for a better understanding of the findings. Then the three research questions will be addressed with a summarized figure displaying the factors at play and their relationship in the process.

4.2 Background to site

The case study selected was a BSFL plant at Isipingo Waste Water Treatment Works (WWTW). Figure 4.1 shows the location of the site and a satellite image of the Isipingo WWTW site and the sheds. It was a collaboration project in the form of a Public-Private Partnership (PPP) between the Biocycle and the eThekweni Municipality. Biocycle is a private company that operates the BSFL plant, and the eThekweni Municipality is the government entity paying gate fees for processing the sludge at the Isipingo plant. The capital expenditure for the plant was funded by the Bill & Melinda Gates Foundation. The Khanyisa Project was the implementing agent for the plant and grant holder from the Bill & Melinda Gates Foundation.

The aim of the BSFL project at the Isipingo WWTW was to develop a cost-effective faecal sludge treatment process using BSFL. For this project to be undertaken, a collaboration was necessary. eThekweni Municipalities require an alternative means to deal with the build-up of human faeces in urine diversion (UD) toilet systems. Over the last ten years, the eThekweni Municipality has conducted a mass rollout of UD toilet systems in semi-urban and rural areas

around the city. This was done to provide sanitation services to communities that are located in remote and unsuitable areas for alternative sanitation methods.

BSFL were identified as a possible means of processing the UD waste sustainably and profitably. Due to the profitability of this project, Biocycle were involved. Biocycle is a subsidiary company of Agriprotein, a private South African organisation specialising in BSFs reared from organic waste. Biocycle differs from Agriprotein in that they deal with BSF and rearing them off alternative waste streams, such as the UD waste.

Biocycle researched and developed a proposed plan which was viewed to be viable. Through donations from the Bill & Melinda Gates Foundation, they were able to, in partnership with the eThekweni Municipality, set up a pilot site at the Isipingo WWTW to develop and test this concept.

The study was granted two years, in such time the concept was to be developed and tested. At the two-year mark, an assessment was set out to assess the viability of the concept and the possibility of a viable business model. Construction on the site concluded in mid-2017 and operations began in late 2017 and ran until late 2019. At that point, assessments were made and a close-out report with the relevant findings was published (Grau & Alcock, 2019, pp. 1-68)

The project was deemed a success by the operators and funder on completion due to the number of lessons learned. These lessons will guide future plant installations and BSFL processing procedures in conditions similar to that of the Isipingo project.



Figure 4.1 Map and satellite imaging of the Isipingo WWTW site

Source: Google Earth

4.3 Stakeholders required to operate a commercially viable supply chain using BSF

Section 4.3 provides a breakdown of the stakeholders that were involved in the operations at the Isipingo WWTW BSFL site and defines their positions and roles within the supply chain. Figure 4.2 shows the stakeholders involved and their relationships with one another at the site and was developed through the analyses of the close-out report from the study site.

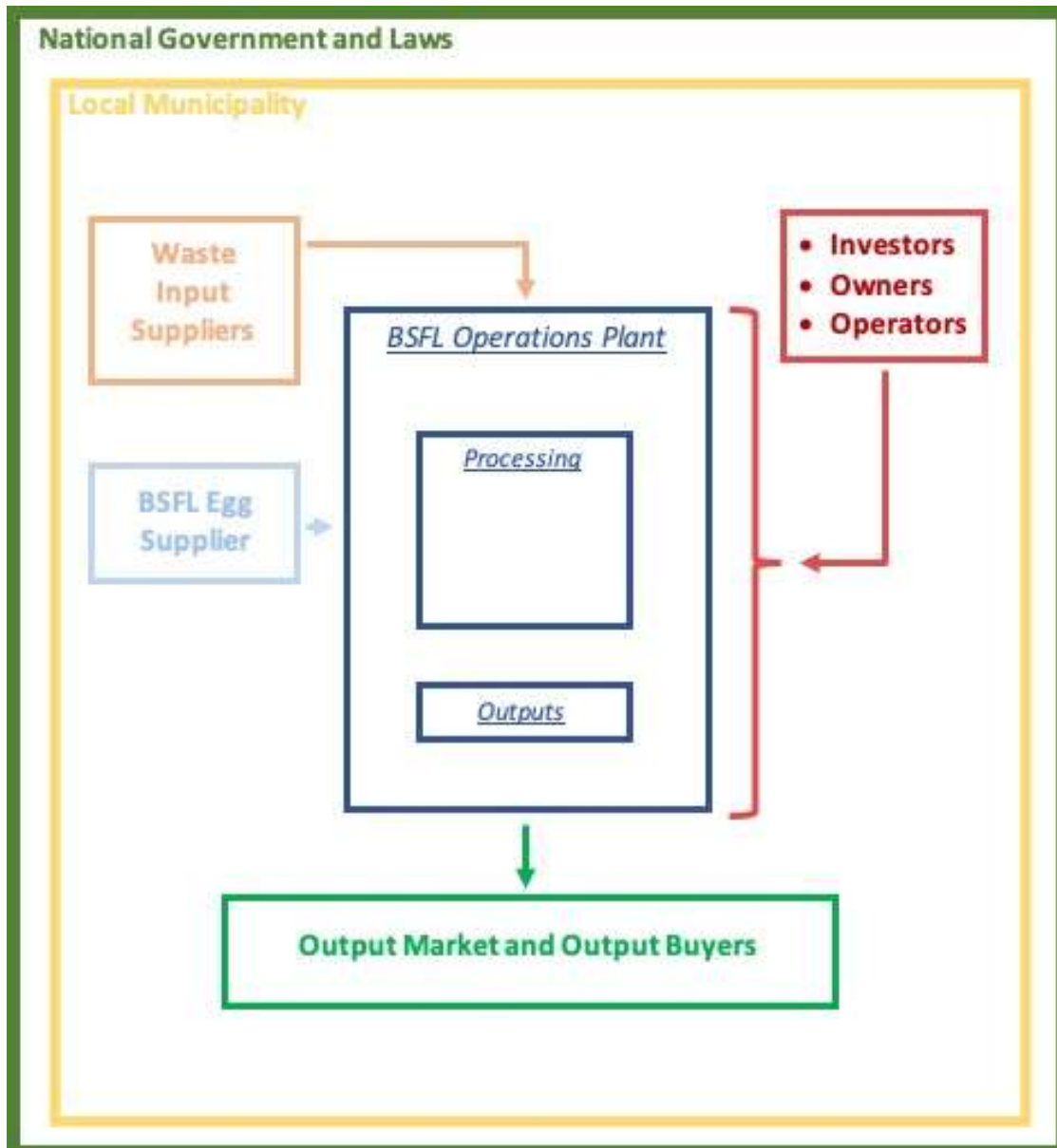


Figure 4.2 Stakeholders involved and their position in the supply chain

Source: Author's creation

4.3.1 National government and laws

The national government and subsequently their laws are considered because they are responsible for the laws that govern how companies conduct business and because the national policies and agendas affect how funding is available and allocated from government budgets.

The laws that govern animal feed and agricultural fertilisers are regulated by the Department of Agriculture, Forestry and Fisheries (DAFF) in South Africa. Act 36 of 1947 is the current regulating act for fertilizers, farm feeds, agricultural remedies, and stock remedies. Products

that need to be approved and licenced, need to be obtained from DAFF. The regulators have a significant impact on the opportunities and possibilities in the development of a commercially viable BSFL concept.

In South Africa, for BSFL to be used as animal feed commercially, the product must be licensed by DAFF. The mandatory licencing process for animal feed is complicated and time-consuming. BSFL is considered a raw product used in the production of feed. It is necessary to license the end-product as it indirectly feeds into human food chains. The licencing for animal feed is intensive and requires that the feed production methodology be stable, meet quality standards and be continuously monitored for safety. The law does not prohibit the use of human or hazardous waste for rearing larvae for animal feed. The only requirement is to demonstrate that the final blended product is safe and stable.

For BSFL and the BSFL residue to be used in fertiliser, it is recommended that it obtains a license. Although the raw products for fertiliser do not need to be licensed, the process of licensing the final product becomes significantly easier when the raw product is licensed. The fertiliser produced from the residue would require statistical trials for licencing. These trials will compare the potential protein of the residue fertiliser with other traditional organic fertilisers as well as demonstrate compliance with Act 36.

The second influence the national government has is over the policies and agendas it presents and passes. The South African Government has supported efforts to address issues about climate change and environmental degradation by supporting and actively participating in achieving the SDGs. Methodologies and parties involved in providing solutions to meet the SDGs, naturally, receive more attention and subsequently support, participation, awareness and funding.

4.3.2 Local municipality

The local municipality plays a key role in the operations of the BSFL site. In the case of the Isipingo WWTW BSFL site, the local municipality, eThekweni, were partners in the project and played a key role in the operations. The municipality approved the operation to take place on-site at the Isipingo WWTW and paid the gate fees per tonne of UD waste taken in by the site and processed.

This involvement of the local municipality is proven to be key to the possibility and success of a viable BSFL site. Having buy-in and cooperation from the municipality who normally is the responsible party for MSW allows for partnerships and supply chains to be created.

4.3.3 Investors, owners and operators

For the BSFL site to be possible, initial capital needed to be raised. In the case of the Isipingo WWTW BSFL site, the capital was invested by the Bill & Melinda Gates Foundation. The capital allowed for initial purchases and setups to be undertaken which allowed in turn for the plant to begin operation.

Through the commencement of operation at the site, necessary improvements and changes were identified and the more significant ones were implemented. Some of the necessary changes were not undertaken due to the cost. The final recommended process requires more initial investment than originally estimated. The investment amount will be set to vary depending on location, size, process volume and climate. The main cost points for initial capital expenditure are:

- Physical site
- Climate-controlled nursery
- Climate-controlled growout sheds
- Machinery

Biocycle operated the plant as they have experience with BSF through AgriProtein and with hazardous waste such as the UD waste used on this site. The owner and operator responsibilities could be done by the same party, in the case of the Isipingo WWTW, it was two separate entities, The Khanyisa Project and Biocycle

4.3.4 Waste input suppliers

Two third-party private waste suppliers were used as two waste streams were combined to make the feedstock for growout. The first supplier handled the delivery of UD sludge and was responsible for collecting UD waste from UD toilets across the surrounding areas and delivering it to the site. The second waste stream was food waste, delivered to the site by a supplier who collects, sorts and processes various sources of waste.

There were two suppliers selected to supply UD and food waste to the Isipingo site. The number and nature of suppliers could vary depending on the local needs or supplies within the surrounding area. As reported in Section 2.5.4, BSFL can process a wide range of organic waste and thus the BSFL concept is a viable solution to process both UD and food waste.

4.3.5 BSFL egg supplier

Effective mass breeding of BSFL in a controlled environment is complex. In the case of the Isipingo site, the BSF eggs were bred offsite as the site did not have the facilities or expertise to undertake an efficient breeding program. The eggs were acquired from the AgriProtein breeding site in Cape Town and couriered to the Isipingo site. At the Cape Town site, BSF eggs have successfully been bred on a large scale. Due to the 14-day incubation period of the BSF eggs, the transit time from Cape Town to Isipingo was not necessarily of concern, however, maintaining the controlled environment through transit was critical. During the establishment of new sites, outside of South Africa, that are unable to mass-produce BSF eggs, securing a reliable supplier of BSF eggs is integral to the operation.

4.3.6 BSFL operations

The on-site operations include (1) the nursery, (2) processing and screening of waste, (3) the growout, (4) harvesting of BSFL and (5) BSFL product processing. The detailed breakdown of the on-site processes is addressed in Section 4.4.

The primary on-site operator is Biocycle. Biocycle provides both the site managers and operational staff. Third-party contributors to the on-site operations include (1) utility companies who provide water and electricity, (2) machinery suppliers and servicers who provide, install and maintain on-site machinery and (3) consultants who guide the climate-controlled systems i.e., Nursery and growout sheds.

The nature of operational stakeholders will vary per site as suppliers and site needs will change every time. Additionally, the third-party contributors will depend on the expertise and capacity of the internal staff.

4.3.7 Output markets and output buyers

The commercially attractive element of the BSFL concept is the creation of valuable products as a by-product. The markets and buyers within the market for BSFL by-products are a key consideration in the potential viability of the concept. The Isipingo project focused on the market for three by-products (1) whole dried BSFL, (2) BSFL protein for the use in animal feed and fertiliser and (3) the BSFL residue for the use in organic fertiliser. During the feasibility phase of the project, no buyers were found for the BSFL oil to discuss potential markets and prices, further market assessment is needed.

As part of the closing report of the Isipingo BSFL project site, a market assessment was conducted and several companies were contacted to discuss the potential market value of the various potential BSFL products. The companies that were contacted by members of the Khanyisa Project are listed in Table 4.1 and the findings of the assessments are presented thereafter.

Table 4.1 The companies contacted in discussions regarding the relative market value of BSFL by-products

Market	Company Name	Website
Specialised Fertiliser	Zylem	www.zylemsa.co.za
Animal Feed	De Heus	www.deheus.com
Animal Nutrition Specialist	Jasuthi	www.jasuthi.co.za

Source: Author’s creation

In relation to the fertiliser market, Zylem was the specialist fertiliser company contacted by members of the Khanyisa Project. The fertiliser industry in South Africa traditionally aims to sell large volumes of Nitrogen, Phosphorus and Potassium fertilisers, also commonly known as NPK fertilisers which are targeted towards plants’ nutritional needs. The current view on manufactured commercial fertiliser combined with intensive agriculture activity results in degradation of the soil and the future agricultural potential. As a result, more recently the fertiliser market has shifted focus to producing fertilisers to target soil nutritional health. These fertilisers provide the necessary NPK nutrients to the soil but in turn, improve the soil health and longevity. The development and accessibility of sustainable organic fertilisation is a key component of SDGs 2, 11 and 15.

These new fertilisers have the potential to provide various micro-nutrients and amino acids alongside NPK. Based on the complex composition of BSFL protein (containing NPK, micro-nutrients and amino acids), this protein could provide an alternative source of key ingredients for specialised fertilisers.

The first point discussed was regarding the use of by-products from other commercial enterprises for fertiliser production, Zylem explained that the company currently utilises two raw by-products in the processing of organic fertilisers. The first is the by-product of the alcohol fermentation of molasses to produce organic fertilisers. This by-product has a similar complex

composition as the BSFL protein. The buying price for the raw molasses by-product is R1000 per tonne.

The second by-product is “liquid fish”. The liquid fish is specifically produced for Zylem as a by-product from fish meal production through fermentation and achieves a better complex matrix, close to the fish meal itself. The buying price for this raw product is R8000 per tonne. The liquid fish might be a product that closely mirrors the BSFL in terms of composition. However, for Zylem to utilise the BSFL, it would first have to be converted to a liquid product to substitute or supplement the liquid fish.

The second point discussed with Zylem by members of the Khanyisa Project was regarding the use of the BSFL residue. BSFL residue is the remaining sludge from the growout phase and any lost organic waste through the harvesting and processing phases, including BSFL. The residue is not significantly commercially valuable however, contains a high percentage of Nitrogen and amino acids. The residue can be sold in a solid-state to apply directly to agricultural fields. The residue can be compared with chicken manure which has an estimated market value of R600 per tonne.

Discussions regarding the animal feed market were held with the team from De Heus and Jasuthi to investigate the potential of the BSFL protein being used in the animal feed market. The BSFL protein is considered an ideal constituent for animal feed due to its composition of high proportions of protein, micro-nutrients and amino acids. The proportion and makeup of BSFL protein are similar to fish meal which is traditionally used in animal feed.

Lysine and Methionine are considered to be the most important amino acids for livestock growth. Fish meal contains approximately 7.5% Lysine and 2.7% Methionine (at 65% protein content) compared to AgriProtein BSFL product called Magmeal which has values of 7.08% Lysine and 2.06% Methionine (at 50% protein content).

The market price for fish meal has steadily increased and is currently between R15000 to R18000 per tonne. The high price has caused animal feed producers to move towards cheaper alternatives in the production of animal feed, such as soybean meal. Soybean meal has a lower protein content of 44% and has 3% Lysine and 0.65% Methionine. The buying price for soybean meal is R5000 per tonne. Although the nutritional value of soybean meal is lower than fish meal, the nutritional requirements for animal feed are met and at a cheaper buying price. For BSFL protein to be attractive and viable as a product, the price needs to be competitive to interest animal feed producers. A price range of R5000 – R8000 per tonne was suggested by De Heus as a potential price point.

Looking ahead to the potential use of BSFL for animal feed, the consumer perception around using BSFL protein grown on human faeces might play a defining role. It was noted from discussions with De Heus that, in recent years, awareness around livestock farming and feed sources has increased. Consumers are no longer supporting the use of animal waste products (such as dead chicken, slaughterhouse waste streams and others that is then milled to animal feed) as feed. The animal feed producers are being more strictly regulated due to the outbreaks of diseases in livestock caused by such animal feed practices. Animal feed producers are now using mostly maize, wheat and other plant-based products. Consumers are not as supportive of non-sustainable practices of fishing in the ocean or the intense fish farms used for the production of fish meal. Thus, animal feed producers are moving away from traditional products such as fishmeal and animal waste products and utilising more sustainable and consumer-friendly substitutes such as soybean meal.

A look into foreign markets for partners of the BSFL products was conducted and an option was found in Kenya in a company called Sanergy. Sanergy has an operational BSFL plant, which rears BSFL on human and organic waste streams. The local market in Kenya seems favourable for whole dried BSFL products and legislation or consumer perception does not seem to be a major obstacle.

Sanergy was willing to buy whole dried BSFL at R7700 per tonne as their operation could not keep up with the demand for the product. The benefit of this option is that no licencing is required to sell the product in Kenya. Regular testing may be required to quality control the product. The selling of whole dried BSFL would require no further in-house processing in South Africa thus reducing costs for equipment and labour.

4.4 Logistical and operational processes required to beneficiate organic waste using BSF

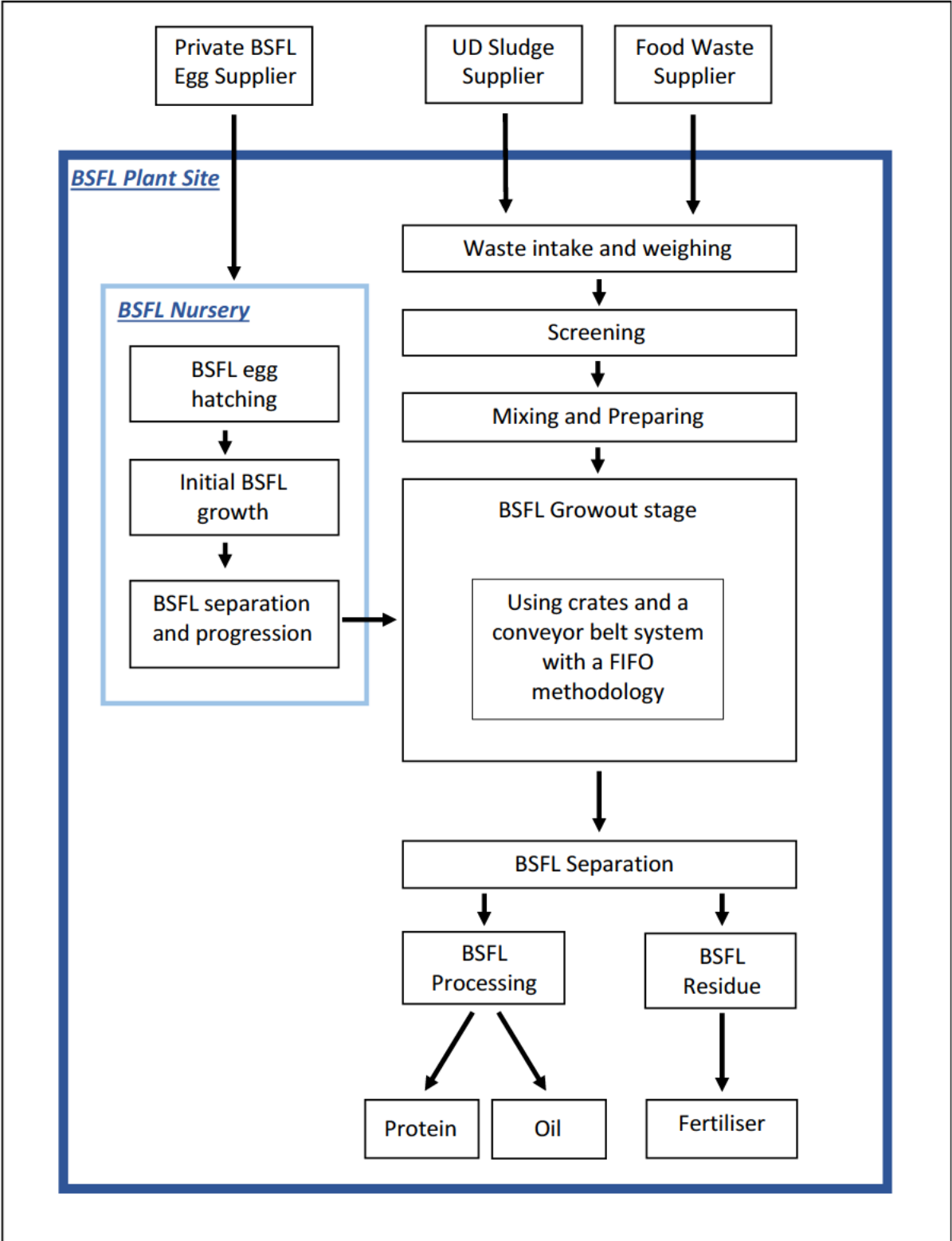


Figure 4.3 Logistical and operational processes required to beneficiate organic waste using BSF

Source: Author's creation

Section 4.4 outlines the operational processes on-site and all logistical activity that resulted in a functional site. Figure 4.3 presents the process, and it is explained in detail below step by step.

4.4.1 UD sludge and food waste suppliers

The Isipingo site utilised two input sources of waste, UD sludge waste and food waste, both were sourced from the surrounding local area and combined to make the feedstock blend on which the BSFL feed. UD sludge waste in the form of human faeces was sourced from UD toilet systems. The objective of the Isipingo BSFL site is to provide a sustainable means of dealing with the UD waste generated within the greater Durban area. The UD waste was collected and delivered by an external third-party supplier contracted by the eThekweni Municipality and is held to a service level agreement.

Organic food waste constitutes food scraps and expired food goods from restaurants and grocery shops. The organic substrate serves to increase the nutritional value of the feed blend, due to the range of vitamins, carbohydrates, starches, and protein in the food waste. It is added to meet the nutritional needs of the BSFL not met by the UD waste.

Organic waste is sourced from external, established waste management providers. These companies source various waste streams and process and sort the waste at off-site processing facilities. Similarly, at the facility, the organic waste is further processed by removing all contaminants and packaging to provide and deliver a pure form of organic waste to the site.

4.4.2 Waste intake and weighing

Upon arrival, the UD and food waste supply vehicles are weighed on a weighbridge to calculate the mass of UD and food waste delivered, respectively. The UD waste must be weighed for Biocycle to charge eThekweni Municipality the appropriate gate fee (charge rate per tonne) for the waste. The private food waste supplier is not charged. By weighing the waste, it provided accurate data on the volume of waste intake to be used in the operation. Once weighed, the waste is then unloaded onto a bed within the growout shed. The two waste streams are kept separate at this stage.

4.4.3 Waste screening

Waste screening had to be introduced into the operations due to the significant amount of detritus and contaminants in the UD waste delivered to the site. Multiple screening steps were

introduced to produce a waste medium that was suitable to use in the growout phase. This was a unique challenge for this site but is a good lesson for future potential sites.

The UD waste underwent an initial manual screening by hand, the aim of this is to remove any large objects that could easily be removed to avoid potential damage to machinery. This screening stage was performed by staff onsite wearing personal protective equipment (PPE). Once initially screened, water was added to the raw UD sludge to increase the liquidity and allow better separation in the trommel. The UD sludge was then loaded using a bobcat into a trommel screen that was installed onsite. A trommel screen is typically used in larger solid waste separation and soil classification processes in the mining industry.

A trommel screen with a one-metre diameter and two-metre trommel length was constructed, tested and selected as a suitable part-solution to the screening processes. The screen of the trommel has spacings of 40 millimetres for screening the UD sludge as it passes through the trommel screen. The raw sludge is fed from the back, passing along the 40-millimetre spaced screen and moves along the trommel. Any detritus moves along the trommel and is collected in a chute at the end. Trash larger than 40 millimetres and larger plastic pieces and bags were successfully screened out. Suitable UD sludge passes through the screen and is collected in a tray below the trommel where it is transferred into crates.

The food waste that was delivered to the site was clear of unwanted waste such as packaging. The food waste does however come in a range of forms and therefore, needs to be shredded and blended into an even consistency and mixture. This is done in a large size motorised drum with blades that shred and blend the food waste.

4.4.4 Waste mixing and preparing

Once the UD waste is processed through the trommel screen and the food waste is shredded and blended. The two waste streams are mixed in the same machine to combine the two waste streams and get an even consistency and distribution. To achieve the desired moisture content, water is added at the mixing stage. The mixed waste streams are now referred to as feedstock.

The feedstock is then put through a screw press to ensure that any remaining unwanted detritus waste material does not proceed through to the growout stage where BSFL are added. A screw press with a screening mesh size of 5 millimetres was used on site. The screw press functioned well with the detritus compacting at the choke valve end and thereby separating it from the feedstock. A limitation encountered was when the moisture content of the material was too low,

blockages occurred on the screen wall. As a result, the moisture content is important for the screw press stage and the growout phases.

4.4.5 Private BSFL egg supplier

It was not feasible to mass breed BSF eggs on site. The eggs were purchased from a private supplier and couriered to the site. See Section 4.3.5 for more details.

4.4.6 BSFL nursery

The nursery was required to be well insulated with effective climate control to achieve optimum activity of BSFL hatching, rearing and bioconversion. The most feasible solution was to utilise a converted shipping container on site. The 12-meter-long shipping container was fully insulated, heated, ventilated and air-conditioned using an HVAC system to ensure automated climate control. The climate-controlled nursery allowed for the optimal conditions maintaining the temperature at $30^{\circ}\text{C} \pm 2^{\circ}\text{C}$, the relative humidity at $70\% \pm 10\%$ and allowed for sufficient ventilation to avoid a potential build-up of ammonia gas.

The converted shipping container proved to be successful, and the BSFL grew to significantly larger sizes than what was achieved in the un-insulated sheds. The control of relative humidity was important as it kept the feedstock at the optimal moisture content. If the feedstock hardens during grow out, the BSFL “hide” in the solid feedstock and separation is difficult or the BSFL cannot penetrate the dried feedstock to achieve higher bioconversion and does not reach maximum size.

The delivered BSFL eggs were placed in crates of feedstock in the container. The eggs hatched and began to rear in the controlled environment. The BSFL were kept for four days in the nursery to achieve sufficient growth. Once large enough, the BSFL were moved across to be used in the growout phase. The BSFL are separated from the feedstock using water separation and a backend trommel screen. This screen is similar to that used on the front end for waste separation but uses a two- millimetre screen spacing.

4.4.7 Growout processing

The growout sheds require the same climate control conditions as the nursery. The challenge in the growout sheds was that the sheds were larger and more difficult to maintain consistent conditions. Additionally, the required HVAC systems for the growout sheds were unable to be installed due to the cost of the equipment and installation. The recommendation was that a fully

automated HVAC system be installed in both the nursery and the growout sheds, with airlocks at entrances to be able to maintain the temperature and relative humidity.

Regardless, the growout sheds achieved effective rearing of BSFL on organic waste. Several different techniques were trailed on site. It was concluded that a crate and conveyor belt system was the most effective method due to its ability to utilise the height within the sheds, be more closely controlled and the ease and simplicity to run once set up.

The feedstock out of the screw press was loaded into small crates and filled with 10-25 kilograms of waste. The volume will depend on the crate dimensions used at a specific site. The crates were loaded onto a conveyor belt from the front which lined the sides of each shed. The crates were loaded with young BSFL from the nursery, the volume of young BSFL added to each crate was based on the volume of feedstock in the crate and the conversion rate being achieved with that feedstock. New feedstock and BSFL were put into new crates each day and added into the growout sheds. The use of conveyor belts allows for a first-in-first-out (FIFO) approach to be used in the operation. The input points were along the front of the conveyor belt. New crates would replace extracted ones, daily, on the conveyor belt. The sheds were 45 metres long and thus 100 crates could fit side by side on the conveyor belt and stacked up to 6 crates high. With two conveyor belts per shed, the sheds had a capacity of 1200 crates.

Each shed had a capacity of 26.7 tonnes, across an 11-day retention time of an individual crate. The daily feedstock loading rate per shed is 2.4 tonnes. The site had seven operation sheds which resulted in the capacity to process over 16 tonnes of waste a day. An 11-day retention time was used because this was deemed a suitable length of time for the BSFL to mature and harvest.

The dimensions and processing capacity presented are specific to the Isipingo site. However, the conveyor belt methodology is the most feasible as it allows for effective use of both the shed footprint as well as vertical space.

4.4.8 BSFL separating and harvesting

Once the crates have been in the growout phase for 11 days, they are extracted from the back of the conveyor belt. The next stage is separating the residue and the mature BSFL using the trommel screen used to harvest the young BSFL from the nursery. The trommel screen has a one-metre diameter, two-metre screen length and has a screen spacing of two millimetres. To improve separation, water is added to the output from the growout phase to increase liquidity. After the water was added, the crates are emptied into the trommel screen and fed through. The

residue passes through the screen, while the BSFL move along the trommel screen. This method is highly effective with a non-significant number of BSFL lost in the screening. Once the BSFL have been separated they are harvested.

4.4.9 BSFL residue

BSFL residue is produced after the BSFL have been separated from the remaining feedstock. The BSFL residue can be dried and sold as a fertilising agent to apply directly to agricultural soils. The degree of drying could vary depending on who the buyers are and their subsequent use of the product. No further treatment for the residue was intended.

Once the BSFL have been processed for protein and oil extraction, the remaining solid fraction can be harvested and used to supplement the residue. Additionally, the oil and protein that cannot be recovered following the extraction process had the potential to be utilised as liquid fertiliser as it contains water-soluble nutrients and amino acids

4.4.10 BSFL protein and oil processing

The processing of BSFL was not able to be conducted in this study due to complications with the intended machinery. This resulted in the BSFL not being able to be pressed for oil and protein to be extracted. It is still recommended that processing the BSFL for protein and oil is the profitable route. All recommendations for the operations are presented as if BSFL products were produced as this was the intention. Further development in the processing machinery is required and it is believed to be possible based off Agriprotein being able to produce BSFL products.

In conclusion, there are two possible processing routes for BSFL products. Firstly, to keep them whole and dry them to a desired moisture content and sell them as whole dried BSFL. Secondly, to process them into BSFL protein and oils providing two separate product streams. The second process of BSFL protein and oils is the recommended route due to its greater commercial potential.

4.5 Factors influencing the efficiency and commercial viability of the supply chain using BSF to benefit off organic waste

Section 4.5 will investigate the factors that influence the efficiency and viability of the BSFL supply chain. The key variables will be broken down for each step and provide a clear outline

of the factors to be focused on to achieve an effective supply chain. Figure 4.4 presents a summary of the processes and the key factors.

4.5.1 Inputs

The inputs into the BSFL system are two-fold, the UD sludge and food waste enter the system into a screening process and the BSFL eggs enter the nursery.

The key factors that need to be known regarding the two streams of waste input are the delivered waste quantity (measured in tonnes) and the moisture content. The moisture content is measured as a percentage of the total volume of waste. The total solids are calculated as a percentage of the total volume of waste after measuring the moisture content.

The BSF eggs are delivered from a third-party supplier. The volume (measured in grams) of the eggs delivered is calculated and pre-ordered before entering the nursery.

4.5.2 Screening

The waste screening processes vary for the UD sludge and food waste. UD sludge is screened initially by hand and followed by a trommel screening process. The total quantity of UD sludge input is known from the weighbridges. During the screening process, detritus is screened out and removed (by hand and the trommel screen). The weight of the removed detritus is utilised to determine the percentage of inputs that are lost. The total quantity after losses (in tonnes) can be calculated from the percentage of losses and the input quantity.

The desired moisture content of the screened UD sludge as a percentage of the total input volume needs to be stated. The difference between the original moisture content and the desired moisture content and the required water volume can be calculated and added to the sludge to achieve the desired moisture content. The volume of water to be added is calculated in litres. Once the water is added the final quantity of the sludge can be calculated from the total quantity after losses and the volume of water added together.

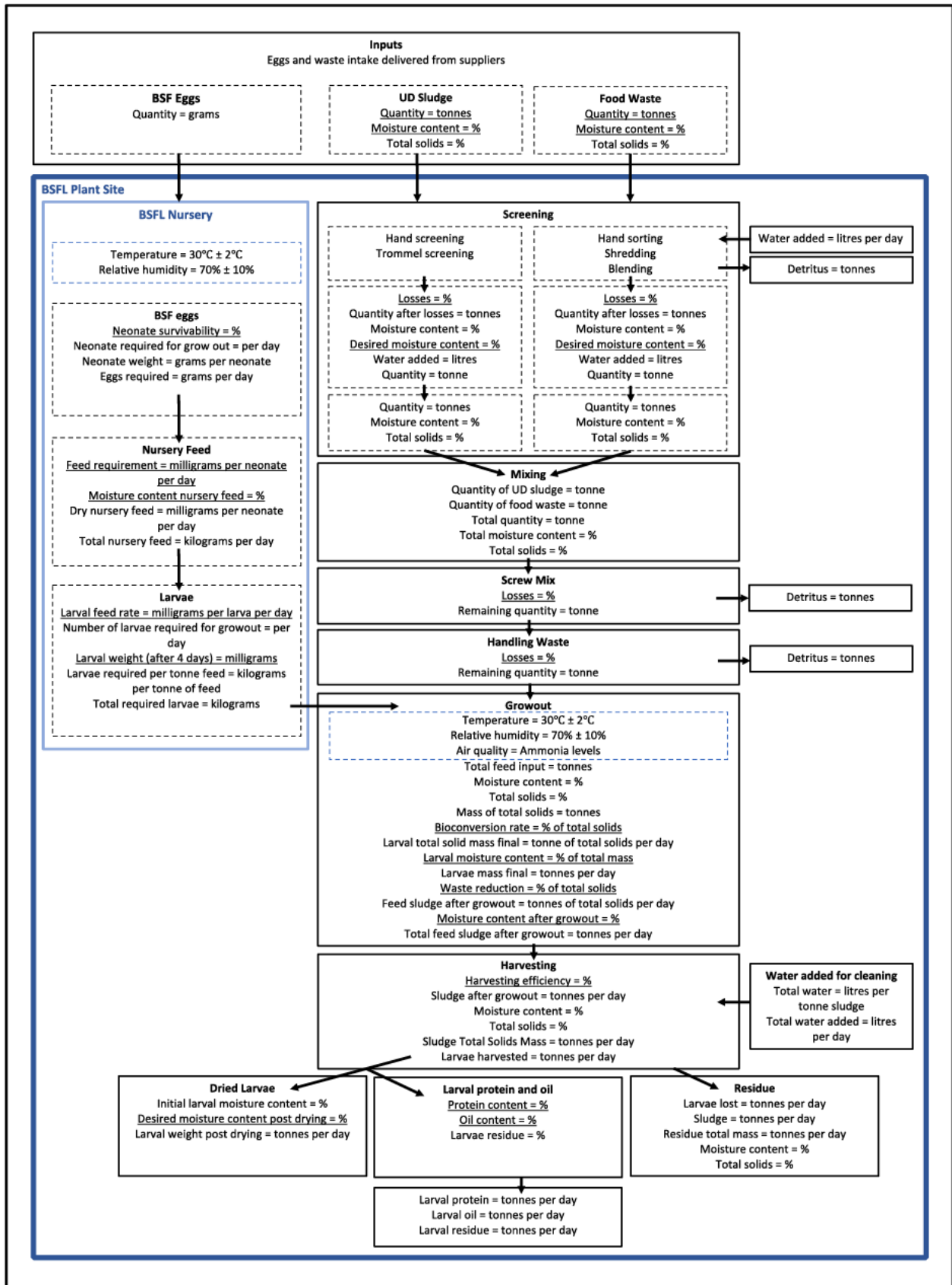


Figure 4.4 Factors influencing the efficiency and commercial viability of the supply chain using BSF to beneficiate off organic waste

Source: Author's creation

Food waste undergoes hand screening to ensure it does not contain any detritus. The food waste is shredded and blended. The detritus losses are calculated by weighing the detritus and calculating the loss as a percentage of the total input quantity. The quantity after losses is calculated in tonnes. The desired moisture content of screened food waste as a percentage of the total input volume needs to be stated. The difference between the original moisture content and the desired moisture content can be calculated and the required water volume can be calculated and added to the sludge to achieve the desired moisture content. The volume of water to be added is calculated in litres. Once the water is added the final quantity of the sludge can be calculated from the total quantity after losses and the volume of water added together.

From the screening stage, there is an additional input in the form of water and output in form of detritus. The water is added to the UD sludge and the food waste to meet the required moisture content. The total volume of water added to the UD sludge and food waste is estimated in litres per day. The total weight of the detritus removed from the UD sludge and the food waste is measured in tonnes.

4.5.3 Mixing

The quantity, moisture content and total solids of UD sludge and food waste from the screening process enter the mixing stage. After mixing the UD sludge and food wastes, a combined total quantity is calculated in tonnes, combined total moisture content as a percentage of the total volume is measured and the total solids are calculated as a percentage. The combined waste streams are now referred to as feedstock.

4.5.4 Screw press

The screw press is a final screening stage to remove the remaining smaller pieces of detritus from the feedstock before growout. The feedstock quantity is fed through a screw press. The detritus lost in the screening is weighted (in tonnes) and the percentage of feedstock lost is calculated as a percentage of the total original feedstock quantity. The final total feedstock quantity is calculated in tonnes.

4.5.5 Handling waste

Losses can occur throughout the process. The most significant is through the removal of the detritus, but losses can occur when waste is spilt or gets stuck in machinery. The total handling

losses are estimated as a percentage of the feedstock and the remaining quantity can be calculated in tonnes.

4.5.6 BSFL nursery

The NSFL nursery runs alongside the on-site BSFL operations and feeds into the process daily at the growout stage where the young BSFL from the nursery, are introduced into the growout stage along with the screened feedstock. The nursery is a climate-controlled environment with the temperature and relative humidity retained at 30°C with a 2°C allowance and 70% with an acceptable variance of 10%, respectively.

The BSF eggs are an input into the nursery. The volume of eggs required from the supplier to introduce into the nursery each day is calculated by understanding the number of neonates and weight of the neonates required to process the daily input of waste. With an allowance made for the survivability percentage of BSFL, the weight of eggs (in grams) required daily can be calculated.

The total volume of nursery feed required per day is calculated by understanding the volume of feed each neonate is able to consume a day in milligrams. By measuring the moisture content of the nursery feed in order to calculate the total solids (dry nursery feed). By knowing the number of neonates required per day and the dry nursery feed consumption per neonate per day, the total nursery feed required can be calculated in kilograms per day.

Once the neonates begin to establish at approximately four days after hatching, they are then referred to as BSFL and the feed rate increases. In order to calculate the volume of BSFL required for the growout stage to process the input waste, the volume of BSFL required to process one tonne of waste needs to be calculated and then multiplied according to the volume of waste brought in a day. To calculate the required BSFL amount per tonne, the volume of feedstock a single BSFL can process a day needs to be determined. Based on the required BSFL amount per tonne, the number of BSFL it will take to process a tonne of feedstock per day can be calculated. The mass of a BSFL after four days in the nursery needs to be known. With the number of BSFL required to process a tonne of feedstock and the mass of a four-day-old BSFL, the mass of BSFL required to process a tonne of waste a day and the mass of BSFL measured in kilograms can be calculated. The mass of BSFL per tonne is multiplied by the feedstock processed a day to calculate the volume of BSFL required for the growout per day measured in kilograms.

4.5.7 Growout

The growout stage has the young BSFL entering from the nursery and the feedstock from the screw press. Although the HVAC system was not installed at the Isipingo WWTW site, the sheds used for the growout stage ideally are installed with an HVAC system to maintain a consistent climate. The recommended temperature is 30°C with a 2°C range allowance and internal the relative humidity restricted to 70% with an acceptable variance of 10%. There is also a requirement for a ventilation system which monitors for harmful gasses such as ammonia.

The final total feedstock, moisture content and total solids entering into the growout stage are confirmed. The bioconversion rate for the BSFL in the feedstock is estimated as a percentage of the total solids of the feedstock quantity. The bioconversion rate is obtained from previous assessments and prior trials. The rate should be regularly verified.

Utilising the bioconversion rate, the total solids weight of the mature BSFL in tonnes can be calculated by multiplying the bioconversion rate with the mass of total solids in the feedstock. Then by measuring the moisture content of the mature BSFL the percentage of total solids can be calculated to then figure out the total mass of the mature BSFL in tonnes per day.

Then the feedstock remaining after the growout is calculated. This is done by getting the waste reduction percentage, this is measured as a percentage of total solids. By taking the waste reduction percentage of total solids and multiplying it by the starting total solids volume in tonnes the feedstock after growout volume of total solids is calculated. Then by measuring the moisture content of the final feedstock the percent of total solids can be calculated and the final total mass of the remaining feedstock can be calculated in tonnes per day.

4.5.8 Harvesting

After 11 days in the growout phase, the mature BSFL are separated from the feedstock (from now referred to as residue) using a trommel screen. The harvesting efficiency is stated as a percent of total BSFL and is calculated based on historical operations and the types of machinery utilised in the harvesting processes. Once the BSFL are separated from the residue, the residue and the BSFL are weighed independently, the residue is weighed in tonnes harvested per day and the BSFL in tonnes harvested per day. The moisture content is measured and from that, the total solids (in tonnes) remaining per day within the residue can be calculated.

4.5.9 BSFL product processing

Through the harvesting, the residue and the BSFL are separated. Once the residue is separated, the volume of BSFL lost through the harvesting needs to be calculated, this can be done by subtracting the harvested volume of BSFL from the total final BSFL mass calculated in the growout. This will give the volume of BSFL in tonnes that were not harvested and remain in the residue. The harvested feedstock is combined with the BSFL volume to give a total residue volume in tonnes per day. The moisture content will need to be measured and total solids percent calculated.

For the BSFL that are harvested, there are two product routes, The BSFL could either be processed as whole dried BSFL or processed into BSFL protein, oil and residue. For dried BSFL, the initial moisture content of the BSFL needs to be measured. Then the desired moisture content needs to be stated in order to calculate to what extent the BSFL need to be dried.

The total volume of BSFL after drying is determined by calculating the mass of total solids prior to drying from the BSFL harvested and the moisture content before drying. The total solid mass remains consistent before and after drying. The moisture content will vary. The volume of moisture after drying is calculated from the desired moisture content as a proportion of the total larval weight post drying. The volume of water contained in the BSFL after drying is added to the total solid mass to determine the total dried BSFL mass. Conversely, a simpler method would be to weigh the dried BSFL after drying.

For the BSFL protein and oil processing, the percentage of protein and oil contained in the BSFL needs to be measured. Through the processing and removal of the substrates, the BSFL residue remains behind. The volume of protein, oil and residue is equal to the total initial volume harvested. By calculating the volume of each substrate according to its percentage, the volume of BSFL protein, oil and residue can be calculated.

4.6 Conclusion

In conclusion, this chapter set out to answer the questions stated in the introduction of Chapter 4 and to achieve the research objectives:

- To identify the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.
- To identify the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*).

- To determine the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.

Figures 4.2, 4.3 and 4.4 aim to address each of these objectives. Figure 4.2 presents an understanding of the potential stakeholders that could be involved in a functioning supply chain that uses BSFL to convert organic waste into a commercially valuable output. Figure 4.3 outlined the logistics and processes within the supply chain. Figure 4.4 provides a breakdown of the processes and the variable factors within the supply chain. These factors require focus in order to achieve efficiency and commercial viability.

This chapter presents a framework from which future BSFL supply chains can be developed. Although the case study is specific to the Isipingo WWTW, the framework is robust and flexible to allow for application to other sites. There will, however, be variations in processes and parameters for different sites but the fundamental concepts remain valid.

CHAPTER 5: DISCUSSION

5.1 Introduction

Chapter 5 is the final chapter concluding the study. The introduction reviews the content of the dissertation; key points from the previous chapters are discussed and the aim, research questions and objectives of the study are revisited. It presents the supply chain developed through this study and addresses the contribution to the BSFL concept. The discussion focuses on the observations recorded in the study. It concludes with the limitations, recommendations and focus areas for future studies.

Chapter 1 introduces the study and highlights the challenges that are currently being faced regarding waste generation. It also introduces the concept of BSFL and the need that they can address through the diversion of organic waste from landfills and the valuable outputs that can be produced. The study aims and objectives are presented, the contribution of this study is outlined and the potential contribution to nine sustainability development goals is summarised. A conceptual framework guiding the study is explained.

Chapter 2 presents the available literature surrounding waste production and management. The current efforts to handle and address the generation of waste as well as the socio-economic and environmental effects are explained. The value of circular economies and the role in which BSFL can play in an effective circular economy are addressed. The biology of the BSF, including the lifecycle and bioconversion ability, and the development of the concept for processing organic waste are presented. Finally, the importance of a supply chain to a successful operation and the benefits it provides are summarised.

Chapter 3 explains the research methodology of this study, an exploratory study. A single case study approach is applied that utilises qualitative documentation data to gather findings and content analyses is used.

Chapter 4 presents the findings from this study. The chapter focuses on addressing the research questions outlined in Chapter 1 and identifies the stakeholders involved in the operations at the Isipingo WWTW site. Each phase of the on-site processes are outlined and explained. The important variable factors to achieving efficiency and commercial viability of the supply chain are discussed.

Chapter 5 summarises the findings from Chapter 4 into a supply chain that can be applied and utilised in the establishment of future sites and to guide future studies to progress the advancement of the BSFL concept.

5.2 Revisiting the aims and objectives

The focal point of the study is a collaboration project in the form of a Public-Private Partnership (PPP) between the Biocycle and the eThekweni Municipality. Biocycle is a private company that operates the BSFL site, and the eThekweni Municipality is the government entity paying gate fees for processing the sludge at the Isipingo plant. The capital expenditure for the plant was funded by the Bill & Melinda Gates Foundation. The Khanyisa Project was the implementing agent for the plant and grant holder from the Bill & Melinda Gates Foundation. The focus of the site was to attempt to commercialise the production of BSFL from biodegradable organic food waste and human faeces.

The purpose of the study was to analyse the Isipingo BSFL site and identify the various factors that are affecting the economic and operational viability of the process and therefore the sustainability of the BSFL concept as a source of protein for agricultural and aquaculture purposes and nutrients for fertilisers. The aim was to develop a supply chain which identified the whole process, the stakeholders and the key focal factors.

To achieve the aim of the study, a set of research questions and objectives were developed.

Research Questions:

- Who are the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?
- What are the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*)?
- What are the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes?

Research Objectives:

- To identify the stakeholders that need to be included in a commercially viable supply chain using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.
- To identify the various logistical and operational processes required to beneficiate organic wastes using Black Soldier Flies (*Hermetia illucens*).
- To determine the factors that influence the efficiency and commercial viability of enterprises using Black Soldier Flies (*Hermetia illucens*) to beneficiate organic wastes.

Chapter 4 aims to address the above-mentioned questions and meet the objectives of the study. The BSFL concept is in the early stages of commercial development, globally, and although

there is a current body of scientific research and literature, the concept has many variables and complexities that require further research, especially from a commercial standpoint.

There is limited research available on large-scale BSFL enterprises and the commercial potential of BSFL products. This study is unique in that it seeks to define a potentially viable and sustainable commercial supply chain delivering innovative products to an emerging market. A contribution to the large-scale operations and commercialisation knowledge is a significant advancement to the BSFL concept. The development of a viable supply chain provides a foundation for the concept to be developed further.

5.3 Contributions of the study

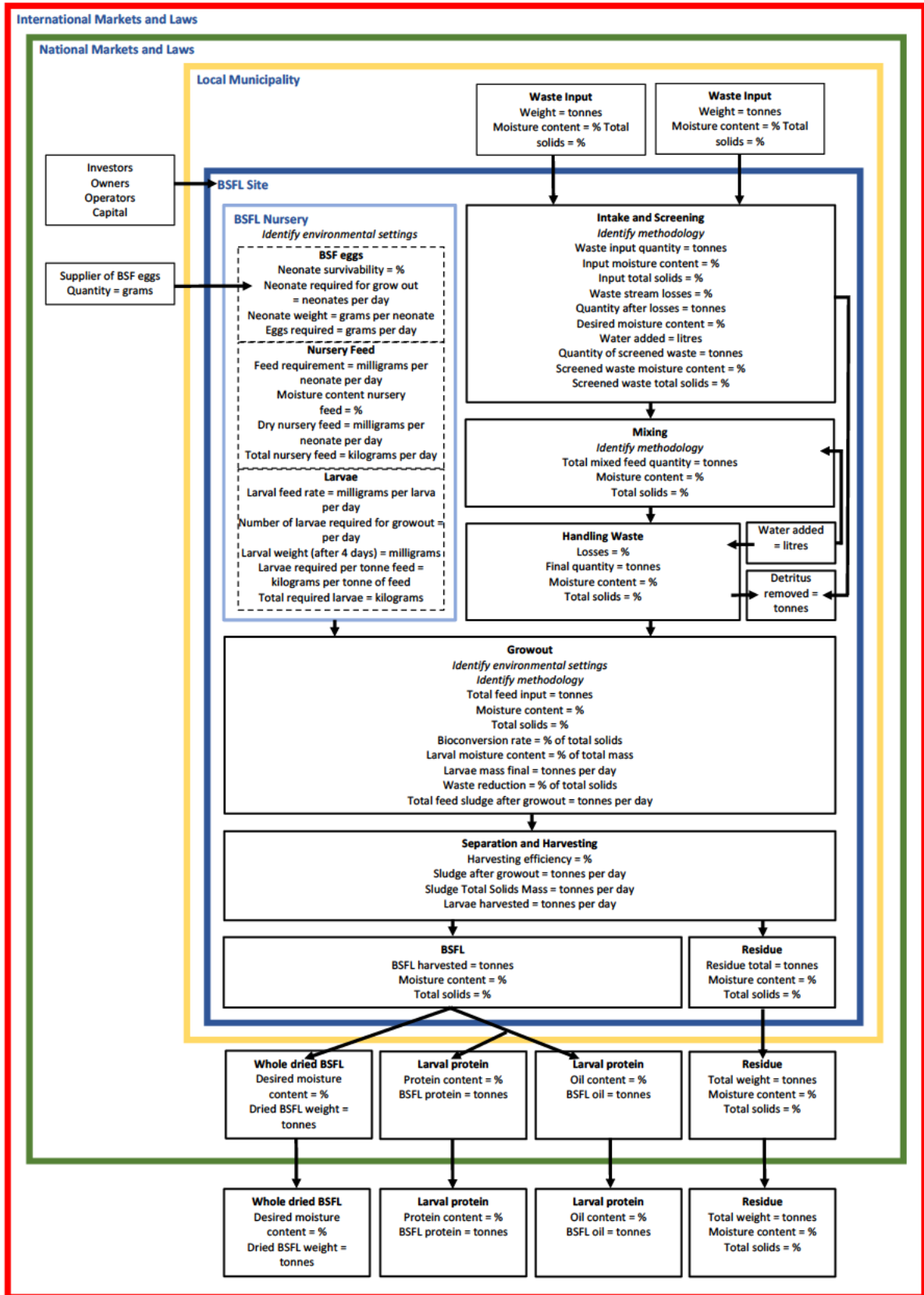


Figure 5.1 Supply chain of BSFL rearing operation

Source: Author's creation

5.3.1 Explanation of the Supply Chain

Figure 5.1 presents the supply chain of a BSFL rearing operation.

5.3.1.1 International markets and laws

The international markets and laws have the potential to be a key factor in achieving success with the BSFL concept. From the market research undertaken for the close out report, a buyer was found in Kenya who offered competitive prices for an unprocessed and unlicensed whole BSFL product. Identifying and investigating markets that are open to products made from whole BSFL and offer competitive prices, could allow for a simpler first entry point into the market. This can allow the BSFL concept to get off the ground and to increase the demand for further product markets.

The international market space is largely unknown. A global market assessment focussing on the laws allowing the use of BSFL products has yet to be undertaken. Through a study looking at international opportunities, markets could be identified and further explored regarding the type of products that are suitable and their pricing.

The BSFL products have the potential to feed into the international markets in various forms. The product can be sold within the international market at various degrees of processing, either as raw unprocessed BSFL, whole dried larvae or BSFL protein, oils and residue. These markets could be more lucrative than local markets due to exchange rates, a greater willingness to utilise insect-based products, increased market demand for animal feed and fertilisers, and the nature of competing products in the market. ‘Investors, Owners and Operators’ can arise not only from national markets but also from international markets.

5.3.1.2 National markets and laws

It is assumed that generally ‘Investors, Owners and Operators’ will arise from within the national market however, there is potential for them to be of international capacity. The purpose of investors is to help raise capital to fund initial costs and investment in infrastructure. Owners are responsible for the operation from securing funders and overseeing operations, and operators are responsible for managing the on-site operation. The site can be operated by the owners or contracted out.

The supply chain requires a supplier of BSF eggs. When it is not possible to produce the eggs on-site an external supplier is required. Often the use of an external supply is recommended as current knowledge of the mass production of BSF eggs is not publicly available. It is, however,

assumed that the infrastructure required to mass-produce the BSF eggs would be expensive and would require expert operators and biological knowledge. The separation of the egg supplier and the BSFL operation allows the site operators to focus on the core purpose of rearing the BSFL. The BSF eggs supplier would need to be a national entity, due to the need for the transportation time to not exceed the egg incubation duration.

The national markets and laws are important for the BSFL products that are produced and sold at a national level. The national laws are what dictate the limits of what can be produced in the BSFL space. The BSFL product markets in South Africa were assessed and there was a general interest in BSFL products. However, extensive assessments need to be undertaken focussing on possible product avenues, the licensing laws that apply and best practise to meet the legal requirements and industry standards. To achieve success in the BSFL market, close collaborations with established parties, DAFF and other operators will be necessary.

5.3.1.3 Local municipality

Partnering with the local municipalities is key in South Africa as they are the stakeholder responsible for waste management and provides access to a large input supplier. Suppliers of input waste should be looked for within the local municipal area, this is to limit the distance waste will need to be transported. The potential sources of input waste are broad, the BSFL concept can utilise organic waste from households but also other sectors such as breweries, food processing sites or UD sludge.

Identifying possible waste sources is a key first step in the process of establishing a BSFL site. Ideally, the waste management system will advance to where organic waste can be separated at the source and not enter into the current waste management system. A stream of organic waste from households, shops and restaurants that can be fed straight into a BSFL site can be created. Resulting in organic waste being diverted from landfills. Multiple input streams are recommended, this will avoid dependence on one single supplier. It will most likely allow for a larger volume of waste to enter into the BSFL operation and in turn, increase the outputs. Utilising various input sources will widen the nutritional value of the feedstock blend more than in one single waste stream.

The local municipal area is where the BSFL site selection will take place. The site should be established within a local municipal area where a sufficient waste stream is available, the supply of electricity and water is possible and vehicle access is not limited

5.3.1.4 BSFL site

The BSFL site is the location where the operations take place. Due to the recommendation of using an HVAC system for both the nursery and grow-out, the possible location a site can be established is not bound by environmental conditions, as originally thought. A piece of land with access to utilities and vehicle access is sufficient to establish a site. Adopting a climate-controlled methodology increases the possibility of using BSFL as a global waste management solution. The BSFL nursery runs alongside the on-site BSFL operations and feeds into the process daily at the grow-out stage where the young BSFL from the nursery, are introduced into the grow-out stage along with the screened feedstock.

5.3.1.5 BSFL nursery

The nursery is a climate-controlled environment where BSF eggs are reared for four days before being introduced into the grow-out phase. The BSF eggs are obtained from a third-party supplier and input into the nursery. The number of eggs required for input into the nursery each day is from the number of neonates, and subsequent weight, required to process the daily waste intake. Making consideration for the BSFL survivability rate, the weight of eggs required daily can be calculated.

The volume of nursery feed required is approximated by measuring the moisture content of the available feed and understanding the volume each neonate is able to consume per day. Once the number of neonates required for a day is known, the total nursery food required can be calculated in kilograms per day.

Four days after hatching the neonates begin to establish as BSFL and the feed rate increases. Knowing the larval feed rate and the volume of waste available for consumption in the grow-out, the number of larvae required is calculated. The weight of larvae required to consume a tonne of waste is calculated using the weight of the individual BSFL. The total required larvae to consume the waste available in the grow-out is calculated by multiplying the volume of larvae required per tonne of waste and the volume of waste.

5.3.1.6 Intake and screening

The waste screening processes vary depending on the types of waste entering the BSFL site. Waste can be screened by hand or through other mechanical screening processes. The total quantity of waste input is known from the weighbridges and the moisture content of the incoming waste can be measured. During the screening process, detritus is removed, and the

weight of the removed detritus is utilised to determine the percentage of lost inputs. The total quantity after losses can be calculated from the percentage of losses and the input quantity.

The desired moisture content of the screened waste is known and the difference between the measured moisture content and the desired moisture content is fulfilled by adding water to the waste. Once the water is added the final quantity of the screened waste can be calculated from the total quantity after losses and the volume of water added.

From the screening stage, there is an additional input in the form of water and output in form of detritus. The water is added to the waste to meet the required moisture content.

5.3.1.7 Mixing

The quantity, moisture content and total solids of waste from the screening process enter the mixing stage. During mixing, the waste from the various input stream is blended to a uniform consistency. Mixing can be achieved through several methods using various machinery. Additional, screening for finer materials can occur during the mixing phase depending on the methodology chosen. A combined total quantity, moisture content and total solids of the mixed waste are calculated. The combined waste streams are now referred to as feedstock.

5.3.1.8 Handling waste

Losses can occur throughout the waste handling processes. The most significant loss is through the removal of the detritus, but losses can occur when waste is spilt or gets stuck in machinery. The total losses are calculated as a percentage of the input waste and the remaining quantity can be calculated by considering the losses.

5.3.1.9 Grow-out

The grow-out stage has the young BSFL entering from the nursery and the feedstock from the mixing phase. Ideally, an HVAC system is installed to ensure optimal climate control. The setup and methodologies utilised in the grow-out phase are site-specific and depend on the space and technology available. The recommended method is to use crates loaded with feedstock and a conveyor belt system within the sheds. The final total feedstock, moisture content and total solids entering the grow-out stage are assessed. The bioconversion rate for the BSFL in the feedstock is stated as a percentage of the total solids of the feedstock quantity. The bioconversion rate should be known from prior trials or operations. Utilising the bioconversion

rate, the weight of the mature larvae, the volume of feed sludge, moisture content and the percentage of waste reduction after grow-out can be forecast per day.

5.3.1.10 Separating and harvesting

After leaving the grow-out phase, the mature BSFL are separated from the remaining residue. The harvesting efficiency is deduced based on the type of machinery utilised in the harvesting processes. The residue and the BSFL are weighed independently. The measured moisture content is used to calculate the total solids remaining per day within the residue.

Post-harvesting the BSFL can be used for various products, such as whole dried BSFL or protein and oils. The volume of BSFL and the moisture content after harvesting is known before processing. Similarly, the residue is harvested generally for use in fertilisers. The volume and moisture content of the residue is known before processing or sending directly to market.

5.3.1.11 Summary

When establishing a new site, it is recommended to begin with the identification of the waste and BSF egg suppliers. It is essential to identify the market and buyers of the by-products to streamline the harvesting and processing stages to meet the market value for the products. The operational framework can then be developed to most effectively rear the BSFL, decompose the waste and produce the by-products.

The conceptualisation of the supply chain allows interested parties to utilise the framework to establish or improve a BSFL site. Defining this supply chain from all available knowledge allows for gaps and unknown entities to be focused on in future studies and trials. These studies could focus on further refining the overall concept or testing and trialling individual aspects. As a new market and research space, there is an opportunity for operational innovation and in-depth market research.

5.3.2 Value of the supply chain

The supply chain developed in this study may have considerable value and make a significant contribution to the BSF concept. The supply chain concept progresses through an initial concept phase of investigating the capabilities of the BSF and their bioconversion and then breeding attempts and upscaling to achieve commercial level processing. The concept advances in all these areas and progresses to the next stage which is commercialisation.

Currently, there is a lack of available literature and research in this commercial BSF area due to the work being done, almost exclusively, in the private sector. Contributing to the supply chain concept by devising a potential supply chain, there is now a foundation for a range of further research topics to be investigated.

5.4 Discussion

The requirements needed for a BSFL site have been identified throughout Chapters 4 and 5. This discussion section will address some further points and aspects that have been observed through the study. A partnership with government and municipal bodies would be mutually beneficial. The aim would be to incorporate the BSFL concept into existing municipal waste management systems. This could be done by diverting organic waste from landfills and re-directing it into BSFL processing sites. Government buy-in to the concept could open the possibility of separation at the source of organic waste such as households, resulting in a more seamless input into the BSFL processing site.

By diverting organic waste from landfills, the landfill site becomes less reactive. Reducing the amount of reactive waste going to landfills, will result in a reduction in the operating cost, extend the life span of the landfill and decreases the risk to health and safety associated with landfills. The municipality would be saving money as well as contributing to their social responsibility and improving the provision of basic services.

There is a potential that the money saved by diverting organic waste from landfills could then be reallocated to the investment in the BSFL concept or a contribution towards the payment of gate fees when delivering the organic waste to BSFL sites.

Local authorities may also contribute by providing land on which to operate an enterprise and capital investment to build the required facilities and purchase the necessary equipment. This approach will mitigate funding and capital requirement limitations that hinder the adoption of the technology, especially in developing countries where the use of landfills is the greatest, and the expected population increase is the highest. Additionally, as with other sustainability focussed initiatives, further assistance could be given in the form of tax rebates.

Following the challenges faced at the Isipingo WWTW regarding the processes of producing the BSFL products, it is recommended that the focus should be shifted to market research. This is to better understand the market and its requirements. Engagement with market stakeholders and potential buyers will provide a better understanding of the sector requirements, product specifications and pricing of the products in demand. By obtaining an understanding of the

pricing of the BSFL products, research can be undertaken into the commercial viability of the BSFL concept. And with a better understanding of the market's product requirements, the process of producing the BSFL products will be more guided and streamlined.

Due to the complexity, cost and need for expert knowledge throughout the overall BSFL concept, it is suggested that the BSF mass breeding, growout and product processing stages should be separated. Currently, mass breeding is separated from the growout and product processing operations. However, it would be beneficial to further separate the growout and product processing operations.

By mass processing at a central point, the initial investment and operating costs are shared over a greater mass than compared to each individual site operating its own processing plant. Additionally, centralising processing improves quality control measures as well as the consistency of the produced products. Separating the overall operations into the three stages allows for greater focus to be placed on maximising capacity, efficiency and profitability at each stage.

The development of a holistic understanding of the BSFL operations, from mass breeding to commercialisation and market requirements, has allowed for the expansion of the concept. As knowledge continues to increase from initial pilot sites, the concept will gain more industry credibility and benefit from reputational precedent and therefore more sites will become feasible.

In a new and developing field, many lessons can only be learnt when operating at scale. Despite the biology being well understood, practical and operational understanding is gained once the site is built, and the full operation is underway. The more sites that begin to operate and variables in play, the more rapid and varied the learnings will be. The larger number of operational sites will expand the knowledge network and encourage more rapid research and development of the concept as well as infrastructural optimisation.

Despite all the development and advancements of the concept, it is still in its early stages as a sector. Therefore, all new BSFL sites will be different, and each site will face unique challenges. The supply chain created will be at the core of each of the operations, however, there will be variations brought about by the waste inputs selected, the layout of the site and any differences in methods and machinery selected for the site.

5.5 Limitations

Due to the limited number of BSFL sites and more importantly the number of sites with publicly available results, this study was limited to the analysis of a single site case study and close-out report. However, due to the PPP nature of this site, the report of the findings is publicly available and thus allowed this study to be possible.

Due to the financial costs associated with the requirements for the site, not all identified and recommended solutions were able to be fully implemented and tested. Namely, the HVAC system and a fully installed crate and conveyor belt system in the grow-out sheds. Nonetheless, this remains the recommended approach. Ideally, there would have been a site fully fitted with all recommended systems to trial.

Another limitation of the study is the back-end product processing. Due to the machinery not working as intended and no solution found within the time frame of the project, this remains a key aspect that remains unresolved. The private sector is achieving results based on the products available. This is a key aspect that needs addressing with the assistance of mechanical engineers and detailed market research. Due to this study resulting in no product output, a more detailed market study could not be undertaken.

5.6 Recommendations

The recommendation for enterprises proposing to utilise the supply chain proposed in this study, would be to establish a BSFL site and to start by focusing on the required inputs and desired outputs. These are two areas outside the BSFL operation's control, yet are critical to achieving a successful result. Identifying waste suppliers and securing consistent, quality waste input streams is imperative for a successful operation. The terms of the agreement with waste suppliers should be secured, with the responsibilities and financial agreements of all parties clearly outlined.

It is equally important to identify and engage with buyers for the outputs. This will assist with understanding their needs, requirements and the pricing potential. Better financial planning and forecasting will be achieved and a more effective business plan developed. A robust business plan will be necessary to secure required capital.

The proposed supply chain serves as a framework to guide the development of individual supply chains. Supply chains will differ as there will be unique features of each site, feedstock and market, and this will require a level of flexibility and agility. However, the framework does allow for a large amount of customisation and flexibility. By using an HVAC system in the

grow-out and nursery stages, this will allow greater flexibility in choosing the location of the site, with the natural climate then being of reduced concern.

Additional recommendations are mentioned below:

- It is recommended that if making use of hazardous waste inputs, sites that can keep and process waste streams separately should be selected, or sites should focus on producing fertiliser products only. Hazardous waste streams directly entering the animal food chain as feed should be avoided. The use of organic food waste would serve as a better alternative for BSFL products used for animal feed
- It is recommended that the various stages of the overall BSF process be separated. For example, separate BSF breeding sites producing the BSF eggs should be maintained and these serve as suppliers to several grow-out sites. Similarly, the BSFL processing sites should be separated. The grow-out sites would deliver to a central site that processes BSFL for multiple sites. Each site is then able to focus on its core purpose and competence, thus avoiding over/under utilisation. The operations of individual sites and the supply chain as a whole may then be optimised
- It is recommended that municipalities and provisional and national governments be engaged. A private/public partnership will be the most likely route to success with this concept. Currently, the responsibility for waste management and the costs thereof are managed by municipalities and funded by tax and municipal revenues. A partnership would be mutually beneficial as it will divert organic waste from landfills and save municipalities money. Additionally, municipal buy-in is key in waste collection and delivery.
- Further research and development need to be undertaken to resolve the issue of developing and producing products from BSFL. It is recommended to engage with the market early in this process to fully understand and explore the needs of the market and the most financially viable options. A better understanding of product requirements should be developed in order that the key processes to achieve these can be focused on. Over time and with further engagement amongst stakeholders, various BSFL markets and innovative new products may be developed and the different barriers to entry may be reduced.

5.6.1 Future studies

There are many future research areas involving the BSFL concept that require attention. A list of recommended future studies that can be explored to potentially advance the development of the BSFL concept include:

- An exploratory study focusing on identifying suitable markets that BSFL products can compete in and the requirements of these sectors, including sector trends, competitors and pricing.
- A study focusing on product development, processes that deliver these BSFL products and key factors of success.
- A study of international markets to identify key countries and their stance on the BSFL concept, and the potential markets they might represent.
- Further commercial feasibility studies to test and assess various production parameters, other factors and the outcomes.
- A feasibility study utilising a full, purpose-built BSFL site based on current recommendations. Empirical data is required to develop more accurate performance and costing models that will provide better estimates of BSFL organic waste beneficiation potential, rather than to retrofit solutions and adaptations.

5.7 Conclusion

In conclusion, this study aimed to develop an operational supply chain that utilised BSFL to convert organic waste into a range of valuable products. This was achieved by identifying the stakeholders involved in the overall operations, defining the operations and processes on site and outlining the key factors and process variables. The study has produced a framework for an operational, BSFL mediated supply chain.

The Isipingo WWTW site provided valuable insight into the requirements and operations of a large-scale processing site. This unique insight makes significant contributions to the BSF concept and advances it to the next stage of development.

The supply chain framework proposed in the current study provides a basis for future studies than can focus on the specific, commercial potential of the concept, on new product development and on process engineering. The aim should be to combine these developments in order to initiate full scale BSFL sites providing solutions to current waste management challenges and to produce cost effective products for animal feeds, biodiesels and fertilisers.

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ETHICAL CLEARANCE CERTIFICATE



Mr Brandon Smith (214540703)
School Of Man Info Tech & Gov
Pietermaritzburg

Dear Mr Brandon Smith,

Protocol reference number: 00012382

Project title: Developing a Black Soldier Fly supply chain that beneficiates organic wastes: A Durban case study

Exemption from Ethics Review

In response to your application received on 30 June 2021, your school has indicated that the protocol has been granted **EXEMPTION FROM ETHICS REVIEW**.

Any alteration/s to the exempted research protocol, e.g., Title of the Project, Location of the Study, Research Approach and Methods must be reviewed and approved through an amendment/modification prior to its implementation. The original exemption number must be cited.

For any changes that could result in potential risk, an ethics application including the proposed amendments must be submitted to the relevant UKZN Research Ethics Committee. The original exemption number must be cited.

In case you have further queries, please quote the above reference number.

PLEASE NOTE:

Research data should be securely stored in the discipline/department for a period of 5 years.

I take this opportunity of wishing you everything of the best with your study.

Yours sincerely,


Prof Maria Isabel De Azevedo Martins
Academic Leader Research
School Of Man Info Tech & Gov

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