

Exploring gypsum wallboard waste disposal alternatives

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ABSTRACT

Most landfills in South Africa are rapidly running out of airspace. This calls for the implementation of sustainable alternative waste management solutions to move waste, such as gypsum wallboard waste, up the waste management hierarchy. Although the environmental and social impacts associated with the disposal of gypsum wallboard waste in landfills are well understood, and the alternatives to landfill disposal are extensively researched on an international scale, there is limited publicly available research on the use of gypsum wallboard waste in South Africa.

This study aimed to explore alternative options to landfill disposal of gypsum wallboard waste within the South African context. This was achieved through evaluating the physico-chemical properties of gypsum wallboard waste, identifying the alternatives to the landfill disposal; and investigating the opportunities and challenges associated with gypsum wallboard waste alternative use. The study employed a mixed-method design, using qualitative and quantitative techniques.

The results of the study indicated that gypsum wallboard waste is non-hazardous and is not likely to pose any physical, health or environmental hazards. In addition, the physico-chemical properties of the gypsum wallboard make it suitable for potential alternative uses identified in literature, prompting further investigation of alternatives through field experiments and interviews.

The results from field experiments indicated that the presence of the gypsum wallboard waste in composting dampened the temperature of the compost, but the pH, EC and moisture content of the compost remained within the required composting limits. Also, the sodium and the heavy metal concentrations of the compost were reduced suggesting that gypsum wallboard waste is capable of reducing the salinity and toxic levels of heavy metals in compost to below lethal levels. The study also found that up to 20% of gypsum wallboard waste can be added to produce a fertilizer before reducing the concentrations of boron to deficiency levels. Of interest to this study, the gypsum wallboard waste drastically reduced the concentrations of pathogens, and increased the concentrations of calcium and sulphur nutrients in correlation to the quantity of gypsum wallboard added. This suggested that gypsum wallboard waste supplied the essential nutrients required by plants to the compost and has the potential to sterilise the infectious pathogens in compost that are harmful for human and animal consumption.

The results from interviews indicated that 78% of composters interviewed were not interested in utilising gypsum wallboard waste in their composting processes - mainly because of its quality and origin. On the other hand, gypsum wallboard manufacturers expressed their interest in utilising recycled gypsum in the manufacturing of new wallboard with the aim of improving company image, achieving environmental targets and earning points from the green building council. To make alternatives such as fertilizer production from wallboard waste more favourable than landfill disposal, measures such as landfilling gate fees and landfill restrictions/bans for the disposal of gypsum wallboard waste are suggested.

Keywords: Gypsum wallboard waste, Composting, Fertilizer, Recycling, Landfill disposal, Reuse

ABBREVIATIONS AND ACRONYMS

B.C	Before Christ
C & D	Construction and Demolition
C:N	Carbon nitrogen ratio
DEA	Department of Environmental Affairs
DAFF	Department of Environment, Forestry and Fisheries
EC	Electrical conductivity
EPA	United States Environmental Protection Agency
EU	European Union
FGD	Flue-gas Desulphurization
GHS	Globally Harmonized System of Classification and Labelling of Chemicals
GN R	Government regulation number
GtoG	Gypsum to Gypsum
LCT	Leachable Concentration Threshold
LEED	Leadership in Energy and Environmental Design
NEM: WA	National Environmental Management: Waste Act
NWMS	National Waste Management Strategy
NPK	Nitrogen Phosphorus Potassium
RQ	Research Question
SACN	South African Cities Network
SANS	South African National Standard
SDS	Safety Data Sheet
TOC	Total Organic Carbon
TCT	Total Concentration Threshold
WML	Waste Management License

KEY DEFINITIONS

Compost

A product of controlled aerobic, biological decomposition of biodegradable materials. The organic waste undergoes mesophilic and thermophilic temperatures, which significantly reduces the viability of pathogens and weed seeds, and stabilizes the carbon such that it is beneficial to plant growth.

GN R 1132 of 2019

Composting

Means a controlled biological process in which organic materials are broken down by micro-organisms by means of an aerobic process to produce compost or fertiliser.

GN R 1132 of 2019

Fertilizer

Means any substance which is intended or offered to be used for improving or maintaining the growth of plants or the productivity of the soil.

GN R 732 of 2012

Gypsum wallboard

Also known as plasterboard, drywall or sheetrock. A layer of gypsum core enclosed between two layers of paper. It is used in the construction industry for partitioning, linings, ceilings and to cover the interior of walls. It is composed of 90% gypsum and 10% paper.

(Townsend & Cochran, 2003:2)

Gypsum wallboard waste

Wallboard waste generated from wallboard manufacturing processes, construction and demolition projects.

(AWCI, 1992)

Recycle

Means a process where waste is reclaimed for further use, which process involves the separation of waste from a waste stream for further use and the processing of that separated material as a product or raw material.

NEM: WA (59 of 2008)

SANS 10234

The latest edition of the South African National Standard Globally Harmonized System of Classification and labelling of Chemicals (GHS)

GN R 634 of 2013

Waste

(a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette, but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste—(i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered; (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered; (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.

NEM: WA (59 of 2008) as amended

Waste Classification

establishing (a) whether a waste is hazardous based on the nature of its physical, health and environmental hazardous properties (hazard classes); and (b) the degree of severity of hazard posed (hazard categories).

GN R 634 of 2013

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CHAPTER 1 INTRODUCTION

1.1 Background

The utilisation of gypsum as a building material is well documented throughout history. Gypsum is one of the oldest, abundant and widely used construction and building materials in the world, with a widespread occurrence in all six continents (Olson, 2001). Records dating back to as early as 9000 B.C indicate gypsum was used as a plaster in the Catal-Huyuk ruins of modern-day Turkey for building and decoration purposes (Knauf, 2012). Gypsum was also used in Israel in 7000 B.C to make floor screeds. During the reign of the Pharaohs of Egypt, gypsum was the main ingredient used to construct tombs during 5000 B.C (Felsing & Potter, 1930) as well as for interior decoration of the Giza pyramids later in 3000 B.C (Eurogypsum, 2015b).

1.1.1 Mineral gypsum

Gypsum is a naturally occurring evaporate mineral composed of calcium sulphate dihydrate with a chemical formula $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$. The origin of gypsum dates back to some 230 million years, where calcium sulphate deposits were formed in large sedimentary basins (Eurogypsum, 2015b). Gypsum is usually white to transparent in colour but the presence of impurities can change the colour to pink, brown, grey or black (Olson, 2001).

There are two main types of gypsum - natural and synthetic gypsum. Natural gypsum is mined and extracted from open quarries. In South Africa, these mines are located in the Northern Cape, Kwazulu-Natal, as well as the Eastern and Western Cape (Zitholele, 2009). Various types of synthetic gypsum are recognised. The main type is flue gas desulphurization (FGD) gypsum produced from coal-fired power plants (Dragomir *et al.*, 2017). Other types of synthetic gypsum include fluorogypsum (from production of hydrochloric acid) and phosphogypsum (a by-product of phosphate ore with sulphuric acid).

The unique chemical properties of gypsum make it an attractive material to use in construction. This is because gypsum loses three-quarters of its water when heated and converts to calcium sulphate hemihydrate also known as a 'Plaster of Paris' (Olson, 2001). When the water is added back to the plaster, the material reverts to the original composition of gypsum. This reversible chemical reaction is represented as follows:



1.1.2 Gypsum wallboard

Also known as plasterboard, drywall or sheetrock, gypsum wallboard is a layer of gypsum sandwiched between two layers of hard paper. The wallboard is composed of 90% gypsum and 10% paper (Townsend & Cochran, 2003). Gypsum wallboard is used in the construction industry for partitioning, linings, ceilings and to cover the interior of walls in the absence of plaster and mortar (Jiménez-Rivero *et al.*, 2016).

The modern use of gypsum as a construction and building material dates back to the 1880s when Augustine Sackett developed a machine that produced the first gypsum wallboard prototype. The wallboard was composed of several layers of paper with gypsum in between (Eurogypsum, 2015b). Two decades later, this technique was improved and patented by Stephen Kelly who produced gypsum wallboard similar to that produced today, consisting of gypsum at the core enclosed by one layer of paper on each side (Eurogypsum, 2015b).

Gypsum wallboard is known for its various unique properties including fire resistance, non-combustibility as well as its sound and thermal insulation properties (Eurogypsum, 2015b; Olson, 2001). These properties make wallboard an attractive material to use in construction.

Wallboard is produced in various thicknesses ranging from 6.4 mm, 9.5 mm, 12.7 mm to 16 mm board size (Formisano, 2019). The different gypsum wallboard sizes are used for different applications (Formisano, 2019). The 6.4 mm and 9.5 mm board sizes are commonly used for residential repairs/renovation in a single or double-layer applications. The 12.7 mm size wallboard is the most common type of gypsum wallboard and is used in residential construction as a single application. The 16 mm size can be used in residential areas, or where sound or fire rating is required. Additionally there is type X wallboard, a fire-resistant wallboard with a fire rating of more than 1 hour. Type X wallboard is composed of glass fibres which help increase the strength of the board, resistance, elasticity and fire-resistance properties (Eurogypsum, 2015a). There is also moisture resistant wallboard, which is resistant to water and mould and is used in wet applications such as bathrooms.

1.1.3 Status quo of the gypsum wallboard industry

The gypsum wallboard industry is a growing industry globally. The market is expected to grow due to increased investment in the construction industry particularly in the Asian-Pacific region, increased green building projects, increased demand in the residential sectors and increased consumption in the Americas (Mordor Intelligence, 2019).

It is estimated that 80 million tonnes of new gypsum wallboard are generated globally every year (GRI, 2013). Sixty eight million tonnes are generated by the USA, Europe and Japan. Of the 80

million tonnes of new gypsum wallboard, approximately 15 million tonnes become waste and are disposed in landfills every year (Ahmed *et al.*, 2011:208).

In Africa, the South African gypsum wallboard market occupies a higher percentage volume share (measured in m²) (Mordor Intelligence, 2019). Approximately 132 475 tonnes (per annum) of new wallboard were generated in 2018 in South Africa (Mordor Intelligence, 2019). The market is expected to increase at a 6.5% annual rate to 194 349 tonnes per annum by 2024 (Mordor Intelligence, 2019). The volume of gypsum wallboard waste produced in South Africa varies between 10 000 to 12 000 tonnes/annum (Interviews, 2020). These volumes need to be managed using sustainable management methods that do not impact negatively on the environment.

1.1.3.1 The demand for gypsum in South Africa

There are five main industries that utilise gypsum in South Africa, namely: the plasterboard/wallboard manufacturing industry; the plaster manufacturing industry; the agricultural industry; the cement manufacture/industry and the mining industry. The demand for gypsum in these industries is projected to increase over the next 18 years (Figure 1-1). A study by Zitholele (2009) has shown that the highest demand will be in the cement and plasterboard manufacturing industries with the agricultural and mining showing the least demand over the 18 year period. The demand for gypsum presents an opportunity for the utilisation of gypsum from wallboard waste within the various industries. This means that an opportunity exists in South Africa to divert gypsum wallboard waste from landfill into the various existing end markets.

In addition to the gypsum demand, the percentage of gypsum purity required by the various industries varies. The plasterboard industry requires a gypsum purity of >95%, the cement industry requires a gypsum purity of >82% whilst >75% gypsum purity is required by the agricultural industry (Zitholele, 2009:20).

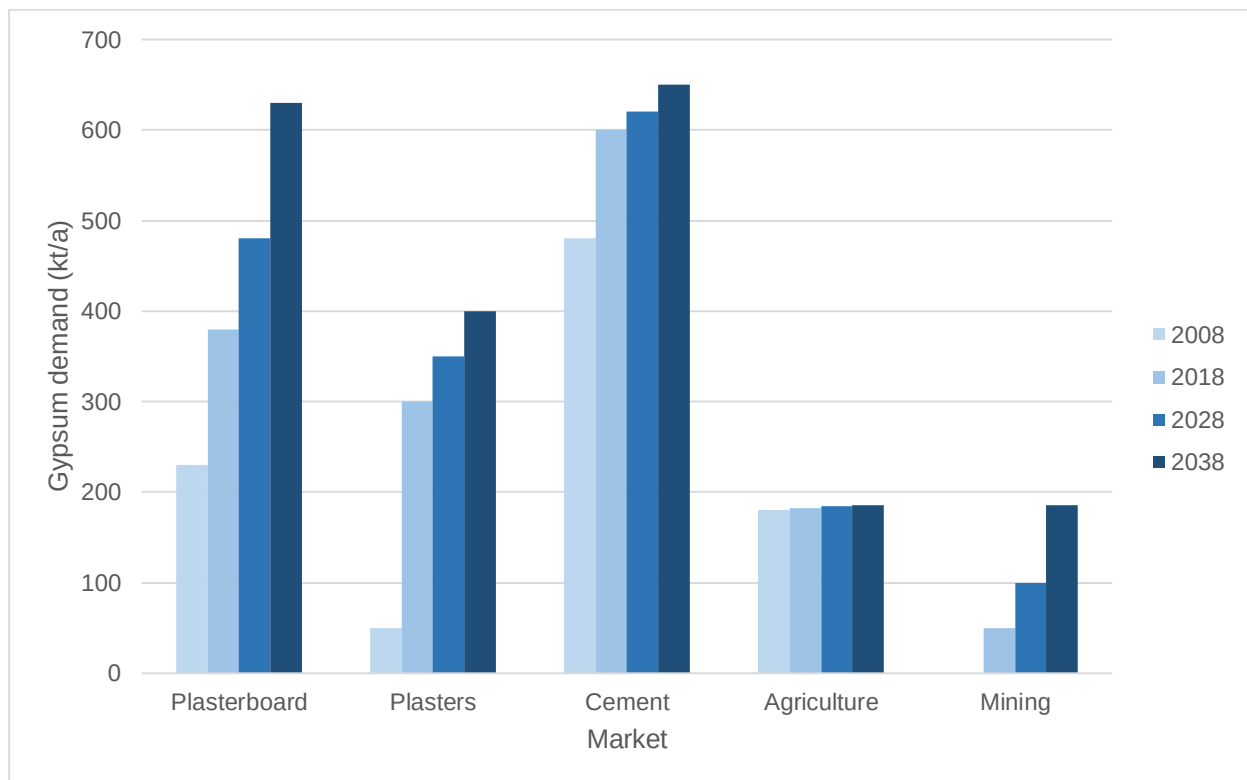


Figure 1-1: The projected demand for gypsum (in kilotonnes per annum) in the different industries in South Africa from 2008 to 2038 (adopted from Zitholele, 2009:52).

1.2 Rationale for the research

The National Waste Management Strategy (NWMS) aims to achieve the objectives of the National Environmental Management Waste Act (Act 59 of 2008) (NEM:WA) through implementing the waste management hierarchy. The Strategy is structured around a framework of eight goals, each with its own actions and deliverables. Goal one of the Strategy promotes the waste management hierarchy for reducing, reusing, recycling and recovery of waste as indicated in Figure 1-2 (DEA, 2011). The goal aims to divert 25% of waste from landfill and places emphasis on the disposal of waste to landfill as a last resort.

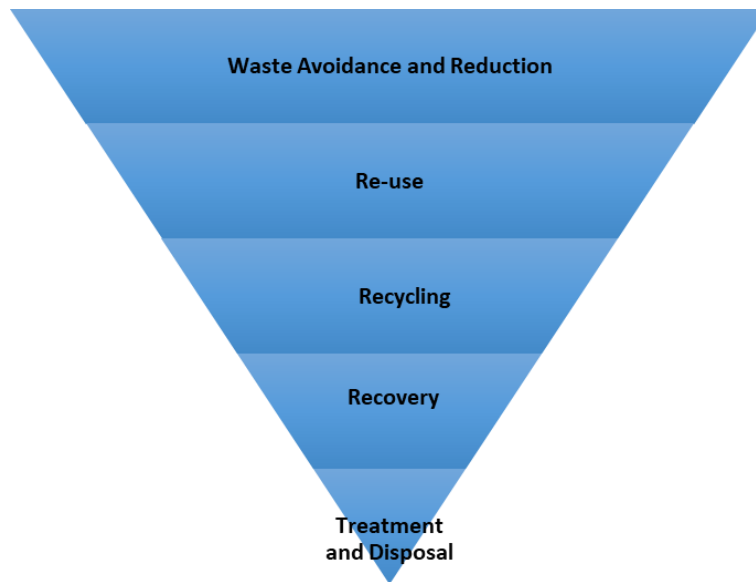


Figure 1-2: The national waste hierarchy (adapted from the NWMS; DEA, 2011).

However, the reality is that South Africa is far from implementing the hierarchy. Landfill disposal is currently the most prevalent method for waste management and little attention is given to waste recycling/recovery/reuse/reduction initiatives. According to the *National Waste Information Baseline Report* (DEA, 2012) approximately 90% of waste generated in South Africa is destined for landfill disposal, while only 10% is re-used, recycled or recovered. This is contrary to countries such as Denmark, Germany and Switzerland who successfully recycle more than 80% of their waste and landfill less than 20% (DST, 2014:3). Of primary concern in South Africa, is that most permitted landfill sites across the country are rapidly running out of landfill airspace (SACN, 2014). It is therefore evident that there is an urgent need to establish alternative solutions to landfill disposal to divert waste from landfill to move waste up the hierarchy. Waste streams with a proven history of reuse/recycling and the potential for diversion from landfill should be prioritized. Construction and demolition waste, including gypsum wallboard waste, is one such type of waste stream, according to a report by the Department of Science and Technology (DST, 2014)

Internationally, extensive research has been done on the alternative uses of gypsum wallboard waste (Arnold, 2010; Carr & Munn, 2001; Das & Keener, 1997; Geraldo *et al.*, 2017; Marvin, 2000; Oh, 2019; Raghavendra & Udayashankar, 2015; Richards, 2013; Townsend & Cochran, 2003; Wolkowski, 2003). However, the production environment, recycling capabilities, end-use markets and recycling economy is different from the South African setup, therefore, it is pertinent that the research is tailored to the local environment. In addition, there is limited available research on the use of gypsum wallboard waste in South Africa. Researchers have focused on the re-use and recycling of construction and demolition waste in masonry and concrete aggregate applications which excluded wallboard waste (Bester *et al.*, 2017; Macozoma, 2006; Zedda *et al.*, 2014). Where gypsum waste was studied, waste gypsum from the mining and fertilizer industries was

investigated for use as a retarder in Portland cement (Van der Merwe & Strydom, 2004), for recovery of elemental sulphur and precipitation of calcium carbonate (De Beer, 2014; De Beer *et al.*, 2014; Nengovhela, 2009) or in the production of calcium sulphide for waste water treatment (Mulopo & Radebe, 2012; Mulopo, 2015). It is clear based on the above evidence that further research on the alternative uses for gypsum wallboard waste, within the South African context is required.

1.3 Problem statement

Due to the composition of gypsum wallboard (containing sulphur), the disposal and/or destruction of gypsum wallboard waste is problematic. Firstly, gypsum cannot be incinerated as the sulphur content results in the release of sulphur dioxide (Mustakas, 2009: 30). Secondly, when gypsum wallboard waste is landfilled with putrescible or organic wastes, the moist, anaerobic environment increases quantities of anaerobic bacteria, which decomposes the sulphate component of the gypsum producing hydrogen sulphide (H_2S) gas (Ndukwe & Yuan, 2016:312; Townsend & Jang, 1999). H_2S is a flammable hazardous gas with an offensive (nuisance) odour (Mustakas, 2009). Additionally, levels of H_2S of higher than 1000 ppm are considered to be lethal to humans (van de Merwe, 2009:102). H_2S concentrations of between 50 000 and 150 000 ppm, as a result of gypsum wallboard waste decay, have been recorded from landfill simulation studies by Plaza *et al.*, (2007). In another study, Yang *et al.*, (2006) reported H_2S concentrations as high as 63 000 ppm as a result of gypsum wallboard waste decay in landfills. Exposure of humans to such high concentrations of H_2S can cause brain damage (Tvedt *et al.*, 1991), permanent nervous system damage (Zhang & Bian, 2014) and even death (Ballerino-Regan & Longmire, 2010).

Furthermore, the decomposition of gypsum increases the concentration of sulphates in the landfill leachate (Townsend *et al.*, 1999). This causes the contamination of soil, surface and groundwater from landfills that lack the proper leachate management systems (Naveen *et al.*, 2018). It has also been reported that methane and carbon dioxide are generated as a result of the decomposition of the paper fraction of the gypsum wallboard waste, which may be released to the atmosphere contributing to a landfill's greenhouse gas emissions (Jimenez-Rivero *et al.*, 2016).

The potential negative environmental impacts related to the disposal of gypsum wallboard waste coupled with the objectives of the *National Waste Management Strategy* to avoid and minimize waste disposal, in the South African context where limited research has been done on alternatives to landfill disposal of gypsum wallboard waste, highlights the need for further research.

1.4 Aim and objectives of the research

The study aimed to explore the alternative options to landfill disposal of gypsum wallboard waste. The study investigated the opportunities and challenges associated with diversion of wallboard waste from landfill, while focusing on establishing the alternative options available. In light of this, the objectives of this study were to:

- **Research objective 1:** Evaluate the physico-chemical and hazard properties of gypsum wallboard waste.

Research question 1: What are the physico-chemical and hazard properties of gypsum wallboard waste?

- **Research objective 2:** Identify the alternatives to the disposal of gypsum wallboard waste.

Research question 2: What are the alternative uses of gypsum wallboard waste, based on its properties?

- **Research objective 3:** Investigate the opportunities and challenges associated with gypsum wallboard waste in composting and fertilizer production and, investigate the views of gypsum wallboard manufacturers in the use of recycled gypsum from gypsum wallboard waste.

Research question 3: What are the opportunities and challenges associated with wallboard waste in composting and fertilizer production and what are the views of wallboard manufacturers in the use of recycled gypsum (based on legislative requirements as well as the technical and chemical specification requirements)?

1.5 Scope of the research

There are three categories (or streams) of gypsum wallboard waste namely; manufacturing or pre-consumer waste, construction waste, and demolition waste. This study only focused on *manufacturing waste* from a gypsum wallboard manufacturer in the Gauteng Province. This manufacturer produces 5000 to 6000 wallboard waste per annum. Construction and demolition (C&D) wallboard waste is contaminated with other impurities such as nails, wood, bricks (Townsend & Cochran, 2003:5). Also, the wallboard waste from demolition projects usually contains paint which is associated with the risk of lead contamination (Breslin 2010, Townsend & Cochran, and 2003:1). This material is not ideal for reuse or recycling purposes as it may test as hazardous waste (Breslin, 2010). Also, the gypsum wallboard waste from C&D projects tends to be crushed by other material making it difficult to recover for further use (Delaware, 2003: 27). It is for these reasons that C&D waste was excluded from the scope of this study. The findings of the research could, however, be applicable to C&D gypsum wallboard wastes, should it be possible to remove the contaminants from these wastes.

Exploring the use of gypsum wallboard waste was limited to investigating its use in ***composting; fertilizer production and the potential to utilise recycled gypsum to produce new wallboard.*** the practicality of the alternative within the South African context and consideration of

other options such as the application of the alternative to the waste hierarchy, the application of the South African regulatory framework to the alternative and access to resources.

The results presented in this study were obtained from reviewing existing literature and secondary data sources, in addition to composting and fertilizer production field experiments, and interviews. The field experiments were conducted between February and May 2020.

1.6 Limitations of the research

Gypsum research in South Africa has focused on extracting elements and compounds for onward use from gypsum waste originating from the mining and fertilizer industry (De Beer, 2014; De Beer *et al.*, 2014; Mulopo & Radebe, 2012; Mulopo, 2015; Nengovhela, 2009; Van der Merwe & Strydom, 2004). Applicable studies relating to alternative uses of gypsum wallboard waste in South Africa are limited. As a result, the researcher has inferred from advanced first world international practices commonly employed to divert gypsum wallboard waste from landfill, and extrapolated to South Africa, a third world country.

Also, South Africa does not have parameter guidelines for the quality of recycled gypsum required in wallboard manufacturing processes as well as parameter guidelines for finished compost (unless the intention is to use the compost is used to produce fertilizer). Thus, data obtained in this study was compared to international parameter guidelines.

1.7 Possible contributions of the research

This research will contribute to South Africa's limited literature on alternative options for diverting gypsum wallboard waste from landfill. This may encourage the re-use and recycling of gypsum wallboard waste by shedding light on the international best practices employed for this waste stream and therefore, provide an understanding of the opportunities and challenges associated with the alternative uses of this waste. In addition, this form of research may allow researchers to determine what alternatives to landfill disposal options are worth exploring for gypsum wallboard waste now and in the future.

1.8 Structure and outline of the dissertation

The dissertation consists of five chapters. Chapter 1 provides a history and background on the subject of gypsum wallboard. The reason for conducting this study, the problem statement, the aims and objectives, as well as the scope and limitations are outlined. Chapter 2 describes the methodology and the research design employed to address the research problem and objectives. The methodology chapter is provided before the Literature Review chapter to provide the background and context against which Chapter 3 (Literature Review) must be considered.

Chapter 3 provides a review of the literature on gypsum wallboard waste from generation to the alternative uses of the waste, including its physico-chemical properties and classification which informs the alternative uses. The challenges and opportunities associated with gypsum wallboard waste are also addressed in this chapter. Chapter 4 provides the analysis, interpretation and discussion of the research findings linked to the research objectives (provided in Chapter 1). Chapter 5 concludes the findings of the research and makes recommendations, where applicable.

1.9 Chapter summary

This chapter presented a brief background on the mineral gypsum and gypsum wallboard. The rationale, problem statement, aims and objectives as well as the potential contribution of the research were discussed to provide the reader with an understanding of the reasons behind the chosen research topic. The next chapter presents the methodology followed to address the research questions.

CHAPTER 2 RESEARCH DESIGN AND METHODOLOGY

2.1 Introduction

This chapter describes the research approach, design and research methods used in this research. The researcher also justifies the research design and methods used in this study. In addition, the chapter explains the methods for collecting, validating and analysing data, as well as the ethical considerations for conducting the research.

The research is exploratory in nature and aims to investigate the alternatives to landfill disposal of gypsum wallboard waste produced from a manufacturing process, a topic which has not been studied extensively within the South African context (Bhat, 2020). Based on the research problem, the research aim and the research questions in this study, a mixed-method approach was seen as the best-suited option for the research, because both qualitative and quantitative techniques were required to answer the research questions. Employing both qualitative and quantitative methods yielded a better understanding of the research problem than when either approach were used alone (Creswell, 2014b:48).

For this research study, *qualitative* data were collected and analysed (through secondary data and literature review), followed by the collection and analysis of *quantitative* data (field experiments). Findings from the quantitative data were used to build onto the qualitative data, followed by the collection of more qualitative data (through interviews) (Figure 2-1) (Creswell, 2014b; Wium & Louw, 2018:6) (Also refer to Section 2.2 and Table 2-1).

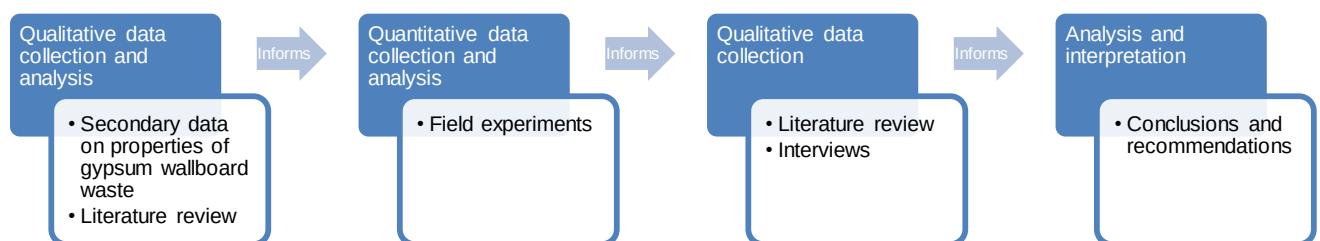


Figure 2-1: Exploratory mixed method design employed in this study(Creswell, 2014a).

2.2 Research design

The *research design* provides a plan, structure or strategy of how a researcher will conduct their investigation to provide answers to the objectives or problem of the research (Kumar, 2011:95). In essence, the research design outlines how information for a study will be collected and analysed. The research design aims to ensure that the appropriate methods are employed to

achieve the research objectives, and allows a researcher to make decisions regarding the steps they will follow (i.e. data requirements, where data can be found, data collection, sample selection, and data analysis and communication) (Kothari, 2004; Kumar, 2011:96).

Table 2-1 outlines the summary of the research design for this study, with an overview of methods selected and justification thereof.

Table 2-1: Summary of the Research design and methodology used in this study.

Research objective	Methodology	Justification
Research objective 1: Evaluate the properties of the gypsum wallboard waste to inform potential alternative uses	Secondary data on the composition, physico-chemical properties, and hazard categories of gypsum wallboard waste was evaluated to determine hazard properties and other physical and chemical characteristics of the wallboard waste. The data was obtained from a technical specification sheet from a business entity.	The composition of gypsum wallboard is well-known and documented in countless available gypsum wallboard safety data sheets (American Gypsum, 2020; British Gypsum, 2019; Certainteed, 2018; CGC Sheetrock, 2016; CSR Gyprock, 2019; Pabco Gypsum, 2015; USG Boral, 2016; United States Gypsum, 2013). The SANS 10234 classification results (outlined in the technical specification sheet and safety data sheet) were used to determine whether gypsum wallboard waste may have the potential to pose any physical, health or environmental hazards, since the research focuses on uncontaminated pre-construction (manufacturing) waste. No additional classification was done based on GNR 634 of August 2013 (the Waste Classification and Management Regulations), since the wallboard used in the study did not undergo any processing. The physico-chemical properties were used to determine if wallboard would be suitable for alternative use based on the requirements of the alternative use.
Research objective 2: Identify alternatives to gypsum wallboard waste disposal to landfill	1. International and national literature review to identify the alternatives to gypsum wallboard waste disposal. The main resources included: Academic journals, Online articles, Theses, Government and	1. Review of international and national literature was done to determine potential alternatives to the disposal of gypsum wallboard waste. 2. Experiments were conducted in a natural setting where the gypsum wallboard waste was likely to react more “normally” than when conducted in the artificial settings of a laboratory

Research objective	Methodology	Justification
	organizational reports, Company websites, Books written by experts and Conference papers. 2. Field experiments to determine the viability and feasibility of selected alternatives (based on prioritisation criteria).	(Walliman, 2011:104). Thus the results obtained mimic what would happen in the real world and may be used to make generalizations for gypsum waste alternatives.
Research objective 3: Investigate the opportunities and challenges associated with gypsum wallboard waste in composting and fertilizer production and, investigate the views of gypsum wallboard manufacturers in the use of recycled gypsum from gypsum wallboard waste.	1. International and national literature review to provide an overview of challenges and opportunities related to selected alternatives. 2. Interviews with selected interest groups to determine the challenges and opportunities related to the potential alternatives.	1. To understand the broad school of thought on the challenges and opportunities experienced when gypsum wallboard waste is utilised in alternative uses. 2. To understand the thoughts, views and experiences of the South African industry on the subject as well as investigate whether an interest to utilise recycled gypsum in the manufacturing of new wallboard exists (Alshenqeeti, 2014; McGrath <i>et al.</i>, 2019:1002).

2.3 An overview of the data collection methods used to address each research question.

The research design is outlined in Table 2-1. The research was conducted through the collection of data on the characteristics (properties) of gypsum wallboard waste, literature review, field experiments on selected alternatives, and semi-structured interviews (Figure 2-2). Details on the methods that were followed is outlined in the sub-sections to Section 2.3 of this dissertation.

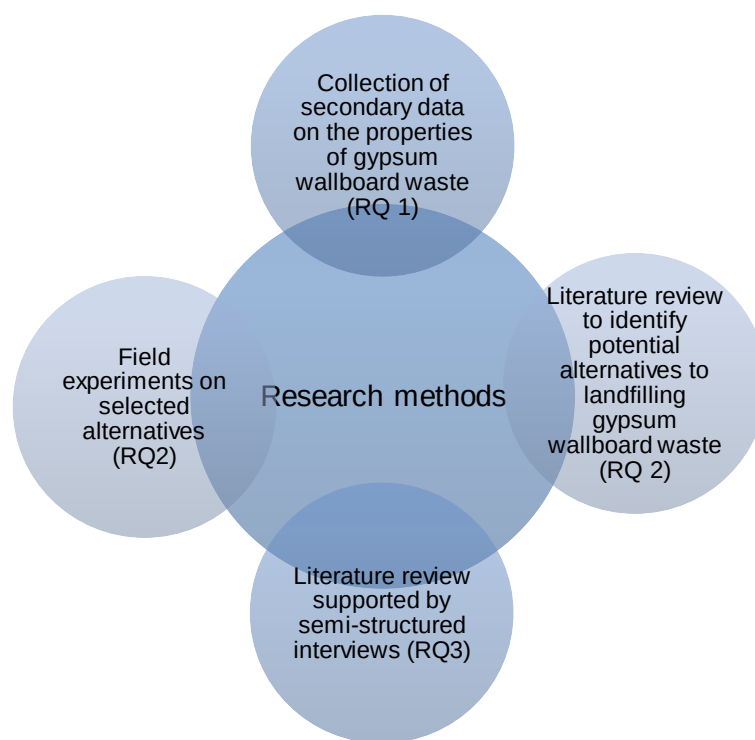


Figure 2-2: Research methods employed in this study.

2.3.1 Evaluating the properties of gypsum wallboard waste (RQ 1)

The chemical composition, physico-chemical characteristics and properties of gypsum wallboard are well-known and documented by various gypsum wallboard manufacturers (American Gypsum, 2020; British Gypsum, 2019; Certainteed, 2018; CGC Sheetrock, 2016; CSR Gyprock, 2019; Pabco Gypsum, 2015; USG Boral, 2016; United States Gypsum, 2013). In this study, the data indicating the physico-chemical characteristics (such as moisture, physical state, flashpoint, water immiscibility, pH, EC, heavy metals), as well as the hazard properties of gypsum wallboard waste, as determined in terms of the *Globally Harmonised System for the Classification of Chemicals* (SANS 10234, 2008) were obtained from a secondary source. Since gypsum wallboard waste from manufacturing processes did not undergo any additional processing, the physico-chemical properties of the gypsum wallboard waste is similar to newly manufactured wallboard. Thus, the composition of the gypsum wallboard waste can be compared to that documented in international safety data sheets (American Gypsum, 2020; British Gypsum, 2019; Certainteed, 2018; CGC Sheetrock, 2016; CSR Gyprock, 2019; Pabco Gypsum, 2015; USG Boral, 2016; United States Gypsum, 2013).

2.3.1.1 Classification of gypsum wallboard waste in accordance with SANS 10234

The SANS 10234 classification results (as outlined in the safety data sheet) were used to determine whether gypsum wallboard waste may have the potential to cause any physical, health or environmental hazards:

- **Physical characteristics/hazards:** Explosive, flammable gas, flammable aerosol, oxidizing gas, gas under pressure, flammable liquid, flammable solid, self-reactive substance, pyrophoric substance, self-heating substance, substance that on contact with water emits flammable gases; oxidizing substance, organic peroxide, corrosive to metals;
- **Health characteristics/hazards:** Acute toxicity, skin corrosion and skin irritation, serious eye damage and eye irritation, respiratory sensitization and skin sensitization, germ cell mutagenicity, carcinogenicity, reproductive toxicity, specific target organ toxicity – single exposure and repeated exposure, aspiration hazards; and
- **Environmental characteristics/hazards:** Hazards to the aquatic environment.

2.3.1.2 Compositional characteristics, physical and chemical properties of gypsum wallboard waste

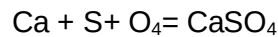
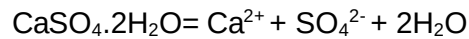
As mentioned above (section 2.3.1), the chemical compositional characteristics (heavy metals and metalloids total and leachable concentrations, inorganic anions), the physical properties (moisture content, water immiscibility, physical state, flashpoint) and the chemical properties (pH and EC) of the gypsum wallboard waste were obtained from a secondary data source which was compared to other secondary sources internationally. The compositional parameters were analysed for total concentrations (TC) and leachable concentrations (LC) for comparison to the Total concentrations threshold (TCT) and Leachable concentrations threshold (LCT) values for landfill disposal, stipulated in the *National Norms and Standards for the Assessment of Waste for Landfill Disposal* (RSA, 2013b). The total concentrations were analysed using a portable X-ray Fluorescence and the leachable concentrations were obtained through toxicity characteristics leaching procedure (TCLP) based on Australian standards (AS 4439.1 and AS 4439.3).

The physical and chemical parameters were also compared to the limits acceptable in landfills as stipulated in the *National Norms and Standards for Disposal of Waste to Landfills* (RSA, 2013c). These norms and standards (RSA, 2013b and RSA 2013b) are used for assessing the type of waste (i.e. Type 0, 1, 2, 3 and 4), to determine the appropriate landfill class (A, B, C and D) required to dispose of the waste and to enforce restrictions on the properties of the waste permitted in landfills (e.g. wastes with <40% moisture, pH >6<12 etc.). Their application in this study however, was not for the purposes of landfilling but rather to assess whether the waste would have potential negative impacts on the soil/land as a result of composting or fertilizer production activities as an alternative to landfill disposal.

2.3.1.3 Gypsum percentage/purity of the waste

Gypsum is a calcium sulphate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) consisting of 23.278% Calcium (Ca), 2.342% Hydrogen (H), 55.756% Oxygen (O) and 18.624% Sulphur (S). The gypsum purity or

percentage gypsum contained within the wallboard waste was determined based on the stoichiometry principles described below:



Atomic mass Ca: 40.09 g/mol and Atomic mass S: 32 g/mol

Molar mass gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$): 172.082 g/mol

1 mol Ca = 1 mol CaSO_4

1 mol S = 1 mol CaSO_4

Therefore: no limiting reactant

$$\begin{aligned} \% \text{ Gypsum} &= Y \times \frac{1 \text{ mol reactant}}{\text{atomic mass of reactant (g)}} \times \frac{1 \text{ mol CaSO}_4}{1 \text{ mol reactant}} \times \frac{172.082 \text{ g}}{1 \text{ mol CaSO}_4} \\ &= \frac{Y \times 172.082}{\text{atomic mass of reactant}} \end{aligned}$$

Method Adopted from Opentax College (2019) and Sienko & Plane (1979)

The following assumptions were taken into account:

- Concentration of reactant (wt %) = Y
- When wallboard is dissolved in soil or water, the calcium (Ca) in gypsum can be replaced by magnesium (Mg). As a result of the magnesium and calcium action exchange, precipitation of magnesium sulphate can occur when magnesium ions attach to the sulphate ions (Al-khadi *et al.*, 2011). In the absence of quantitative analysis, it is difficult to accurately estimate the percentage gypsum or magnesium sulphate present in the wallboard. Therefore, the estimated gypsum percentage will be based on the lower concentration obtained from either the calcium or sulphur calculations.

2.3.2 Identifying the alternatives to gypsum wallboard waste disposal to landfill (RQ 2)

Once the composition, physico-chemical characteristics and hazard properties of waste were understood, a review of international and national literature was done to determine the potential alternatives to the disposal of gypsum wallboard waste (Section 2.3.2.1). Composting and fertilizer were selected as suitable alternatives within the South African context and were further evaluated through field experiments (Section 2.3.2.2), interviews (Section 2.3.3.2) and further literature review, where necessary.

2.3.2.1 Literature review to determine alternatives to gypsum wallboard waste disposal

This literature review in this study follows a systematic process as indicated in Figure 2-3 below



Figure 2-3: Literature review process followed in this study (Adopted from Danson & Arshad, 2015; Kothari, 2004).

A comprehensive literature review was done to answer *Research Question 2* (Section 1.4) (Cronin *et al.*, 2008). To determine the alternative options available for the use of gypsum wallboard waste, a rapid internet search titled “uses of gypsum wallboard waste” was conducted. This search revealed the various uses of wallboard waste. This assisted the researcher in narrowing the search and focusing on the research question. The next step involved finding secondary data relevant to each of the uses of the gypsum wallboard waste.

Successful research was achieved by interchanging the word ‘wallboard’ with ‘plasterboard’, ‘drywall’, ‘plaster of Paris’ or ‘sheetrock’. This is because wallboard is known by different names in different parts of the world. In terms of gypsum wallboard waste uses in Africa (excluding South Africa), the search criteria involved specifying the name of the country and the alternative use. For example, “uses of gypsum wallboard waste in concrete in Nigeria”. This is because a generic search only provided data from mainly Europe, America and Asia. In South Africa “gypsum waste” was used to search for studies. This is because most research has focused on ‘waste gypsum’ from mining and fertilizer industry. Searching for ‘gypsum wallboard’ did not yield any results.

In addition to the above, an inclusion and exclusion criteria was also used which involved the following (Cronin *et al.*, 2008; Siddaway, 2014):

- All the secondary data used were in English;
- Secondary data used involved studies conducted to investigate the recycling or reuse capability of gypsum wallboard waste in different applications; and
- Most of the journal articles used in this study were published between 2010 and 2020.

The secondary data was obtained from academic search engines available on the North-West University library platform and online platforms such as Google Scholar, Semantic Scholar, Research Gate, business entities and company websites. The type of data sources used included,

academic journals, online articles, theses, government and organizational reports, company websites, books written by experts and conference papers.

The literature review has revealed that there is limited research on the use of gypsum wallboard waste in South Africa (De Beer, 2014; De Beer *et al.*, 2014; Nengovhela, 2009; Van der Merwe & Strydom, 2004). Thus, the researcher conducted an extensive review of international literature, which was then related to the South African context. The literature review was aimed at providing information on the following:

- *The potential alternative uses of gypsum wallboard waste (RQ 2);*
- *The properties of gypsum that make it suitable/attractive for alternative uses (i.e. building and construction) (RQ 2);*
- *The most common uses and best practices for gypsum wallboard waste, and the factors influencing these uses (RQ 2);*
- *Best practices, guidelines and permissible endpoints for utilising recycled gypsum wallboard waste (RQ 2); and*
- *The opportunities and challenges associated with recycling/reusing this waste (RQ 3).*

2.3.2.2 Field experiments

A literature review was used to determine the current international alternatives and practices on the uses of gypsum wallboard waste (as explained in Section 2.3.2.1). **Composting** and **fertilizer** production were selected as alternatives for further research, using field experiments, while the potential to utilise recycled gypsum to produce new wallboard were further researched by means of interviews.

Walliman (2011:103) describes experiments as “*the obtaining of information on the causes and effects of a particular phenomenon*”. Experiments aim to establish what happens when a change is made, why, when and how this change is made (Walliman, 2011:103). There are two types of experiments: laboratory experiments or experiments conducted in a natural setting (nature). In this study, the latter was conducted.

2.3.2.2.1 Composting experiments

The researcher in collaboration with a professional composter conducted composting trials of gypsum wallboard waste and organic material over a period of three months (90 days). Gypsum wallboard waste was composted with organic matter of straw, paper pulp, horse manure, sawdust, sunflower husk and a proprietary ingredient (of which the composition information is not made available for the purposes of this study) (Table 2-2) The initial C: N ratio of the organic matter ingredients used in the compost was 50:1.

Table 2-2: C:N ratios of the ingredients used in compost.

Ingredient	C:N ratio	Cumulative C:N ratio
1 part paper pulp	25:1	50:1
1 part straw	40:1	
1 part horse manure	22:1	
1 part saw dust	200:1	
1 part sunflower husk	67:1	
4 part propriety ingredients	25:1	

The compost trial was carried out to investigate the effect of varying proportions of gypsum wallboard waste on the compost after 90 days of composting. Four heaps of gypsum wallboard waste and organic matter were created. The 1st, 2nd, 3rd and 4th heaps consisted of 10%, 20%, 30% and 50% gypsum wallboard waste respectively which were mixed with 90%, 80%, 70% and 50% organic matter respectively (Figure 2-4 and Figure 2-5). The proportion of the gypsum wallboard waste and organic matter mixture in each heap added to 100%. The size of the gypsum wallboard waste used in the trial ranged between 0.1 - 0.6m. Prior to disposal of the wallboard waste by the manufacturer, the gypsum wallboard waste is crushed to smaller pieces to ensure portability during transportation. A compost heap consisting of 100% pure organic material was used as a control measure, with a similar experiment running parallel to the other compost mixtures containing gypsum for validation purposes (Figure 2-4 Right) (Walliman, 2011).



Figure 2-4: In-field mixing of organic matter with gypsum wallboard (a). The original organic material used in the mixture (b).



Figure 2-5: Wallboard waste and organic matter compost heaps after mixing. (a) 10% wallboard waste and 90% organic matter, (b) 20% wallboard waste and 80% organic matter, (c) 30% wallboard waste and 70% organic matter and (d) 50% wallboard waste and 50% organic matter.

The temperatures of the compost heaps were monitored on a daily basis using a temperature probe (Figure 2-6) and the moisture content of the heaps was monitored once a month to ensure the functionality of the process. For the moisture analysis, a 500 ml sample was collected and submitted to a laboratory (Figure 2-7).



Figure 2-6: Temperature probe used to measure temperatures of the compost heaps.



Figure 2-7: Samples collected for moisture analysis.

The compost heaps were turned on day 35 of the trial after a drop in temperature was noticed. Thereafter, the heaps were not turned for the remainder of the 90-day trial. The trial was terminated when the temperatures of all the compost heaps dropped consistently to below the minimum acceptable ranges of 45°C (Rynk, *et al.*, 1992). Upon completion of the trial, a representative sample of each heap was collected in a 50 litre bucket and the samples were sieved utilising a 25 mm and 8 mm sieve (Figure 2-8). These sizes were chosen because they are the most commonly used sizes for screening final compost (Boldrin, 2011 and Smith, 2018). During sieving, the 8-25 mm size fraction was recirculated into the compost, and the greater than 25 mm size fraction was discarded. The sieving exercise was performed to determine the percentage size distribution of the final compost, and to determine the percentage of undersized and oversized material. The results of the sieve tests were normalised to 100%.

Compost with less than 8 mm particle sizes is the most common size fraction of compost used in the various applications internationally (Boldrin, 2011 and Smith, 2018). Based on this, the 8 mm particle size was selected for laboratory analysis (Figure 2-9).

Three kilogram samples were collected from each 8 mm sieved sample and sent to the laboratory to be analysed for various parameters, including pH (In accordance with ISO 10390:2005), Electrical Conductivity (EC) (in accordance with ISO 11265:1994-determination using EC electrode probe), moisture content (in accordance with ISO 18134-1:2015) heavy metal concentrations (determined by Perchloric acid and Nitric acid digestion with ICP-EOS), and, total nitrogen contents (in accordance with ISO 13878).



Figure 2-8: Gypsum wallboard waste and organic matter compost heaps after the completion of the trial. Control compost heap (a). 10% wallboard waste and 90% organic matter (b). 20% wallboard waste and 80% organic matter (c). 30% wallboard waste and 70% organic matter (d). 50% wallboard waste and 50% organic matter (e).



Figure 2-9: Samples collected and analysed (less than 8mm in size) after sieving of the different stockpiles. (a) Base compost, (b) 10 Gypsum wallboard waste, (c) 20% Gypsum wallboard waste, (d) 30% Gypsum wallboard waste and (e) 50% Gypsum wallboard waste.

Since the experiments were conducted in a natural setting, the gypsum wallboard waste and the compost material were more likely to react normally than when conducted in the artificial settings of a laboratory (Walliman, 2011:104). Thus, the results obtained mimic what would happen in the real world and may be used to make generalisations when composting clean, pre-consumer gypsum wallboard waste with similar organic matter. Thus internal and external validity was easily achieved (Walliman, 2011:104).

2.3.2.2.2 Fertilizer production from composting gypsum wallboard waste

Gypsum wallboard waste has been successfully applied directly to plants as a fertilizer and has yielded successful results (Bernard, 2013; Wolkowski, 1998; Wolkowski, 2000). This research intended to establish whether the gypsum wallboard waste compost consists of adequate nutrients to be used as a fertilizer in accordance with the *Fertilizer, Farm Feeds, Agricultural Remedies and stock remedies Act (Act 36 of 1947)* (RSA, 2012) as indicated in Table 3-4. A three kilogram (3kg) sample was collected (as explained in Section 2.3.2.3.1) and tested for fertilizer parameters such as nitrogen, phosphorus and potassium (determined through Perchloric acid

and Nitric acid digestion with ICP-EOS), ash content (in accordance with ISO 11722), heavy metals and other plant nutrients i.e. calcium, sulphur, magnesium, boron, etc. (determination through Perchloric acid and Nitric acid digestion with ICP-EOS). Since horse manure was used as one of the compost ingredients, the presence/absence of pathogens; Viable *Ascaris* ova/Helmith (TT 262/06), *Salmonella* (Method 9260 B), and Faecal coliforms (TT 262/06) was also investigated.

2.3.3 Investigating the opportunities and challenges associated with gypsum wallboard waste in composting and fertilizer production and, investigating the views of gypsum wallboard manufacturers in the use of recycled gypsum from gypsum wallboard waste (RQ 3).

The results of research question 2 were used to inform the design of research question 3. A further review of the literature (Section 2.3.3.1), supported by interviews (Section 2.3.3.2) were used to investigate the potential for recycling gypsum wallboard waste into the wallboard manufacturing process in South Africa and also determine the challenges and opportunities for the selected alternatives, namely:

- Composting;
- Fertilizer production from composting gypsum wallboard waste; and
- The use of recycled gypsum in new wallboard manufacturing

The first step involved reviewing available literature to understand the broad school of thought on the challenges and opportunities experienced in the use of gypsum wallboard waste in alternative applications. Interviews were then conducted to understand the opportunities and challenges of selected participants on the alternative use of gypsum wallboard waste and, to investigate the views of wallboard manufacturers in utilising recycled gypsum in manufacturing processes (McGrath *et al.*, 2019:1002).

2.3.3.1 Literature review to identify challenges and opportunities

The literature review considered secondary data sources that described the experiences in terms of challenges and opportunities associated with reusing and recycling gypsum wallboard waste with a focus on composting, fertilizer production and gypsum wallboard manufacturing. These data sources included information from various waste management companies (NWGR, 2020), journal articles on gypsum wallboard waste recycling (Gibson, 2011), wallboard manufacturing company websites (Saint Gobain Gyproc, 2017), wallboard waste recycling companies (GRI, 2013) as well as studies or research conducted around gypsum wallboard waste recycling, (Eurogypsum, 2015a) and studies aimed at understanding experiences from stakeholders

(JJimenez-Rivero & Navarro, 2017a). An overview of relevant literature, as it relates to the research questions and context of this study, is provided in Chapter 3 of this dissertation.

2.3.3.2 Interviews

Interviews are used to collect data. They typically involve verbal communication between the interviewer and the interviewee (Mathers *et al.*,1998:1). Semi-structured interviews with open-ended questions were chosen as the best fit for this study as they provided the participant's in depth views on the challenges and opportunities encountered when utilising gypsum wallboard waste, and the participants were also able to express their thoughts and perceptions regarding the use of gypsum wallboard waste (Alshenqeeti, 2014:39). Semi-structured interviews are commonly used in exploratory research to gain insight on a problem with limited information similar to the one studied in this research (Mathers *et al.*,1998). The aim of the interviews in this study was to:

- Investigate the challenges and opportunities associated with utilising gypsum wallboard waste by composters, gypsum containing fertilizer producers and wallboard manufacturers; and
- Investigate the views of wallboard manufacturers in utilising recycled gypsum in their processes.

2.3.3.2.1 Interview Sampling

The participants in this study were selected through purposive sampling (Ilker *et al.*, 2016:3). Experienced and knowledgeable experts on gypsum wallboard and gypsum wallboard waste were intentionally selected to participate as they had/ a better understanding of gypsum wallboard and gypsum wallboard waste and therefore, provided more insight on gypsum wallboard waste with regards to the opportunities and challenges experienced at the different stages of the gypsum wallboard waste cycle (i.e. manufacturing to disposal or recycling). (Tongco, 2007:147). The purposive sampling method has been successfully used in understanding waste management trends and waste management options by other researchers (Masange, 2014; van der Merwe, 2009), and was deemed to be suitable for this research study.

A research schedule guide was designed and used to guide the interview process (**Appendix A**). This consisted of a set of open-ended questions in a sequence chosen by the researcher, adopting the guideline described by Mathers *et al.*,(1998:9). To understand the challenges and opportunities, the interview questions were designed to investigate the experiences of the composters and fertilizer producers when gypsum wallboard waste is used in their processes. For wallboard manufacturers, the interviews aimed to understand the views of gypsum wallboard manufacturers in utilising recycled gypsum in their processes. In addition, a guideline outlining

the required recycled gypsum quality parameters for the use in the manufacturing of new gypsum wallboard in Europe was provided to the gypsum wallboard manufacturers to establish whether the requirements in South Africa were similar to those used in Europe (Table 3-2).

Face-to-face interviews were conducted with one gypsum wallboard manufacturer and one composter prior to the South African national lockdown (due to COVID-19). The interviews were held at each of the participant's premises. The completed interview schedule was forwarded to the participants to ensure the accuracy of the information. The remaining interviews were conducted telephonically and via email (due to COVID-19 lockdown restrictions). The participants were contacted telephonically and via email and the purpose of the research was explained to them. An invitation to participate (**Appendix B**) and an interview consent form (**Appendix C**) were sent to each of the participants. The consent forms were signed as confirmation of voluntary participation by the participants. The interview questions were forwarded via email and responses were also received via email. The responses received were also discussed with the participants telephonically in instances where further elaboration or clarity was required.

A total of twenty one participants were invited to participate in the study (two wallboard manufacturers, twelve gypsum composters and seven gypsum fertilizer producers). Thirteen participants responded including two wallboard manufacturers, nine gypsum composters and two gypsum fertilizer producers. Thus, the response rate was 100% for the wallboard manufactures, 75% for composters and 29% for fertilizer producer. The overall response rate for this study was 62%, which was considered to be acceptable.

2.4 Data analysis

This section describes the data analysis used for field experiments and well as data obtained from interviews.

2.4.1 Data analysis of field experiments

The analysis of data collected during composting and fertilizer production field experiments are described in the next sections.

2.4.1.1 Composting

Data collected from composting field experiments was presented in the form of tables and graphs in order to show the impact of the gypsum wallboard waste on the different parameters of compost. This was achieved by comparing the percentage gypsum wallboard waste with the various parameters mentioned in section 2.3.2.2.1 above. The results were also compared to the

result obtained from the control compost heap and to the parameters required for composting as stipulated by Brinton (2000) and Rynk *et al.*, (1992) in Table 3-5 and Table 3-6.

2.4.1.2 Fertilizer production gypsum wallboard waste compost

Analysis of the data collected for the purpose of assessing the fertilizer production potential was done in a similar manner to that of composting data (refer to Section 2.4.1.1) but with a focus on comparing the heaps with the varying percentages of gypsum wallboard waste to the parameters required as stipulated in the *Fertilizer, Farm Feeds, Agricultural Remedies and stock remedies Act (Act 36 of 1947)* fertilizer regulations (RSA, 2012). The data was also presented in the form of tables, and graphs to show the impact the gypsum wallboard waste had on the required fertilizer parameters mentioned earlier. The results were also compared to the control heap.

2.4.2 Data analysis of interviews

Thematic analysis was used to analyse the results from the interviews. This was conducted in accordance with Braun and Clarke's (2006) framework for carrying out thematic analysis. The results from interviews were validated by conducting a comparison with literature and data obtained from experiments, where possible (Yin, 2011).

2.5 Ethical considerations

According to the North-West University (NWU, 2018), ethical considerations should be acknowledged and taken into consideration during research. The study was conducted based on secondary data gleaned from the literature, and field experiments, supported by interviews (limited human interaction). The study involved human participants, but did not include any sensitive respondents (i.e. children, persons with disabilities, etc.). The research proposal was submitted to the Scientific Committee of the Environmental Management Research Group (EMRG) in the Unit for Environmental Sciences and Management of the North-West University, Potchefstroom Campus for consideration. The scientific committee found that the project proposal was in accordance with the scientific method and adhered to the required standards as set out in the Academic Rules for Master's and Doctoral Students at North-West University. The Scientific Committee concluded that the proposed methodology posed a low ethical risk, hence exemption from further ethical approval was recommended for the study (Ethics number: NWU-01306-20-A9).

The purpose of the research was discussed with the participants, and participants completed a consent form to ensure that they were willing to participate in the research voluntarily (Leedy & Omrod, 2014:121-124). The purpose of the consent form was to make participants aware that the information they provide from the interview would be kept confidential and their names or

organisations would not be mentioned when the results are released. Instead, unique labels were given to identify the participants (Leedy & Omrod, 2014:121-124).

The researcher declares that the findings of this study were not misinterpreted with the intention to lead the research or mislead others (Leedy & Omrod, 2014:121-124). The thoughts and ideas of others are acknowledged accordingly.

2.6 Assumptions and limitations of the study

- The alternatives investigated during this study were based on options, which were considered to be reasonable and potentially feasible within the South African context, considering what was learned from the review of literature.
- Alternatives to be investigated further by means of field trials were identified by means of using pre-selected inclusion and exclusion criteria.
- Two alternatives (composting and fertilizer production) were further investigated using field trials, and the recycling of gypsum wallboard waste was further investigated using interviews.
- The composting trial was carried out over three months (90 days), due to time limitations. Therefore, the compost and fertilizer results obtained in this study are based on a trial conducted over three months regardless of whether the compost was mature (C/N ratios between 10-12) or immature (C/N ratios above 12).
- Field trials were conducted under natural conditions, while all analyses relating to this research were conducted by specialists in a laboratory.
- Due to the unavailability of a 12 mm sieve (as required by the fertilizer regulations), the particle size percentage passing through the 12 mm sieve size as required by the fertilizer regulation (Table 3-4) was estimated based on visual observations.
- For the purpose of this study, one wallboard manufacturer disclosed partial information relating to recycled gypsum quality parameters they would require should they accept recycled gypsum. In the event that recycled gypsum trials are conducted and the recycled gypsum is to be supplied to the manufacturer, additional information should be obtained to ensure the recycled gypsum meets the specifications required by the manufacturer.
- The results of interviews were based on the views and perceptions of thirteen respondents, which was representative of 62% of the total participants invited to partake in the study.

- As a result of the COVID-19 restrictions, a portion of the interviews were conducted via telephone and email. The interview questions were sent to the participants via email. The extent to which the answers were provided may be limited compared to face to face interviews.
- No samples were collected for pH, EC and moisture analysis during the month of April as it was during the South African national COVID-19 lockdown.

2.7 Chapter summary

The research methods and design used in this research have been clearly explained so that the viewer can understand the rationale behind each decision made in this study. The purpose of this research was exploratory. In order to answer the research questions, the study made use of a sequential mixed method design of qualitative data collection and analysis followed by quantitative data collection and analysis in order to answer the research questions.

Chapter 3 outlines the findings of the literature review.

CHAPTER 3 LITERATURE REVIEW

3.1 Introduction

The purpose of the literature review is to provide the reader with the general context of the research and to also address specific aspects related to research objectives 2 and 3, namely:

Research objective 2: *Identify alternatives to gypsum wallboard waste disposal to landfill by means of reviewing the literature and secondary sources on the re-use and recycling of gypsum wallboard waste and gypsum waste in general in South Africa, Africa and Internationally.*

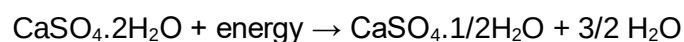
Research objective 3: *Investigate the views of wallboard manufacturers with regards to the reuse of recycled gypsum from gypsum wallboard waste in manufacturing process and, the opportunities and challenges associated with the use of gypsum wallboard waste in composting and fertilizer production, by means of reviewing the literature and secondary sources that focus on challenges and opportunities experienced by various stakeholders' such as waste management companies and gypsum wallboard waste recyclers*

Since this research was based on a mixed-method approach, literature was reviewed in the context of qualitative and quantitative data.

3.2 The gypsum wallboard manufacturing process and waste generation

The gypsum wallboard manufacturing process comprises of two stages. The first stage involves the production of stucco, a mixture of aggregates, water and a binder used in the coating of walls, surfaces and exterior buildings, and the second stage involves the production of the gypsum wallboard (Figure 3-1 and Figure 3-2).

Stucco production involves pre-processing of the raw gypsum feedstock. Gypsum can either be natural or synthetic. Depending on the type and properties of the gypsum, particle size reduction and pre-drying of the gypsum may be necessary. The gypsum is then calcinated, a process whereby the gypsum undergoes dehydration under the influence of thermal energy. This process alters the hydration state of the gypsum dihydrate content thereby producing stucco according to the chemical equation below:



During the gypsum wallboard production, the stucco is combined with water and various liquid and solid additives to produce a slurry. Additives may include starch, lignin, accelerators,

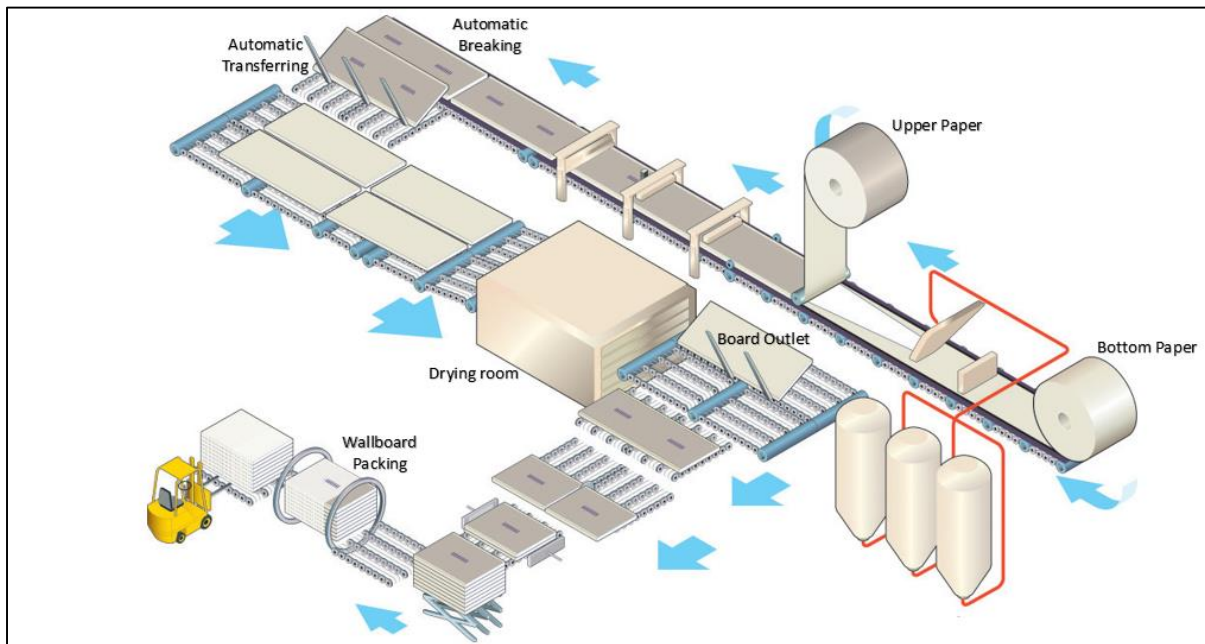


Figure 3-2: Layout view of the wallboard manufacturing process (Eurogypsum, 2015b).

3.3 The physico-chemical properties and associated hazards of gypsum wallboard waste

In August 2013, regulations for the classification and management of waste were promulgated in the Government notice number 634 of August 2013 (RSA, 2013a). With the exception of the waste listed under Annexure 1 of the regulations, it is a requirement that waste be classified in terms of the SANS 10234, the South African standard of the *Global Harmonization System of Classification and Labelling of Chemicals (GHS)*.

The classification of waste requires the compositional characteristics (metals and metalloids, inorganic anions and organics), the physical properties (appearance, odour, solubility, colour, melting point, boiling point, density) and the chemical properties (pH, flashpoint, reactivity) of the waste to be determined in order to delineate the hazards associated with the waste. The laboratory analysis criteria for waste classification, based on the GHS, is outlined in the regulations (RSA, 2013a). The principles of the GHS are focused on protecting the health of humans and the environment. This is achieved by providing a harmonized global criteria to determine the health, physical and environmental hazards associated with the waste (United Nations, 2011):

- **Physical characteristics/hazards:** Explosive, flammable gas, flammable aerosol, oxidizing gas, gas under pressure, flammable liquid, flammable solid, self-reactive substance, pyrophoric substance, self-heating substance, substance that on contact with water emits flammable gases; oxidizing substance, organic peroxide, corrosive to metals;

- **Health characteristics/hazards:** Acute toxicity, skin corrosion and skin irritation, serious eye damage and eye irritation, respiratory sensitization and skin sensitization, germ cell mutagenicity, carcinogenicity, reproductive toxicity, specific target organ toxicity – single exposure and repeated exposure, aspiration hazards; and
- **Environmental characteristics/hazards:** Hazards to the aquatic environment.

The intention of the GHS is to identify hazards and communicate them to the relevant stakeholders through a safety data sheet (SDS), so they can implement the precautionary measures to protect themselves (Lamb *et al.*, 2012). Thus, promoting well-informed decisions and best practices concerning the management of the waste whilst minimizing possible associated risks (Multi Waste, 2016).

Based on the intrinsic physical, health or environmental hazards mentioned above, waste is either classified as hazardous or non-hazardous (while the waste type for landfilling requirements are determined in terms of GNR. 635 *Norms and Standards for the Assessment of Waste for Landfill Disposal*). The GHS further provides the class (e.g. Explosive) for each of the hazards and the category (e.g. Division 1.1) to indicate the severity of the hazards and the H-codes to further indicate the specific type of hazard within a category (United Nations, 2011).

Similar to South Africa, waste classification is mandatory in most countries. Although different countries conform to different classification systems (Meiclass, 2018), most have adopted portions of the GHS onto the waste classification system adopted by their countries. For example, the USA and Canada use the Occupational Safety and Health Administration (OSHA) whereas Europe employs the Classification for Labelling and Packaging of substances and mixtures (CLP). Although the classification systems are different, both these countries have incorporated portions of the GHS to some extent (Persson *et al.*, 2017). The incorporation of the GHS has made it easier to relate classifications of similar waste streams from different parts of the world.

Internationally, gypsum wallboard has been classified as non-hazardous in the European Union (AEA, 2010:18; British Gypsum, 2019), Canada (WEG, 2015), Thailand (USG Boral, 2016), USA (American Gypsum, 2020; Certainteed, 2018; CGC Sheetrock, 2016; Pabco gypsum, 2015; United States Gypsum, 2013) and Australia (CSR Gyprock, 2019). This information is reported in the form of safety data sheets (SDS) which reports on the physico-chemical characteristics (such as composition information, pH, specific gravity, solubility, partitioning coefficient, and decomposition temperature), as well as the hazard properties of gypsum wallboard waste, as determined in terms of the *Globally Harmonised System for the Classification of Chemicals* (SANS 10234: 2008).

Since the wallboard from manufacturing processes is not subjected to physical or chemical modifications post production, this means that the classification of the gypsum wallboard waste used in this study is also non-hazardous, except when contaminated with hazardous waste. Although the South African law requires that waste be classified, the classification of gypsum wallboard waste is in line with gypsum wallboard classifications from most countries.

3.4 Regulatory framework relating to gypsum wallboard waste

Internationally, the regulatory framework is the main driver behind the recycling and reuse of gypsum wallboard waste. The waste hierarchy is used globally as a tool to divert waste from landfill. Similarly, in South Africa, the National Waste Management Strategy (NWMS) (DEA, 2011) through the National Environmental Management Waste Act (NEM:WA) (59 of 2008) aims to divert waste from landfill.

3.4.1 The South African regulatory framework

The National Environmental Management Waste Act (NEM:WA) (59 of 2008) is an important piece of legislation applicable to the management of waste in South Africa (RSA, 2008). Section 3.5.1.1. and its sub-sections provide an overview of the NEM:WA and its applicability to gypsum wallboard waste, while other applicable legislation is outlined in section 3.5.1.2.

3.4.1.1 Legislation encouraging the implementation of the waste management hierarchy: NEMWA and its regulations

The National Environment: Waste Act (NEM: WA) (59 of 2008) came into effect in July 2009. The Act regulates waste management by providing an integrated waste management framework.

3.4.1.1.1 The NEM:WA and the definition of waste

Following the promulgation of the NEM: WA (59 of 2008), numerous regulations were published in an effort to achieve the goals of the NWMS. These regulations apply to material or substances that fit the description of waste as defined in the Act:

- (a) any substance, material or object, that is unwanted, rejected, abandoned, discarded or disposed of, or that is intended or required to be discarded or disposed of, by the holder of that substance, material or object, whether or not such substance, material or object can be re-used, recycled or recovered and includes all wastes as defined in Schedule 3 to this Act; or*
- (b) any other substance, material or object that is not included in Schedule 3 that may be defined as a waste by the Minister by notice in the Gazette,*

but any waste or portion of waste, referred to in paragraphs (a) and (b), ceases to be a waste-

- (i) once an application for its re-use, recycling or recovery has been approved or, after such approval, once it is, or has been re-used, recycled or recovered;*
- (ii) where approval is not required, once a waste is, or has been re-used, recycled or recovered;*
- (iii) where the Minister has, in terms of section 74, exempted any waste or a portion of waste generated by a particular process from the definition of waste; or*
- (iv) where the Minister has, in the prescribed manner, excluded any waste stream or a portion of a waste stream from the definition of waste.*

Therefore, any substance, object or material that falls within the definition of waste must conform to the requirements of the NEM: WA and its regulations.

The NEM: WA (59 of 2008) aims to protect the health of the people and the environment by adopting the waste hierarchy (Figure 1-2) which states that waste must be avoided where possible. Otherwise, waste must be reduced, re-used, recycled or recovered. The disposal of waste should only be considered as a last resort (DEA, 2011).

3.4.1.1.2 The National Waste Management Strategy (NWMS)

The NWMS was established in 2011, to give effect to the NEM: WA (59 of 2008) by promoting the waste hierarchy. The Strategy envisions a 25% diversion of waste from landfill (Goal 1) by employing practices that move waste up the hierarchy (also refer to Figure 1-2 of this dissertation).

To realize the goal of the NWMS, gypsum wallboard waste may, for instance, be recycled and used as a soil conditioner or in the production of new wallboard.

3.4.1.1.3 The Waste Exclusion Regulations

The Regulations Regarding the Exclusion of a Waste Stream or a Portion of a Waste Stream from the Definition of Waste (GN. 715 of July 2018) (RSA, 2018), allows for the exclusion of waste streams from the definition of waste. According to these regulations, waste generators may apply to have their waste excluded from the definition of waste, and should the application be granted, the waste ceases to be waste and may be used as a raw material in other processes. Furthermore, a waste management license (WML) will no longer be required to manage this waste (if the application for exclusion from the definition of waste is approved). Instead, the waste will be managed in terms of a risk management plan. These regulations present an opportunity for gypsum wallboard waste to be diverted from landfill as wallboard manufacturers may be able to utilise their waste in their production processes and in other processes described in Section 3.6 of this dissertation.

3.4.1.1.4 The National Organic Waste Composting Strategy and the draft National Norms and Standards for Organic Waste Composting

The aim of the National Organic Waste Composting Strategy (DEA, 2013b) and the draft national norms and standards for organic waste composting (RSA, 2019) is to promote the diversion of organic waste from landfill into composting. The Strategy outlines the intended measures of government to divert organic waste from landfill whereas the draft norms and standards provide guidance on how to design and operate a composting facility as well as provide facilities that compost organic waste in excess of 10 tons a day to operate without a WML. Should gypsum wallboard waste be used as an additive in the composting of organic waste (Arnold, 2011; Dave, 1999; MTPROG, 2008; Richards, 2013; Townsend & Cochran, 2003), regulations applicable to organic waste composting apply. The organic waste composting legislation indirectly provides an opportunity for gypsum wallboard waste to be utilised in composting especially in applications that already use gypsum in their compost and are interested in replacing natural gypsum with gypsum from wallboard waste.

3.4.1.1.5 List of waste management activities and application for waste management licence

Waste management activities are listed activities in terms of the *List of waste management activities that have, or likely to have detrimental effect on the environment* regulations (GNR 921 of November 2013, as amended) (RSA, 2012a). In these regulations, recycling, recovery, treatment and disposal of waste are divided into three categories (A, B and C).

From a compliance perspective, Category A activities require a waste management licence and an authorization based on a basic assessment, whereas Category B activities require a waste management licence and authorization based on a scoping and full environmental impact assessment (EIA). Category C activities require only compliance with the applicable norms and standards.

Unless the gypsum wallboard waste is excluded from the definition of waste in terms of the *Waste Exclusion Regulations* (as explained in section 3.4.1.1.3 above) the process of reusing, recycling, recovery or treatment of gypsum wallboard waste require a waste management licence.

3.4.1.1.6 National Waste Information Regulations

Any persons recycling general waste at a facility with an operational area in excess of 500m² or recycling hazardous waste in excess of 500kg/day hazardous waste must register with the South African Waste Information System (SAWIS) or relevant provincial waste information system (RSA, 2012b). Similarly, treatment processes in excess of 10 tonnes/day general waste or in excess of 500kg/day hazardous must also register. Therefore, gypsum wallboard waste

alternatives to landfill that involve recycling or treatment of the waste must register if the activities conducted are above the threshold.

3.4.1.1.7 South Africa landfill restrictions on gypsum wallboard waste

The *Norms and Standards for the Assessment of Waste for Landfill Disposal* (RSA, 2013b) and the *Norms and Standards for Disposal of Waste to Landfill* (RSA, 2013c) define four classes of landfills (Class A, B, C and D), their acceptance criteria, and waste disposal restrictions or prohibitions imposed on certain waste streams (RSA, 2013c). Even so, there are currently no special laws, prohibitions or requirements on the disposal of gypsum wallboard waste in South African landfills. Furthermore, there is no legislation specifically enforcing the recycling and reuse of this waste, except for the 25% waste recycling goal stipulated in the NWMS.

3.4.1.2 Other legislation relating to gypsum wallboard waste

Besides the NEM:WA, there are other pieces of legislation, which may also be applicable to the alternative use of gypsum wallboard waste. Table 3-1 only attempts to summarize some of the environmental- and occupational health and safety related legislation, which may be applicable to the alternative use of gypsum wallboard waste. This is just illustrative of the legislative framework, and does not attempt to give a full account of all of the laws and regulations applicable.

Table 3-1: Environmental and occupational health and safety related legislation applicable to the alternative use of gypsum wallboard waste.

Legislation	Relevance to gypsum wallboard waste
Bill of Rights, Constitution (108 of 1996).	Section 24- The right to an environment that is not harmful to health or well-being, to have the environment protected through measures that prevent pollution and ecological degradation, promote conservation, and secure ecologically sustainable development and use of natural resources.
National Environmental Management Act (107 of 1998), as amended.	Section 24- Environmental Authorization (control of activities which may have a detrimental effect on the environment). Section 28 – Duty of care and remediation of environmental damage. Section 2- Environmental management principles.
National Water Act (36 of 1998), as amended.	Chapter 3 – Protection of water resources. Section 19 – Prevention and remedying effects of pollution. Section 20 – Control of emergency incidents. Chapter 4 – Water use.

Legislation	Relevance to gypsum wallboard waste
National Environmental Management Air Quality Act (No. 39 of 2004), as amended.	Air quality management Section 32 – Dust control. Section 34 – Noise control.
Occupational Health and Safety Act (Act 85 of 1993), as amended by Occupational Health and Safety Amendment (Act 181 of 1993).	Provides for the health and safety of persons at work and for the health and safety of persons in connection with the use of plant and machinery

3.4.2 International legislation on landfill restrictions

Enforcing regulatory frameworks has been most successful in diverting gypsum wallboard waste from landfill in international communities (Eurogypsum, 2015a; Geraldo *et al.*, 2017; Ndukwe & Yuan, 2016; Regyp, 2012). As a result of the sulphur content in gypsum wallboard waste, most countries have implemented stringent measures to minimise the risk associated with H₂S in landfills. This includes enforcing legislation that either fully prohibits gypsum wallboard waste from landfilling or bans co-disposal with biodegradable waste. Although the disposal of certain waste streams to landfill is prohibited or restricted in South Africa (in terms of GNR. 636 of August 2013, as mentioned in Section 3.5.1.1.7 of this dissertation), no such restrictions exist for the disposal of gypsum wallboard in the country. It is for this reason that a gypsum wallboard waste legislative comparison between international countries and South Africa is relevant.

3.4.2.1 International landfill restrictions on gypsum wallboard waste

The following sections provide an overview of international landfill restrictions on gypsum wallboard waste.

3.4.2.1.1 European Union

Landfilling in the EU is controlled by the EU directives 31 of 1999, and 33 of 2002 (MTPROG, 2008:8). Directive 31 requires categorizing landfills into three types i.e. Type 1 (Inert), Type 2 (Non-inert) and Type 3 (hazardous waste). Directive 33 determines which waste should be disposed of at what type of landfill and the treatment required. Based on these directives, the gypsum wallboard waste is classified as non-inert and non-dangerous waste and must therefore be disposed of in a separate cell where no organic waste is present.

Furthermore, co-disposal of gypsum wallboard waste with putrescible waste is banned in inert landfills and wastes with >10% sulphate content/load such as gypsum wallboard are to be disposed of in special cells/monocells (Jiménez-Rivero & Navarro, 2017: 121). The disposal of

waste in monocells is more expensive than recycling. Thus, this initiative was successful in driving the diversion of gypsum wallboard waste from landfill.

In Denmark, recycled gypsum is mostly used in wallboard manufacturing processes (Regyp, 2012). This was achieved through mandating the recycling of gypsum wallboard and prohibiting recovery processes such as composting.

3.4.2.1.2 North America

The Environmental Protection Agency in North America has not promulgated national legislation prohibiting gypsum wallboard waste from being disposed of in landfills. However, disposal of wallboard waste is permitted in specialised landfills. Although, some regions initiated localized bans for the disposal of wallboard from landfill.

Canada

Several cities such as the Greater Vancouver Regional District and the city of Guelph, Ontario prohibit the disposal of wallboard waste in landfill.

States in the USA

Similar to the EU, gypsum wallboard waste is classified as non-inert in the USA, according to the “Minimum functional standards for waste handling” (Beck and SCS Engineers, 2003). In addition, numerous states independently regulate the disposal of gypsum wallboard waste in landfills (Jeffrey, 2011; Ndukwe & Yuan, 2016). For example, the State of Tennessee only permits gypsum wallboard waste disposal in specialised landfills whilst the Massachusetts Department of Environmental Protection completely banned the disposal of gypsum wallboard waste in landfills back in 2010.

3.4.2.1.3 South America

Brazil

Gypsum wallboard waste is classified as recyclable according to the Brazilian regulation, Conama resolution 431/2011 (Geraldo et al., 2017:288). As a result of this classification, recycling is a legal obligation and landfill disposal is prohibited. Additionally, the regional district of central Okanagan banned the disposal of gypsum wallboard waste in landfills in 2008 and introduced a fee for accepting the waste which is then delivered to wallboard waste recyclers (Breslin, 2010).

3.4.2.1.4 The impact of enforcing landfill restrictions

The prohibition of gypsum wallboard waste in landfills has played a vital role in meeting recycling targets as it motivated for alternative options to landfill disposal. For example, as a result of the prohibition to dispose gypsum wallboard waste in landfills, the European Union achieves an 80% gypsum wallboard waste recycling rate (Eurogypsum, 2015a).

Another important factor contributing to the diversion of gypsum wallboard waste from landfill is *landfill tax*. Most countries have implemented *landfill taxes* which influenced investment in alternative measures. For example, landfill tax in the Scandinavia and Benelux countries average at R1120/tonne. The Netherlands implemented a landfill tax of R2000/tonne (Ndukwe & Yuan, 2016:314). These countries achieve the highest gypsum wallboard waste recycling rates in the world as a result of the implementation of the *landfill tax*. The implementation of *landfill tax* in Norway yielded a gypsum wallboard waste recycling rate of 70% (Ndukwe & Yuan, 2016:314).

As mentioned earlier, South Africa has no legislation restricting the disposal of gypsum wallboard waste to landfill, and as a result, the disposal of gypsum wallboard waste is still permissible in landfills. In addition, unlike international countries, there is currently no landfill tax charged in South African landfills, and landfill disposal remains a cheaper method of waste management. For example, municipal landfill gate fees range between R150 per tonne and R500 per tonne (GreenCape, 2020), which is minimal compared to the costs associated with alternative options available for diverting gypsum wallboard waste from landfill. (Townsend & Cochran, 2003:7). This presents major challenges and setbacks when considering gypsum wallboard waste landfill diversion initiatives in a country such as South Africa.

3.5 The alternative uses of gypsum wallboard waste

The use of gypsum wallboard waste is well documented in literature. According to Roskil (2014), half of the world's gypsum production is used in cement manufacturing, 38% in wallboard manufacturing and 18% in agriculture. This is also in correlation with the projected demand for gypsum in South Africa over the next 18 years. Therefore, it would seem logical that the alternative uses of gypsum wallboard waste follow the same pattern (based on demand). Other uses of gypsum wallboard include use in drying of paint, fertilizer, ceramics, concrete and waste-water treatment.

3.5.1 International examples

The sub-sections to Section 3.6.1 outlines international examples for the alternative uses of gypsum wallboard waste.

3.5.1.1 Recycled gypsum in the manufacturing of new wallboard

The recycling of gypsum wallboard waste is well established in Belgium, Finland, Sweden, the Netherlands, Denmark and the United Kingdom (Eurogypsum, 2015b). Recycling involves crushing the gypsum wallboard into powder form and separating the gypsum core from the enclosing paper sheets (Wrap, n.d). It is widely known that gypsum wallboard waste is 100% recyclable (Eurogypsum, 2015a) and yields up to 94% recycled gypsum and 6% shredded paper with minimal remnants of gypsum (Eurogypsum, 2015b). However, for the gypsum wallboard waste to be recyclable, the moisture content must be <10% because moisture content of above 10% require the wallboard to be dried for some time prior to recycling (Eurogypsum, 2015b). Also, the presence of contaminants (i.e. soil, plastic, nails, etc.) must be less than 2% (LeBlanc *et al.*, 2013).

The reversible chemical nature of recycled gypsum allows the gypsum to be processed and reused multiple times through the process of hydration and calcining (Penheiro & Camarini, 2015). Studies have shown that the physical and chemical composition of the recycled gypsum are similar to that of natural gypsum (Geraldo *et al.*, 2017; Sayonara *et al.*, 2015; Penheiro & Camarini, 2015). Geraldo *et al.*, (2017) compared the physical and chemical properties of natural gypsum. They discovered that the recycled gypsum showed a high content of calcium sulphate hemihydrate similar to that observed in natural gypsum. This suggests that the quality of recycled gypsum in some instances is better than that of natural gypsum.

Furthermore, recycled gypsum subjected to one (Ahmed *et al.*, 2011), three (Erbs *et al.*, 2018; Rossetto *et al.*, 2016) and five (Geraldo *et al.*, 2017) cycles of hydration and calcination showed increased compressive and flexural strength compared to natural gypsum. In addition, it was found that the energy consumption of recycled gypsum and natural gypsum during calcination in diesel kilns was similar (Erbs *et al.*, 2018), suggesting that the recycled and natural gypsum have similar energy requirements in addition to similar physical and chemical properties and therefore, can be used for similar purposes. Based on the physical and chemical properties of recycled gypsum, up to 25% of recycled gypsum can replace natural or synthetic gypsum as raw material in the manufacturing of new wallboard (GRI, 2003). It was also discovered that utilising recycled gypsum reduced greenhouse gas emissions by 9% when compared to natural gypsum (Jiménez-Rivero *et al.*, 2016), thus, making it an ideal raw material for minimising environmental impacts associated with greenhouse gas emissions.

3.5.1.1.1 Recycled gypsum quality guidelines

Europe has developed a quality parameter guideline which specifies the physical and chemical requirements for recycled gypsum, based on toxicological and technical parameters (Table 3-2

and Table 3-3) (Eurogypsum, 2015b; Jiménez -Rivero & Navarro, 2017). This is driven by the fact that recycled gypsum must meet similar specifications to natural gypsum to qualify in the manufacturing of new gypsum wallboard. South Africa does not possess such a guideline at present, however, since the gypsum wallboard manufacturing companies in South Africa have a global footprint, this guide is useful as a tool for South African gypsum wallboard waste recyclers and wallboard manufacturers by providing an understanding of the level of standard expected for the quality of recycled gypsum expected in the manufacturing of new wallboard.

Table 3-2: Recycled gypsum quality parameters in manufacturing processes (adapted from Jiménez-Rivero & García-Navarro, 2017:3).

Parameter	Unit	Reference standards	Gypsum to Gypsum (GtoG) guidelines on gypsum recycling standards
Maximum size	Mm	EN 933-1	15
Free moisture	% w/w	VGB-M-701	<10
Purity	% w/w	VGB-M-701	>80
Total Organic Carbon	% w/w	EN 933-1	<1.5
Magnesium Salts	% w/w	VGB-M-701	<0.1
Sodium salts	% w/w	VGB-M-701	<0.06
Potassium salts	% w/w	VGB-M-701	<0.05
Soluble chlorides	% w/w	VGB-M-701	<0.05
pH	% w/w	VGB-M-701	6-9

Table 3-3: Recycled gypsum metal endpoint in the EU (adapted from Jiménez-Rivero & García-Navarro, 2017:4).

Parameter	Unit	Gypsum to Gypsum (GtoG) guidelines on gypsum recycling standards
Arsenic (As)	mg/kg	<4
Beryllium (Be)	mg/kg	<0.7
Lead (Pb)	mg/kg	<22.0
Cadmium (Cd)	mg/kg	<0.5
Chromium (Cr)	mg/kg	<25.0
Cobalt (Co)	mg/kg	<0.4
Copper (Cu)	mg/kg	<14.0

Parameter	Unit	Gypsum to Gypsum (GtoG) guidelines on gypsum recycling standards
Manganese (Mn)	mg/kg	<200.0
Nickel (Ni)	mg/kg	<13.0
Mercury (Hg)	mg/kg	<1.3
Selenium (Se)	mg/kg	<16.0
Tellurium (Te)	mg/kg	<0.3
Titanium (Ti)	mg/kg	<0.4
Vanadium (V)	mg/kg	<26.0
Zinc (Zn)	mg/kg	<50.0
Asbestos	Yes/No	No
Radioactivity Index (RI)	<0.5	<0.5

3.5.1.2 Recycled gypsum in the manufacturing of Portland cement

Portland cement is manufactured through blending 95% clinker and 5% gypsum during the clinker cooling process (Abdul-Wahab *et al.*, 2018:246). Up to 10% recycled gypsum can be added to the manufacturing of Portland cement (Islam *et al.*, 2017). Gypsum in cement manufacturing is used as a retarder to reduce the setting time of cement in concrete mixtures. Recycled gypsum from gypsum wallboard waste can replace natural gypsum in the manufacturing of cement. The gypsum may be added as recycled gypsum or the wallboard waste can be added in its original form (Medina *et al.*, 2016: 984). The compressive and flexural strengths of recycled gypsum from gypsum wallboard waste in cement production are similar to those of natural gypsum (Medina *et al.*, 2016). Similar observations were made by (Abdul-Wahab *et al.*, 2018) who also noted in addition, a homogenous mixture with low porosity and slow setting times in recycled gypsum blends. The above mentioned characteristics are fundamental in the production of cement of acceptable quality.

3.5.1.3 Recycled gypsum in concrete

Up to ten percent (10%) recycled gypsum can be used to replace cement in concrete processes without altering the properties of the concrete (Naik *et al.*, 2010). Hansen & Sadeghian (2019) used recycled gypsum from wallboard waste to partially replace cement in varying proportions of mortar mixtures of fly ash, cement, aggregates and water. They discovered that mixtures containing more than 10% recycled gypsum yielded lower compressive strengths. Low compressive strengths were also observed by Drake *et al.*, (2019) who also noted the formation of ettringite (calcium sulfoaluminate hydrate) when the gypsum content was above 10%. The

presence of ettringite causes the concrete blocks to crack, thereby lowering the compressive strength of the concrete material (Naik *et al.*, 2010). Although gypsum from wallboard waste can be incorporated in concrete, the presence of sulphur impacts on the quality of the final concrete as increased concentrations of sulphur lead to expansion and cracking of the final concrete product (LeBlanc *et al.*, 2013:75), thus, limiting the quantities of recycled gypsum permissible in the process. Also, gypsum concentrations above 15% produce H₂S emissions in concrete which contribute to the concrete's greenhouse emissions (Ahmed *et al.*, 2015).

3.5.1.4 Gypsum wallboard waste in agriculture

Gypsum contains calcium and sulphur, two of the essential nutrients required by plants and soils. Gypsum is also soluble in soil, a property that allows it to percolate a farther distance into the soil depth. In addition, the soil effect and chemistry of gypsum from the wallboard waste are similar to that of natural gypsum used in agriculture (Naeth & Wilkinson, 2013:503). Therefore, there is no reason as to why gypsum wallboard waste cannot be used in agriculture. Unlike gypsum wallboard manufacturing processes which only use uncontaminated recycled gypsum, agricultural practices can utilise both the paper and gypsum fraction of the wallboard in their processes.

3.5.1.4.1 Gypsum wallboard waste as a fertilizer

Gypsum as a fertilizer is used as a soil conditioner to provide calcium and sulphur to plants. A study by Scott *et al.*, (1993) observed an increase in the calcium content of watermelons when gypsum was applied, indicating that gypsum contributes to the calcium content of plants. Norton (2009) (cited by Codlin, 2011) also showed that gypsum from flue-gas desulphurization processes improved the calcium and sulphur content of plants and neutralised sodic soils. In another study, pulverised gypsum wallboard waste increased corn and sunflower yields by 25% and 27% respectively when applied to corn and sunflower fields (Bernard, 2013). Wolkowski (1998) also observed that gypsum wallboard waste increased the calcium and sulphur contents at rates similar to those of agricultural gypsum when used on Wisconsin potatoes and corn. Wolkowski (2000) also studied the impact of crushed gypsum wallboard waste applied to Alfafa at varying rates, and reported increased calcium and sulphur contents. However, a decrease in pH and magnesium were observed in areas where the gypsum wallboard waste was applied in high rates, implying that the presence of wallboard impacts on soil pH.

Codlin (2011) studied the effect of gypsum wallboard waste on corn and soybean root growth. It was discovered that the wallboard waste increased corn root growth but no change was observed in the soybean roots. This suggests that wallboard waste as a fertilizer is beneficial to certain types of plants and its compatibility should be studied and well understood prior to application.

Gypsum wallboard waste as a fertilizer may be produced through composting or it can be applied to plants as is (Naeth & Wilkinson, 2013). The final product must meet the criteria stipulated in the South African fertilizer regulations (RSA, 2012) as shown in Table 3-4.

Table 3-4: Specifications required for a fertilizer in South Africa (adapted from RSA, 2012).

Criteria	Acceptable range
Cadmium (Cd)	<20mg/kg
Chromium (Cr)	<1750mg/kg
Copper (Cu)	<750mg/kg
Mercury (Hg)	<10mg/kg
Nickel (Ni)	<200mg/kg
Lead (Pb)	<200mg/kg
Zinc (Zn)	<2750mg/kg
Arsenic (As)	<20mg/kg
Selenium (Se)	<15mg/kg
Boron (B)	<80mg/kg
Particle Size	100% < 12 mm standard sieve
Ash content	< 670g/kg (dry matter basis)
Moisture content	< 400g/kg
Infectious/Pathological/Microbial agents	0 viable Ascaris ova / 10g dry sludge
	0 Salmonella organisms / 10g dry sludge
	Helmith ova <1 ova / 4g
	Max. 1000 Faecal coliforms/ 10g sludge immediately after disinfection/sterilisation
N	<100g/kg
P	
K	
Sum NPK	
Prescribed plant nutrients	
Calcium	>40g/kg
Sulphur	
Magnesium	
Iron	
Manganese	
Zinc	
Molybdenum	
Boron	

3.5.1.4.2 Gypsum wallboard waste in composting

The intention of compost is to provide nutrients to the soil. Gypsum wallboard waste is used as an additive in compost, as a soil amendment which is applied in various applications including for example; golf courses, home gardening, city parks, horticulture and recreational facilities (Bernard, 2013: 23).

Gypsum as a soil amendment is used to reclaim sodic soils, decrease the bulk density of soil, increase water drainage, flocculate fine particles in soils to improve air and water infiltration, and to reduce swelling and cracking in soils (Bernard, 2013; Gharaibeh *et al.*, 2014; Weggel *et al.*, 2010:14). In addition, gypsum also provides aeration in the compost heap whilst preserving the structure, increasing heat, balancing carbon: nitrogen ratio and increasing heap porosity (Batham *et al.*, 2013).

In addition to the soil amendment properties of gypsum, gypsum wallboard waste acts as a bulking agent in composting, supplying calcium and sulphur as micronutrients while the paper fraction adds carbon and absorbs the water content (Marvin, 2000). During composting, the paper fraction will biodegrade with the rest of the organic matter (Townsend & Cochran, 2003). The gypsum does not biodegrade but with regular turning of the compost heap, it breaks down and is mixed into the final compost. This process produces a compost-rich mixture of calcium and sulphur. The calcium and sulphur content of the final compost increases in proportion to the wallboard waste added in the mixture (Saludes *et al.*, 2008). However, white visible gypsum powder is observed in the final mix (Dave, 1999). This is expected because gypsum is inorganic and does not biodegrade but will physically break into small pieces instead.

Composting of gypsum wallboard waste with organic material such as food waste, wood chips, leaves and grass does not impact the length of time required for the compost to be ready (Arnold, 2011; Dave, 1999; MTPROG, 2008; Townsend & Cochran, 2003). Up to 34% of gypsum wallboard waste can be incorporated in composting without affecting the Carbon, pH and EC of the compost (Richards, 2013).

Gypsum wallboard waste also has the capability to regulate odours in compost by preventing ammonia volatilization through the attachment of the sulphate ions in the gypsum to the ammonium in the compost heap (Tubail *et al.*, 2008). Also, the presence of wallboard does not increase the bioavailability of heavy metals in compost (Richards, 2013), an important aspect in preventing leaching of heavy metals.

The composting process in general is a natural sterilization process as it is able to destroy pathogens in the compost. Rynk *et al.*, (1992) reported that temperatures of above 55°C for three days are sufficient for the destruction of pathogens in the compost. However, the presence of

gypsum is as effective in reducing the concentration of pathogens such as *E.coli* and *Salmonella* in soils (Ho *et al.*, 1991; Jenkins *et al.*, 2014; O'Brien, 2017). This is achieved through gypsum's ability to improve air and water infiltration in soils. Ho *et al.*, (1991) found that treating red mud with 5% gypsum drastically reduced *E.coli* from the soil profiles due to gypsum's ability to agitate the soil. In a similar study by Jenkins *et al.*, (2014), *E.coli* from poultry litter was applied to plots treated with FGD gypsum at varying proportions over three years. The area with the highest gypsum application showed the highest decrease in the total loads of *E.coli*. In another study, O'Brien (2017) showed the ability of gypsum to bind with phosphorus in soil which reduced the availability of phosphorus as a nutrient to pathogens and eventually led to the mortality of the microorganisms as a result of nutrient deficiency.

In as much as composting has proven positive benefits, the process must meet certain composting criteria to successfully decompose material while maintaining the required aerobic properties required during the process. The most widely used criteria was developed by Rynk *et al.*, (1992) and is indicated in Table 3-5.

Table 3-5: Criteria for composting (adapted from Onwosi *et al.*, 2017; Rynk, *et al.*, 1992).

Criteria	Acceptable range	Preferred range
Carbon: Nitrogen ratio	20 to 40:1	30:1
Moisture Content	40-65%	50-60%
pH	5.5-9.0	6.5-8.0
Temperature (°C)	45-65	50-60
Oxygen	>5%	>5%
Electrical conductivity (ds/m)	2-4	2-4

In addition to the above criteria, the European Union, Canada and United States of America have developed specific criteria depicting the limits of heavy metals acceptable in final compost for it to be usable (Table 3-6). This criteria was influenced by the problems arising due to mercury and cadmium concentrations in compost. In contrast, the South African legislation does not have a guideline specifically for compost but provides a guideline for a fertilizer used for natural purposes. Thus the international heavy metal criteria developed specifically for compost is useful as a comparison to gauge the concentrations of heavy metals in compost produced in South African.

Table 3-6: Limit of heavy metal concentrations in compost as applied in different regions/ countries (adapted from Brinton, 2000; CCME, 2005).

Heavy metals (mg/kg)	EU	Canada	USA
As	N/a	13-75	N/a
Cd	0.7-10	3-20	39
Cr	70-200	210-1060	1200
Co	N/a	34-150	N/a
Cu	70-600	400-760	1500
Hg	0.7-10	0.5-5	17
Mo	n/a	5-20	n/a
Ni	20-200	62-180	420
Pb	70-1000	150-500	300
Se	n/a	2-14	n/a
Zn	210-4000	700-1850	2800

3.5.1.4.3 Gypsum wallboard waste in animal bedding

The paper from the wallboard waste is crushed and used as a replacement for wood shavings in animal bedding (Breslin, 2010). Gypsum wallboard waste is also beneficial in regulating moisture levels in animal bedding due to its ability to absorb moisture (Beck & SCS engineers, 2010; Ndukwe & Yuan, 2016).

3.5.1.5 Gypsum wallboard waste in waste-water treatment

Mihara *et al.*, (2008) successfully extracted calcium sulphide from gypsum wallboard waste for use in the treatment of waste-water contaminated with high levels of nickel. The treated water showed a reduction in the nickel concentration. The study is similar to the one conducted by (Mulopo & Radebe, 2012; Mulopo, 2015) in South Africa except they utilised waste gypsum from coal mines (FGD gypsum). Of significance to this study, the findings by Mihara *et al.*, (2008) show the ability of wallboard waste to treat water contaminated with heavy metals, and presents an opportunity for similar studies to be conducted in the South African.

3.5.2 African examples

Gypsum wallboard waste was used in the manufacturing of paint to test its effect on the drying rate of paint in Nigeria (Stanley, 2013). The results of the paint treated with gypsum wallboard waste were compared to those of normal paint without gypsum wallboard waste. It was revealed

that the pH, viscosity, opacity and water immiscibility of the two types of paints were similar. However, the drying time of the paint with gypsum wallboard waste was quicker than that of the normal paint. A quicker drying time of paint is desirable for most consumers as it covers larger areas and minimises dripping during painting (Stanley, 2013). Furthermore, recycled gypsum from wallboard can be used as an extender to increase the bulk of the paint, improve the application of the paint or improve the adhesive properties of the paint (Interiordezine, 2020).

In another study by Abidoye (2010), gypsum wallboard waste from construction and manufacturing sites was recycled to produce a powder plaster similar to that used in the manufacturing of new wallboard. The wallboard was milled into powder and then subjected to five different stages of calcination. The results showed an increase in compressive strength and a change in colour from brown to white with increasing temperatures. In addition, the compressive strength was retained throughout the calcination stages. The improvement in colour and constant compressive strength suggest that the recycled gypsum powder is suitable as a raw material in the manufacturing of new wallboard.

A similar study was conducted in Ethiopia by Ayele (2015) but the waste was sourced from the ceramic industry although the chemical properties are similar to those of gypsum wallboard waste. The plaster waste was milled and converted into powder. The recycled powder also showed increased compressive strength with temperature. An elevated increase in compressive strength was achieved when the recycled powder was blended with 40% raw gypsum, suggesting that blending raw and recycled gypsum improves the compressive strength of the final product. The study also proved that the recycled gypsum from the ceramic industry may be recycled into the manufacturing of new ceramics.

3.5.3 South African examples

In South Africa, gypsum research has mainly focused on extracting compounds and elements from waste gypsum for further use. The gypsum waste used was mainly sourced from the mining and fertilizer industry and not from wallboard waste. However, the variations between the chemical compositions of the gypsum from mining, fertilizer and wallboard waste are minimal (Degirmenci, 2008:1221; Strydom *et al.*, 1997:1503). Thus, one can expect that gypsum wallboard waste will yield similar results.

Van der Merwe & Strydom (2004) investigated the potential for phosphogypsum to be used as a retarder in cement production. They found that the chemical properties of the gypsum qualify it to be used as a retarder pending the prior removal of impurities. In a different study, waste gypsum from coal mines was used to produce calcium sulphide and calcium carbonate which were successfully used to treat acid mine drainage contaminated with heavy metals, by neutralizing

the acid (Mulopo & Radebe, 2012; Mulopo, 2015). Based on international studies, Mihara *et al.*, (2008) showed that waste-water contaminated with heavy metals can be treated using gypsum wallboard waste. Thus, an opportunity exists in South Africa.

Other gypsum studies focused on extracting elemental sulphur from gypsum waste from acid neutralization plants and phosphogypsum, which can be used as a raw material in processes generating phosphate fertilizers and sulphuric acid (De Beer, 2014; De Beer *et al.*, 2014; Nengovhela, 2009).

Gypsum wallboard is classified as a construction and demolition waste in South Africa (Macozoma, 2006). Although several studies have investigated the reuse and recycling potential of C&D waste, the focus has been on concrete and masonry units and has excluded gypsum wallboard waste (Bester *et al.*, 2017; Macozoma, 2006; Zedda *et al.*, 2014).

3.6 The challenges and opportunities associated with the alternatives to the disposal of gypsum wallboard waste

The sub-sections of Section 3.7 outline the challenges and opportunities associated with the alternative use for gypsum wallboard waste.

3.6.1 Factors influencing alternative uses of gypsum wallboard waste

The success of utilising gypsum wallboard waste in other applications other than landfill disposal is dependent on various factors that encourage or discourage recycling and reuse of gypsum wallboard waste. Jimenez-Rivero & Navarro (2017a) studied the various motivating factors that influence the use of gypsum wallboard waste in alternative processes. The study found a need for:

- A regulatory framework to ban gypsum wallboard from landfill disposal,
- Landfill taxes and levies,
- Increased landfill gate fees,
- Lower recycling gate fees when compared to landfill gate fees,
- Awareness on the impacts of recycling and landfilling of gypsum wallboard waste,
- Educating and awareness on the use of recycled gypsum or wallboard waste in the various applications, and
- Collaboration of stakeholders through organizations to influence wallboard recycling.

These factors are important for encouraging diverting gypsum wallboard waste from landfill in a country such as South African where only 10 of waste is re-used, recycled or recovered and 90%

of waste is still destined for landfills (DEA, 2012), and people are not motivated to utilise recycled products or waste due to the negative perceptions associated with waste. Also, Jeffrey (2011), Townsend & Cochran (2003) and Ndukwe & Yuan (2016) emphasize that the feasibility of recycling is dependent on the demand for the recycled gypsum as well as available market opportunities. Thus the focus should not only be on recycling and reuse of gypsum wallboard waste, but also on the availability of end-markets interested in utilising products produced from this material.

Furthermore, the factors discussed in should also be considered when selecting a suitable alternative to landfill, especially in a developing country such as South Africa. Thus, it is important that the alternative to landfill disposal solution:

- Promotes the waste management hierarchy, as outlined in the National Waste Management Strategy,
- Is less harmful to the environment and people than disposal thereof; and use less natural resources than disposal (based on the requirements of Section 17 of the National Environmental Management Waste Act, 59 of 2008),
- Is in line with the principles of Section 2 of the National Environmental Management Act (107 of 1998) promoting the “best practicable environmental option (BPEO)”, “pollution prevention”, a “duty of care”, etc.,
- Is feasible/viable within the South African regulatory context? (I.e. legislation, regulations and industry standards),
- Is feasible/viable within the South African socio-economic context (i.e. cost of the alternative, potential for job creation),
- Is practically feasible, considering the available infrastructure and technology available in South Africa.

3.6.2 Recycled gypsum in the manufacturing of new wallboard: Challenges and opportunities

Section 3.7.2 provides an overview of the challenges and opportunities related to the recycling of gypsum wallboard waste to produce new gypsum wallboard products.

3.6.2.1 Opportunities

Recycling and reusing of gypsum wallboard waste = reduces the dependency on natural gypsum material and preserve the landfill airspace because the gypsum wallboard waste, which is bulky and occupies large spaces in landfills, would have been diverted from the landfill (Marvin, 2000:3). It also provides gypsum wallboard manufacturers with an opportunity to acquire raw material at a cheaper rate compared to natural gypsum as recycled gypsum is sold at a lower cost compared to the natural gypsum (NWGR, 2020). In addition, a shift from natural gypsum will preserve natural resources, and reduce the cost of energy and transport as natural gypsum is mined from isolated quarries or imported from other countries (Ndukwe & Yuan, 2016).

Furthermore, through diverting gypsum wallboard waste from landfill, wallboard manufacturers can achieve their company specific environmental targets as well as receive awards for promoting the waste hierarchy. For example, the green building standards “Leadership in Energy and Environmental Design (LEED)” awards credits/points to gypsum wallboard manufacturing companies for recycling the gypsum wallboard waste their generate (Saint Gobain Gyproc, 2017).

3.6.2.2 Challenges

The challenges in the initial stages of recycling gypsum wallboard waste into new wallboard are related to the separation of paper and gypsum (Section 3.6.2.2.1), and the quality of recycled gypsum required to meet the technical specifications (Section 3.6.2.2.2).

3.6.2.2.1 Separation of paper and gypsum

Naturally, gypsum hardens and transforms into a cement like form (Carlson & Kozicki, n.d). This property causes the gypsum to ‘stick’ to the equipment making it difficult to remove. This also leads to the build-up of gypsum onto the equipment and if left untreated, this can cause damages to the equipment. Also, there is increased down-time due to increased maintenance required, which increases the operational costs. This can be prevented by constantly cleaning and removing the build-up. In addition, the hardening of gypsum causes clumping during storage which requires pre –processing before use.

3.6.2.2.2 Quality of recycled gypsum

The complete removal of the paper during gypsum wallboard recycling is of crucial as the presence of the paper impacts directly on the quality of the final product during the manufacturing of new wallboard. With that said, the final quality specifications are highly dependent on the requirements of the manufacturer of the wallboard (Eurogypsum, 2015b). Thus, the quality and specifications of the recycled gypsum is usually decided between the recycler and the end-user.

The properties used to determine quality include free moisture; particle size; TOC- Total organic carbon (residual paper and fibre content); pH, pure gypsum content, silicon content and soluble salts (Eurogypsum, 2015b). The recycled gypsum must meet the criteria indicated in (Table 3-2 and Table 3-3). Variations in quality between the recycled gypsum and the main gypsum raw material affects the production process and process conditions such as water demand, slurry dosage; manufacturing costs; setting time and raw material feeding processes (Eurogypsum, 2015b). The variations require the manufacturing process to constantly adjust the process flow to accommodate the changes in quality which can lead to poor plant performance and damage to the equipment. It is for this reason the quality of the recycled gypsum must be similar to those of natural gypsum being used in the production process.

As a result of the quality requirements, each load of recycled gypsum must be tested before incorporating into the process (Breslin, 2010). This is a lengthy process that incurs cost implications for the person responsible for the recycling of the gypsum (i.e. recycling company or manufacturers). Also, the supply of recycled gypsum must be consistent and the volumes supplied must be constant. This is because the source, type and properties of the gypsum determines the technical properties required in the production process.

3.6.3 Composting: Challenges and opportunities

The challenges and opportunities related to composting as an alternative to landfill disposal are outlined in the sub-sections to Section 3.7.3 of this dissertation.

3.6.3.1 Opportunities

In addition to diverting the gypsum wallboard waste, composting presents a waste management opportunity for managing both the paper fraction and the gypsum waste from the gypsum wallboard (Richards, 2013). This eradicates a waste stream that would have otherwise been disposed at a landfill. Also, composting presents an opportunity to shift compost end-users away from utilising chemical soil enhancers, which minimises the negative environmental impacts associated with chemicals added to soil (Ayilara et al., 2020). In addition, composting provides an opportunity for job creation to starting-up and ramping-up composting facilities. In terms of job creation, end-users who purchase the finished compost indirectly contribute to job security for the businesses that produce and sell the finished compost (Institute for Local Self-reliance, 2014).

3.6.3.2 Challenges

The challenges related to composting gypsum wallboard waste are outlined in sub-sections 3.6.3.2.1 to 3.6.3.2.6.

3.6.3.2.1 Composting process

The challenges experienced in wallboard waste composting are related to the general composting operational procedures (Table 3-7). Composters must ensure the process is carried out within the required parameters as indicated in Table 3-5 to avoid the challenges mentioned in Table 3-7, as these parameters control the entire process and outcome as described by Cerda *et al.* (2018) and Onwosi *et al.* (2017).

Table 3-7: Factors that present challenges during composting (Cerda *et al.*, 2018; Onwosi *et al.*, 2017).

Parameter	Description
Carbon/ Nitrogen (C/N) ratio	Provides carbon and nitrogen source required by micro-organisms during composting. N is required for building cell structure and C is as an energy source. Reduced nitrogen contents causes a reduction in C consumption whereas excess N generates ammonia odours. A high C/N indicates a nutrient micro-organism nutrient deficiency whereas a low C/N relates to increased odour generation.
Moisture content	Moisture content measures water available in composts and assists in supplying soluble nutrients to microorganism. It also controls the temperature, microbial activity, rate of oxygen uptake and microbial activity of the heap. Higher moisture contents decrease the rate of gas diffusion which reduces the rate of oxygen uptake and eventually the microbial activity causing the heap to be anaerobic.
Electrical conductivity	EC is an indication of the amount of salt in the compost. High salt contents impact on the growth of plants. High EC soils can be blended with low EC material to 'dilute' the EC.
Aeration	Supplies oxygen to the compost heap. Lower frequencies of turning the compost heap results in reduced microbial activities whereas increased frequencies may cause high evaporation rates causing anaerobic conditions.
pH	Micro-organisms are able to decompose organic matter with a pH of between 5.5-9. A pH outside this range will impact on the microbial activity resulting in anaerobic conditions.
Particle size	The particle size of material used in composting should not be too large or too small. If they are too large, decomposition will take long and if they are too small, compaction and loss of aeration occurs.

The regular monitoring of temperature, moisture and oxygen is required for a successful composting process and to prevent the compost heap from turning anaerobic (Marvin, 2000). In addition, the finished compost should always be assessed for maturity prior to application. The

monitoring and assessment of compost is associated with cost implications as these parameters can only be analysed at a laboratory (with the exception of temperature).

Furthermore, capability of gypsum wallboard waste to absorb moisture may be problematic in instances where the wallboard waste added has a high moisture content. In this instance, the wallboard contributes to the moisture content of the compost heap instead of absorbing it (Marvin, 2000). Thus, the gypsum wallboard waste needs to be relatively drier than the material used in the compost before composting.

3.6.3.2.2 Leachate generation

The composting of gypsum wallboard waste and organic waste generates leachate high in organic load (Trujillo *et al.*, 2006). The leachate may also contain heavy metals and salts (Maleki *et al.*, 2009). Depending on the composition of the gypsum used in the manufacturing of the wallboard, the addition of the wallboard waste may contribute elevated heavy metals and salt content of the compost. The composition of the leachate renders it unsafe for discharge to the environment due to potential contamination of drinking water (Navarro *et al.*, 2018). Thus, composting facilities should install leachate system to properly monitor and manage the leachate generated from the process.

3.6.3.2.3 Emission of odours

The composting process alone, if not managed properly results in the release of emission of gases such as methane, nitrous oxide and ammonia (Jiang *et al.*, 2015). In addition, the decomposition of gypsum wallboard waste in the presence of organic waste results in hydrogen sulphide emissions which are harmful to the environment and cause offensive odours. Thus, it is imperative that composting facilities are managed appropriately and monitored regularly for air quality emissions.

3.6.3.2.4 Lack of awareness

Composting can reduce the costs of soil enhancers, minimises the dependencies on chemical enhancers, conserve natural resources and benefits plant production (Drechsel & Kunze, 2001). Even so, most farmers prefer the use of chemical enhancers and are reluctant to engage in composting activities because of the presence of pathogens in the final compost, longer periods involved in composting and low possible nutrient content of the final compost. (Ayilara *et al.*, 2020). This suggests a lack of education and awareness on the use of composting as an alternative because compost in the long run presents more benefits than chemical enhancers (Han *et al.*, 2016),

3.6.3.2.5 Lack of support from government

The lack of composting regulations, the lack of regulations to ban gypsum wallboard waste from landfill disposal, the lack of landfill taxes and levies, increased landfill gate fees, and lower recycling gate fees compared to landfill gate fees, have been identified as challenges hindering the composting of waste such as gypsum wallboard waste (Ayilara *et al.*, 2020; Jimenez -Rivero & Navarro, 2017a). At the time of writing this dissertation, South Africa was in the process of finalising the *norms and standards* for composting which would permit composting facilities treating less than 10 tonnes/day of organic waste to do so without requiring a waste license. These norms and standards will provide composting opportunities including the composting of organic waste with gypsum wallboard waste (for facilities that already utilise gypsum in their composting processes).

3.6.3.2.6 Other challenges

As a result of the composting processes occurring over long periods of time, there is a need for adequate spaces required to conduct the composting of the waste and the need for adequate space to process and store the raw material and finished product (Onwosi *et al.*, 2017).

3.6.4 Fertilizer Production: challenges and opportunities

The challenges associated with producing a fertilizer from a mixture of gypsum wallboard waste and organic material are related to the composting process and the associated challenges mentioned above (Section 3.6.3.1). Meeting the specifications required for a fertilizer as shown in Table 3-4 is dependent on the ability to meet and maintain the parameters or criteria required for a composting process as indicated in Table 3-5. This means that a successful composting process can potentially produce a quality fertilizer and vice versa.

On the other hand, the production of fertilizer from gypsum wallboard waste and organic waste compost offers various environmental **benefits** over chemical fertilizers as chemical fertilizer add to greenhouse emissions, kill soil organisms and cause diseases in humans (Ayilara *et al.*, 2020). Furthermore, gypsum wallboard waste and organic waste fertilizer is cheaper than chemical fertilizer (More, 2019). Gypsum from wallboard waste used as a fertilizer provides a source of calcium and sulphur and increases crop yield. The slow solubility of gypsum in soil provides a release of sulphur for over a year after application (Chen & Dick, 2011). The benefits of gypsum as fertilizer were observed in corn, watermelon, soybean, canola and alfalfa (Codlin, 2011; Chen & Dirk, 2011:8; Scott *et al.*, 1993, Wolkowski, 1998; Wolkowski, 2000).

3.7 Chapter summary

The literature review revealed the classification of the gypsum wallboard waste on an international scale. It also showed the extent to which gypsum wallboard waste is recycled or reused internationally and the regulatory measure facilitating these processes. The challenges and opportunities associated with the reuse or recycling of gypsum wallboard waste were discussed from an operational point of view. Gaps were identified in that South Africa does not have the guidelines or endpoints for assessing the quality of recycled gypsum from wallboard waste for incorporation into the manufacturing of new wallboard, and also lacks the limits for the heavy metal concentrations acceptable in compost. Thus international guidelines will be used for comparison.

Chapter 4 discusses the results of this study, as it relates to the three research objectives.

CHAPTER 4 RESULTS AND DISCUSSION

4.1 Introduction

The research explored alternatives to landfill disposal for gypsum wallboard waste. The results of the study are based on secondary data on the characteristics (properties) of gypsum wallboard waste and literature review, as well as primary data from field experiments on selected alternatives, and semi-structured interviews (as explained in Figure 2-2). This chapter serves to report and discuss the results obtained for each of the research objectives:

- *Research objective 1: Evaluating the physico-chemical properties of gypsum wallboard waste;*
- *Research objective 2: Identifying the alternatives to the disposal of gypsum wallboard waste;*
- *Research objective 3: Investigating the opportunities and challenges associated with gypsum wallboard waste in composting and fertilizer production and, investigating the views of gypsum wallboard manufacturers in the use of recycled gypsum from gypsum wallboard waste.*

The data from secondary sources, literature review and field experiments were analysed in the form of tables, and graphs, and the data from interviews were analysed through the use of thematic analysis.

4.2 Results related to research objective 1: Evaluating the properties of gypsum wallboard waste

The physical and chemical properties and hazards of the gypsum wallboard waste were obtained from secondary data sources as explained in Section 2.3.1 of this dissertation.

4.2.1 Classification of gypsum wallboard waste in accordance with SANS 10234

Based on SANS 10234 safety data sheets (SDSs), gypsum wallboard waste was classified as non-hazardous (**Appendix D: Safety Data Sheet**), indicating that the gypsum wallboard waste will not pose any physical, health or environmental hazards when used in alternative applications. The classification of the gypsum wallboard waste is similar to that of the gypsum wallboard produced in the European Union (AEA, 2010:18; British gypsum, 2019), Canada (WEG, 2015), Thailand (USG Boral, 2016), USA (American Gypsum, 2020; Certainteed, 2018; CGC Sheettrock, 2016; United States Gypsum, 2013) and Australia (CSR Gyprock, 2019). This suggests that the gypsum wallboard waste is suitable for similar reuse applications as those currently practiced internationally (see section 3.5 for alternative uses).

In addition, the compositional and physico-chemical properties and hazard categories of the gypsum wallboard waste determine whether the composition and properties of gypsum wallboard

waste would be suitable to allow for potential alternative uses, other than landfilling. These results are reported in the following sections.

4.2.2 Compositional characteristics

As mentioned in section 2.3.1, the compositional characteristics (heavy metals, total and leachable concentrations, inorganic anions) of the gypsum wallboard waste were obtained from a secondary data source (Interwaste, 2019). The compositional parameters were analysed for total concentrations (TC) and leachable concentrations (LC) for comparison to the TCT and LCT values for landfill disposal, stipulated in the National Norms and Standards for the Assessment of Waste for Landfill Disposal (RSA, 2013b). The total concentrations were analysed using a portable X-ray Fluorescence and the leachable concentrations were obtained through toxicity characteristics leaching procedure (TCLP) using methods stipulated in the Australian standards AS 4439.1 and AS 4439.3.

4.2.2.1 Heavy metals

The results indicated that the total and leachable concentrations of the heavy metals in the gypsum wallboard waste were very low when compared to the thresholds (total and leachable concentration thresholds) stipulated in the Norms and Standards for the Assessment of Waste for Landfill Disposal (RSA, 2013b) (Table 4-1), suggesting that the gypsum wallboard waste would not present any harm associated with the presence of heavy metals when used in alternative applications..

Table 4-1: Heavy metal analysis of gypsum wallboard waste (Interwaste, 2019).

Metals	Actual Total concentrations (TC) (mg/kg)	Actual Leachable concentrations (LC) (mg/kg)	Total Concentration Threshold (TCT0) (mg/kg)	Leachable Concentration Threshold (LCT0) (mg/kg)
As	BDL	BDL	5.8	0.01
B	UTD	0.455	150	0.5
Ba	BDL	0.01	62.5	0.7
Cd	BDL	BDL	7.5	0.003
Cr	BDL	BDL	46 000	0.5
Co	BDL	BDL	50	0.1
Cu	BDL	0.341	16	2
Hg	BDL	BDL	0.93	0.006
Mn	BDL	0.453	1000	0.5

Metals	Actual Total concentrations (TC) (mg/kg)	Actual Leachable concentrations (LC) (mg/kg)	Total Concentration Threshold (TCT0) (mg/kg)	Leachable Concentration Threshold (LCT0) (mg/kg)
Mo	BDL	BDL	40	0.07
Ni	BDL	BDL	91	0.07
Pb	BDL	BDL	20	0.01
Sb	BDL	BDL	10	0.02
Se	BDL	BDL	10	0.01
V	46.21	BDL	150	0.2
Zn	BDL	BDL	240	5

UTD: Unable to determine

4.2.2.2 Inorganic anions

The sulphate total concentration was reported at 790 mg/kg or 0.079% (Table 4-2). Therefore, the presence of sulphate ions in the gypsum wallboard waste are an indicator of the concentration of sulphate ions added to the alternative use when gypsum wallboard waste is applied in alternative uses. Based on the total concentration threshold (TCT) values for landfill disposal, there is no threshold limit stipulated for the total concentration of sulphate ions, thus, during composting, gypsum dissolves in soil in the presence of moisture and increases the concentrations of SO_4^{2-} in the soil (Moustafa *et al.*, 2010). Sulphate ions are crucial in compost because of their ability to influence the soil's ability to preserve the essential nutrients through cation exchange, thus, preventing leaching of essential nutrients (Efretuei, 2016).

Unlike composting, the use of recycled gypsum in concrete and cement manufacturing are limited to 10% and 5% by mass respectively before the presence of sulphates reduces the setting time of the cement, or react with water to produce ettringite which causes expansion of the concrete and loss of compressive strength (Hansen & Sadeghian, 2019; LeBlanc *et al.*, 2013:75; Naik *et al.*, 2010). The sulphate limit for fine and coarse recycled aggregate used in concrete is 1% (Rilem, 1994). Based on this limit, the sulphate content (0.079%) of the gypsum wallboard waste in this study is below this limit and therefore, can be suitable for use in concrete. However, when mixed with other aggregates (i.e. sand, cement, gravel etc.), it is imperative to ensure that the mixing ratios maintain the required sulphate parameters.

Table 4-2: Concentration of inorganic anions of gypsum wallboard waste (Interwaste, 2019).

Inorganic anions	Actual Total concentrations (TC) mg/kg	Actual Leachable concentrations (LC) mg/kg	Total Concentration Threshold (TCT0) mg/kg	Leachable Concentration Threshold (LCT0) mg/kg
Sulphate (SO ₄)	790	NT	Not specified	250

NT: Not tested

4.2.2.3 Other reported metals

Calcium and Sulphur are important constituents of gypsum wallboard waste. Natural gypsum contains 18.6% sulphur and 23% calcium (Spectrum Analytic, 2010). However, because of the processes and additives involved in the manufacturing of new wallboard, the calcium and sulphur concentrations were diluted to 9.39% and 9.21% respectively, as reported in Table 4-3 (Interwaste, 2019). These resultant concentrations were used to calculate the percentage of gypsum present in the gypsum wallboard waste based on the stoichiometric molar balance method described in section 2.3.1.3 above.

Table 4-3: Other metals (Interwaste, 2019).

Element	Concentration (wt% presence)
Calcium	9.39%
Sulphur	9.21%

4.2.2.4 Gypsum percentage present in the wallboard waste

As mentioned in section 2.3.1.3, when wallboard is dissolved in soil, the magnesium and calcium cation exchange results in the precipitation of MgSO₄ (Al-khadi *et al.*, 2011). In the absence of quantitative analysis, it is difficult to accurately estimate the percentage of gypsum or magnesium sulphate present in the gypsum wallboard waste. For conservative purposes, the estimated gypsum percentage is based on the least concentration obtained from either the calcium or sulphur calculations. Thus, the calcium was used to calculate the amount of gypsum in the wallboard waste. Based on the calculations, the gypsum percentage was estimated to be 40, 32%. This means that there is 40.32g for every 100g of gypsum wallboard waste.

Assuming Gypsum is produced from Calcium: $= Y(\text{wt}\%) \times \frac{1 \text{ mol Ca}}{40.078} \times \frac{1 \text{ mol CaSO}_4}{1 \text{ mol Ca}} \times \frac{172.082 \text{ g}}{1 \text{ mol CaSO}_4}$ $= \frac{Y \times 172.082}{\text{atomic mass of reactant}}$ $= \frac{9.39 \times 172.082}{40.078}$ $= 40.32\%$	Assuming the Gypsum was produced from Sulphur: $= Y(\text{wt}\%) \times \frac{1 \text{ mol S}}{32} \times \frac{1 \text{ mol CaSO}_4}{1 \text{ mol S}} \times \frac{172.082 \text{ g}}{1 \text{ mol CaSO}_4}$ $= \frac{Y \times 172.082}{\text{atomic mass of reactant}}$ $= \frac{9.21 \times 172.082}{32}$ $= 49.53\%$
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Since it has been established that the recycled gypsum acts as a partial replacement for natural gypsum in alternative uses (GRI, 2003; Richards, 2013), the percentage of gypsum contained within the wallboard waste can be used to estimate the appropriate ratios required to blend with the natural gypsum in alternative uses. Also, it has been proven that the physical and chemical properties of the recycled gypsum are similar to those of natural gypsum, therefore, the recycled gypsum is suitable for use in alternative applications (Geraldo *et al.*, 2017; Sayonara *et al.*, 2015; Penheiro & Camarini, 2015).

4.2.3 Physical characteristics

The physical properties (moisture content, water immiscibility, physical state, and flashpoint) of the gypsum wallboard waste were also obtained from a secondary source (Interwaste, 2019). The physical parameters were compared to the values stipulated in the National Norms and Standards for Disposal of Waste to Landfills (RSA, 2013c). The results indicated that the moisture content of the gypsum wallboard waste was significantly low and the waste was in solid form (Table 4-4), implying that the gypsum wallboard waste would be able to absorb excess moisture when used in composting (Marvin, 2000). Also, these properties will simplify the process of separating the gypsum from the paper during wallboard waste recycling, since the moisture content is less than 10% (Eurogypsum, 2015b) (Table 3-2). The flashpoint was not determined because gypsum is non-flammable.

Table 4-4: The physical characteristics of gypsum wallboard waste (Interwaste, 2019).

Physical characteristic	Result
Moisture content	Dry
Water miscibility	Immiscible
Physical State	Solid
Flash point	Not determined

4.2.4 Chemical characteristics

The chemical properties (pH and Electrical Conductivity) of the gypsum wallboard waste were also obtained from a secondary data source (Interwaste, 2019). Naturally, gypsum has a neutral pH, this is also reflected in the pH of the gypsum wallboard waste (Table 4-5). The presence of the gypsum wallboard waste in alternative uses will have little effect in adjusting soil or water pH and, will not neutralise acidity (not soluble in acid mediums) (Manson & Findlay, 2015). Gypsum wallboard waste did not affect the pH of soil when used in composting (Naeth & Wilkinson, 2013; Richards, 2013; Stanley, 2013; Saludes *et al.*, 2008; Wolkoski, 2003) or when subjected to multiple cycles of recycling through hydration and calcination (Geraldo *et al.*, 2017; Sayonara *et al.*, 2015; Penheiro & Camarini, 2015). In addition, gypsum wallboard waste in aggregate applications require a pH of 6 (NRA, 2014), thus the gypsum wallboard waste is suitable for use in cement-concrete alternative uses.

Table 4-5: The chemical properties of gypsum wallboard waste (Interwaste, 2019).

Chemical property	Result
pH	7.35
Electrical conductivity (ds/m)	2.21

In addition, the reported electrical conductivity (Electrical Conductivity) of the wallboard waste was 2.21 dS/m (Interwaste, 2019). Electrical Conductivity measures the amount of dissolved salts (e.g. Mg, Na, K, and Cl) in the water or soil where the gypsum wallboard waste is used. The initial Electrical Conductivity of the gypsum is crucial as high Electrical Conductivity values contribute to increased salinity of the alternative use of the wallboard waste (Naeth & Wilkinson, 2013). Gypsum wallboard waste has been shown to contribute toward increased Electrical Conductivity values as high as 9.46 ds/m when manure was composted with gypsum wallboard waste (Naeth & Wilkinson, 2013). The threshold for electrical conductivity for material to be utilised as aggregate is 1.5 dS/m (NRA, 2014). However, according to NRA (2014), if the electrical conductivity is above required threshold, the pH should be adjusted to ≥ 10 prior to utilising the material.

Based on the results discussed above and the literature review on alternative uses, the gypsum wallboard waste will not pose any physical, health or environmental hazards when applied in alternative uses. This is in correlation with international classifications of gypsum wallboard suggesting that it can be applied in similar uses as those applied internationally. Also, the gypsum wallboard waste will not influence the properties of the alternative use because the presence of heavy metals were very low compared to the stipulated limits and the neutral pH and low Electrical conductivity values suggested that the wallboard waste will not adjust water and soil pH as well

as contribute to increased salinity when applied in alternative uses. Therefore, the gypsum wallboard waste is suitable for alternative uses.

4.3 Results related to research question 2: Identifying the alternatives to the disposal of gypsum wallboard waste

The review of international and national literature has revealed the various alternatives to the landfill disposal of gypsum wallboard waste (Section 3.5, as summarized in Section 4.3.1 below).

4.3.1 Alternative uses identified through literature review

Reviewing the literature has revealed that alternative uses of gypsum wallboard waste are gaining traction internationally and various alternatives are employed to divert the waste from landfill. A summary of the findings is shown below (see also section 3.6 above):

International examples

- Manufacturing of new wallboard
- Manufacturing of Portland cement;
- Concrete
- Treatment of waste-water treatment contaminated with heavy metals; and
- Agriculture (composting and fertilizer production and animal bedding).

African examples

- Improving the drying rate of paint;
- Manufacturing of ceramics and
- Manufacturing of new plaster

South African examples

- Retarder in the manufacturing of cement;
- Treatment of acid mine drainage contaminated with heavy metals; and
- Extraction of elemental sulphur to be used as raw material in processes generating phosphate fertilizers and sulphuric acid.

4.3.2 Results of field experiments

Composting and fertilizer production were selected for further investigation. The results of the composting field experiments (as explained in Section 2.3.2.2.1) are outlined in the following sub-sections.

4.3.2.1 Results of composting field experiments

4.3.2.1.1 Compost sieve test

Screens with aperture sizes of 8 mm and 25 mm were used to sieve the compost material according to the procedure described in section 2.3.2.3.1 above. These sizes were chosen because they are the most commonly used sizes for screening final compost (Boldrin, 2011 and Smith, 2018). Based on the sieve test results, the highest percentage size fraction observed in all compost heaps was the undersize fraction (less than 8 mm) followed by the medium sized fraction (greater than 8 mm but less than 25 mm) (Table 4.7). This is in agreement with the Boldrin (2011) and Smith (2018) who stated that the less than 8 mm size range is the desired compost size used in various applications. The oversize size fraction (greater than 25 mm) was the least observed size fraction in all the compost heaps (Table 4-6). The results observed could have been improved if the gypsum wallboard waste were shredded prior to composting.

Furthermore, the results also indicated a higher percentage of gypsum present in the less than 8mm size fraction (Table 4-7). The percentage of gypsum observed in all the heaps correlated to the percentage of gypsum added (i.e. highest percentage observed were high amounts of gypsum were added). This is attributed to the fact that gypsum does not biodegrade but instead breaks down and mixes into compost over time (Townsend & Cochrane, 2003). On observation, the composition of the oversized and the middle sized fractions were mainly composed of gypsum, paper and lumps of paper pulp (Table 4-6, Table 4-7). This is due to the fact that the initial size of the gypsum wallboard waste ranged between 0.1 and 0.6 m and was not shredded to a smaller size prior to composting, therefore, it is expected that pure gypsum wallboard waste will report to the oversized category as a result of the larger pieces.

Table 4-6: Sieve test results of the compost (size fractions adopted from Boldrin (2011) and Smith (2018)).

Compost material	Oversize (>25 mm)	Middle size and (>8mm <25mm)	Undersize (<8 mm)
10% gypsum wallboard waste compost heap	1.85%	9.26%	88.9%
20% gypsum wallboard waste compost heap	3.77%	11.3%	84.8%
30% gypsum wallboard waste compost heap	3.81%	17.14%	74.05%
50% gypsum wallboard waste compost heap	13.56%	15.25%	71.19%

Table 4-7: Percentage gypsum across the sieve sizes.

Compost material	Over size (> 25 mm)	Middle size and (>8mm <25mm)	Undersize (< 8 mm)
10% gypsum wallboard waste compost heap	20%	30%	50%
20% gypsum wallboard waste compost heap	15%	35%	50%
30% gypsum wallboard waste compost heap	10%	30%	60%
50% gypsum wallboard waste compost heap	10%	20%	70%

4.3.2.1.2 Compost parameters

Parameters such as temperature, moisture content, C:N ratio, pH and electrical conductivity (EC) are reported in the sub-sections below.

4.3.2.1.2.1 Temperature

The temperature profiles of the compost heaps are shown in Figure 4-1 below.

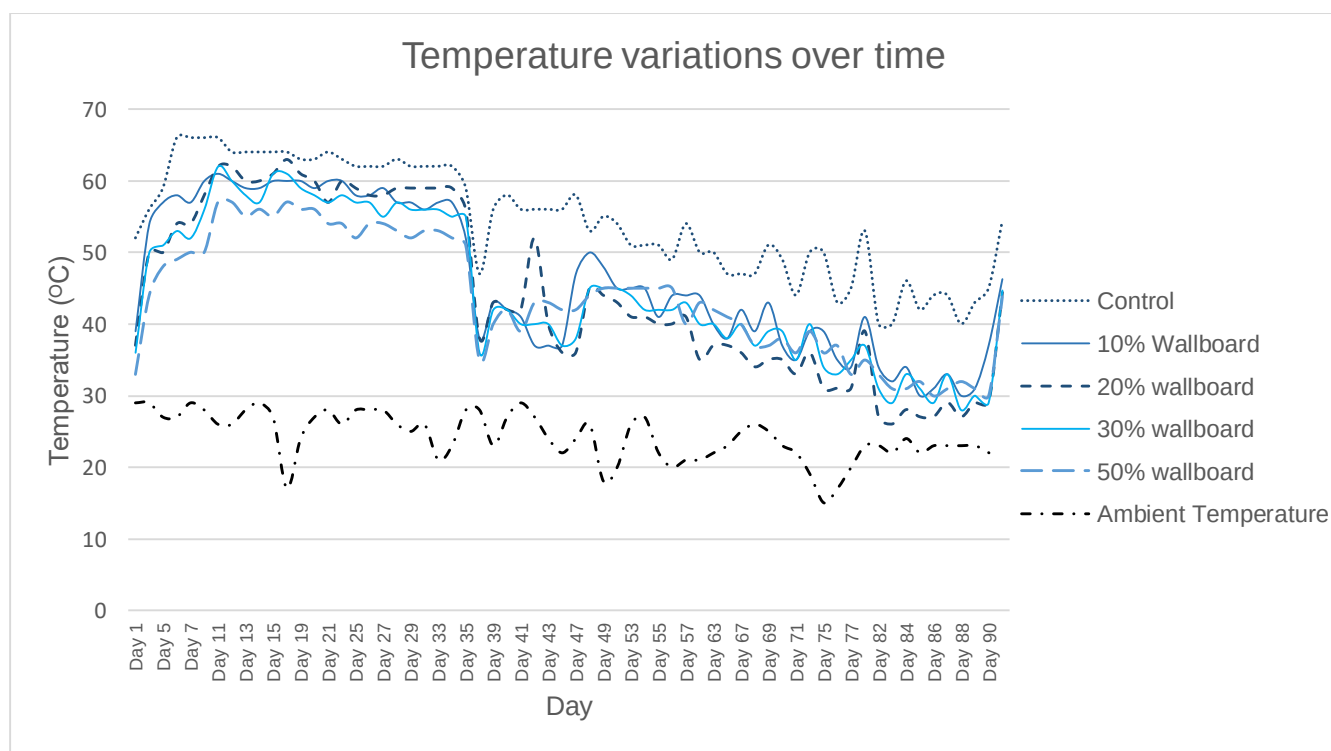


Figure 4-1: Temperature profiles of compost heaps from February to May (2020).

A positive relationship exists between the temperature profile of the control heap and that of the compost heaps with gypsum wallboard waste as shown in the correlation analysis table in **Appendix H**. The control exhibited higher temperatures than the other heaps throughout the composting process. The initial temperatures of the control were 52 °C and increased to above 60 °C in the first 4 days of the experiment and remained above 60 °C for the next 21 days of the experiment. Similarly, the initial temperatures of the compost heaps with 10% gypsum wallboard waste, 20% gypsum wallboard waste, 30% gypsum wallboard waste and 50% gypsum wallboard waste were 39 °C, 37 °C, 36 °C and 33 °C respectively and increased to above 50 °C where they remained for the next 21 days of the experiment.

The observed sharp drop in temperatures across all the compost heaps on day 26 of the experiment was as a result of turning the compost heaps, following a consistent decrease in temperatures. In general, the temperatures of the heaps with gypsum wallboard waste remained within the acceptable limit of 45°C for the first 40 days of the experiment, thereafter, a drop in temperatures below the acceptable limit in all the compost heaps was noticed. The last 50 days of the experiment were characterised by fluctuations in temperatures below 45°C in all the compost heaps with gypsum wallboard waste. The temperatures of the control remained within the acceptable limit of 45°C throughout the experiment.

During composting, microorganisms consume organic compounds from organic matter and release carbon dioxide, water and energy in the form of heat (Rynk *et al.*, 1992). The increasing amounts of heat produced result in an increase in the temperatures of the compost heap. Thus, the temperature of the compost heap is related to the microbiological activity in the compost heap (Rau *et al.*, 2008). High temperatures indicate high microbiological activities as a result of the rapid decomposition of organic matter during the earlier stages of the composting process. Similarly, the low temperature profiles indicate reduced microbiological activity. Therefore, based on the temperature profiles, the highest decomposition occurred in the control because of the presence of higher proportion of organic matter relative to the compost heaps with gypsum wallboard waste.

Based on the temperature profiles observed in this study, there was no direct relationship between the percentage of gypsum wallboard waste and temperatures. However, the low temperature profiles of the heaps with gypsum wallboard waste compared to the control suggested that the presence of gypsum wallboard waste dampened the temperatures of the compost heaps. The carbon content of the compost decreased with increasing gypsum wallboard waste content as is discussed below (Figure 4-3). The presence of the gypsum wallboard waste in varying proportions diluted the organic matter and therefore reduced the availability of nutrients as gypsum is inorganic and lacks the necessary nutrients required by the microorganism. As a result of the lack of nutrients, the microbial activity was reduced and therefore temperatures were affected. Also,

the reduction in microbial activity can be attributed to the loss in moisture over time (Figure 4-2). A similar effect of gypsum wallboard waste on temperatures was also observed by Richards (2013). Although the temperatures were dampened, the observed positive correlation between all the compost heaps in this study also suggested that there was an external factor contributing to the decreasing temperatures. A positive correlation was also observed between the ambient temperature and the temperatures of the compost heaps.

4.3.2.1.2.2 Moisture content

The moisture content of the compost heaps ranged between 52% and 58% during the first month of the trial, to between 48% and 58% during the second month of the trial and slightly reduced to between 47% and 56% during the final month of the trial (Figure 4-2). A decrease in moisture content with increasing composting time is expected as moisture is evaporated during the decomposition of organic matter (Rau *et al.*, 2008). Although the moisture content decreased over time when the composting time increased, it remained within the acceptable range of 40 to 65% (Rynk *et al.*, 1992). In addition, it was observed that the moisture content generally decreased as the gypsum wallboard waste content increased. This is attributed to the fact that the gypsum wallboard waste absorbs and reduces excessive moisture in the compost, and the amount absorbed correlates with the presence of the gypsum wallboard waste (Beck & SCS engineers, 2010; Marvin, 2000; Ndukwe & Yuan, 2016). In this study, the heap with the highest percentage of gypsum wallboard waste (50%) showed the least moisture content throughout the trial. Adding water back unto the system could have possibly maintained the composting process for longer than the observed 90 days.

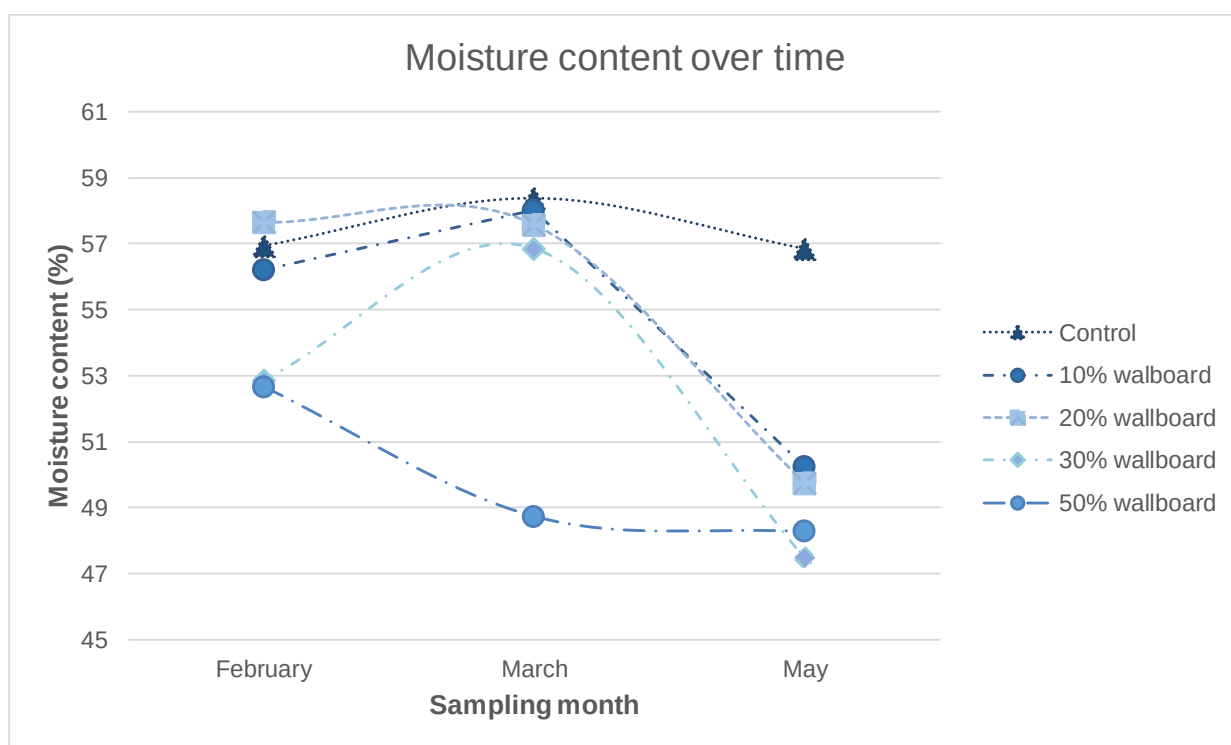


Figure 4-2: Changes in moisture content during the composting process from February to May (2020).

4.3.2.1.2.3 Total carbon, organic matter and total nitrogen

During composting, microorganisms consume carbon for energy and growth and nitrogen for protein and reproduction (Rau *et al.*, 2008; Rynk *et al.*, 1992). It is, therefore, expected that the carbon content of the compost should decrease over time. The total carbon content represents the organic content of the compost and can be used to calculate the organic matter content present in the compost based on the following equation:

$$\text{Organic matter} = \text{Total carbon (\%)} \times 1.72 \quad (\text{Pluske et al., 2020})$$

Based on the equation, a positive correlation exists between organic matter and total carbon (Figure 4-3). The results indicated that the total carbon after the 90 day trial was 30.26% in the control and decreased to 21.51% in the compost heap with 50% gypsum wallboard waste. Similarly, the organic matter was 52% in the control and decreased to 37% in the heap with 50% gypsum wallboard waste (Figure 4-3). These findings were expected since the control heap was composed of 100% organic matter which decreased as the gypsum wallboard was added. This suggests that the observed reduction in organic matter as the gypsum wallboard percentage increased were attributed to the dilution effect.

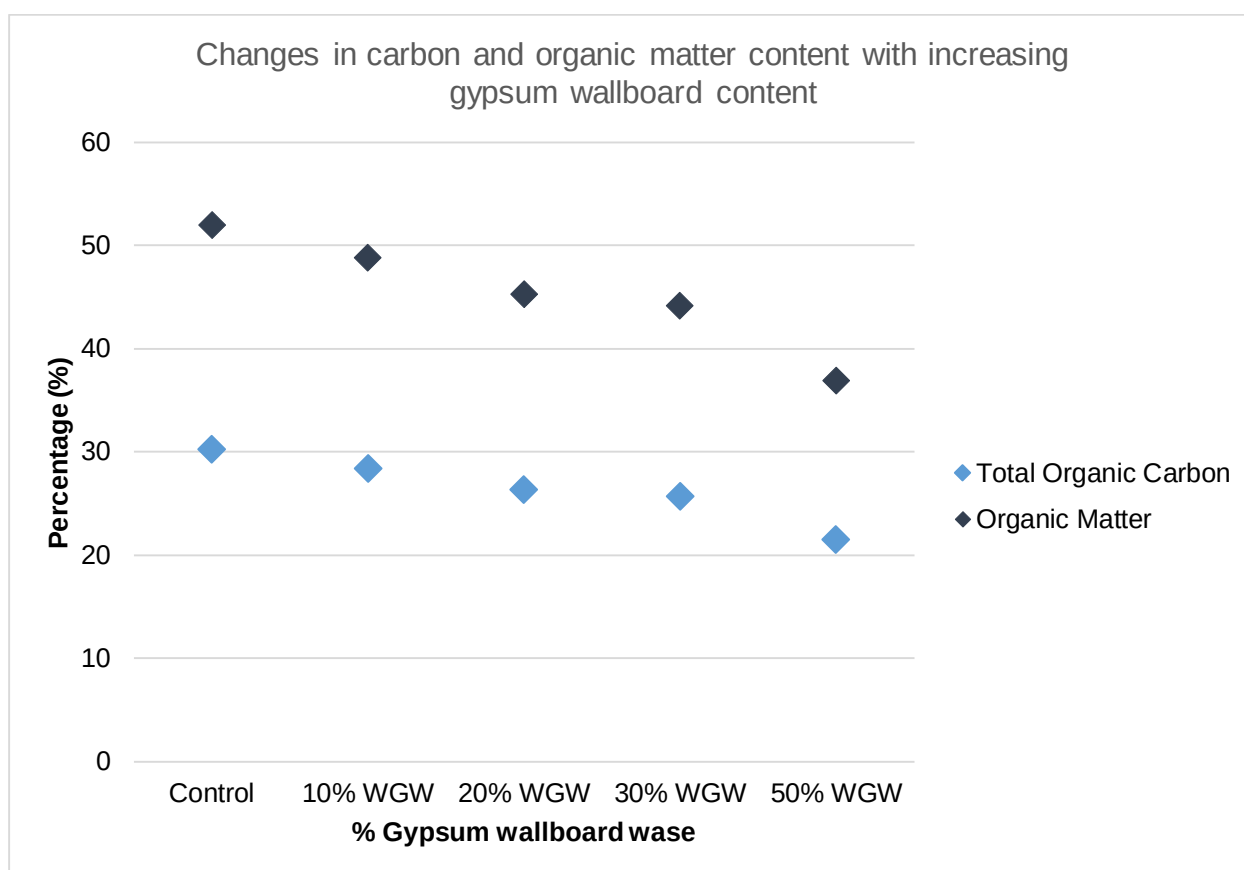


Figure 4-3: Total carbon and organic matter content with increasing proportions of gypsum wallboard waste in compost.

On the other hand, the results indicated that upon completion of the trial, the total nitrogen was 0.84% in the control heap and decreased as the gypsum wallboard waste content increased, reaching 0.55% in the heap with 50% gypsum wallboard waste (Figure 4-4). The relationship between the nitrogen content and the wallboard waste content is similar to that observed for the carbon content. According to A&L Canada Laboratories (2004), the acceptable range of nitrogen in compost is 0-6% (A&L Canada Laboratories, 2004). Therefore, the total nitrogen content observed in this study was within the acceptable range.

Nitrogen in compost is mainly lost through ammonia volatilization (Tubail et al., 2008). The presence of gypsum in compost prevents ammonia volatilization by means of attaching the sulphate in the gypsum to the ammonium present in the compost heap (Tubail et al., 2008), thereby increasing the nitrogen content over time (Richard, 2013; Saludes et al., 2008). However, the findings of this study are contradictory because the nitrogen decreased as the gypsum wallboard waste content increased. Similar observations were made by Arnold (2010) and Naeth & Wilkinson (2013). The reduction in nitrogen with increasing percentages of gypsum wallboard waste can be explained by the dilution effect of the gypsum wallboard waste added to the compost heaps. Gypsum wallboard waste is composed of 90% gypsum and 10% paper (Townsend & Cochran, 2003). The gypsum (CaSO_4) is inorganic and does not contain any nitrogen or carbon

sources and the 10% paper fraction consists of 4-5% carbon and no nitrogen (Richards, 2013). Thus, the addition of the wallboard waste diluted the nitrogen content causing it to decrease with in incremental amounts of gypsum wallboard waste.

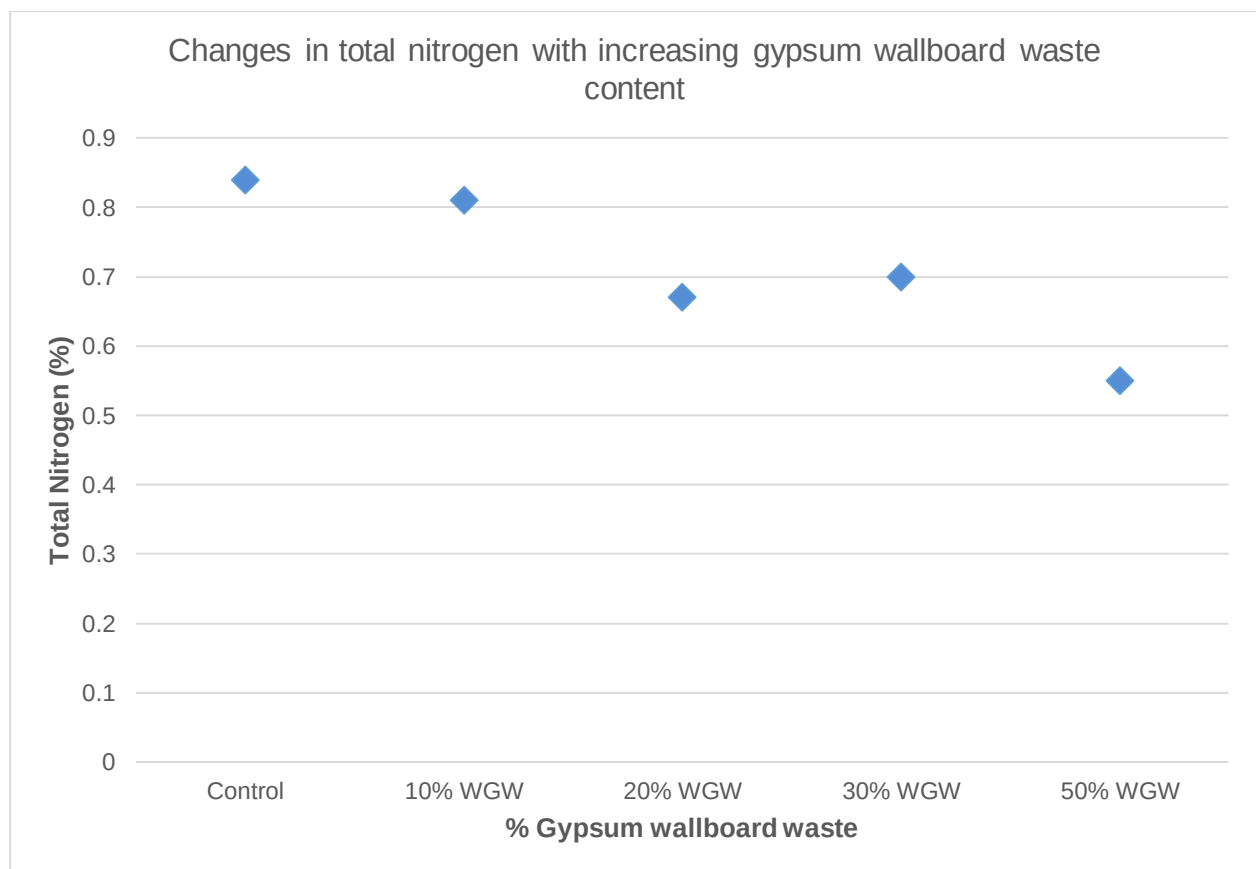


Figure 4-4: Nitrogen content with increasing proportions of gypsum wallboard waste in compost.

4.3.2.1.2.4 C:N ratio

The initial C:N ratio of the of the organic matter was 50:1 (Table 2-2) and the final C:N ratio was 35:1 (Figure 4-5). The results indicate that that the C:N ratios of the compost decreased over the 90 day trial suggesting a decrease in the carbon content of the compost. This was expected as the C:N ratio is supposed to decrease as the carbon in the organic matter is consumed (A&L Canada Laboratories, 2004:15; Onwosi *et al.*, 2017; Rynk *et al.*,1992). Similar observations of decreasing C:N ratios over time were made for compost heaps with gypsum wallboard waste. Although the study did not observe a direct relationship between the C:N ratios and the gypsum wallboard waste percentage, it was noticed that the C:N ratios of the compost heaps containing high gypsum contents were slightly higher than the C:N ratio of the control (Figure 4-5). This was attributed to the dilution effect of the nitrogen content by the gypsum.

It is widely known that finished or mature compost attains a C:N ratio of between 10-12 (Onwosi *et al.*, 2017; Rynk *et al.*,1992; Sullivan *et al.*,2018). The compost in this study attained a C:N ratio

of between 35:1 and 39:1 at the end of the 90 day trial suggesting that compost did not reach maturity stage in the 90 day trial period of composting. This is due to a decrease in temperature and moisture content observed during the composting trial.

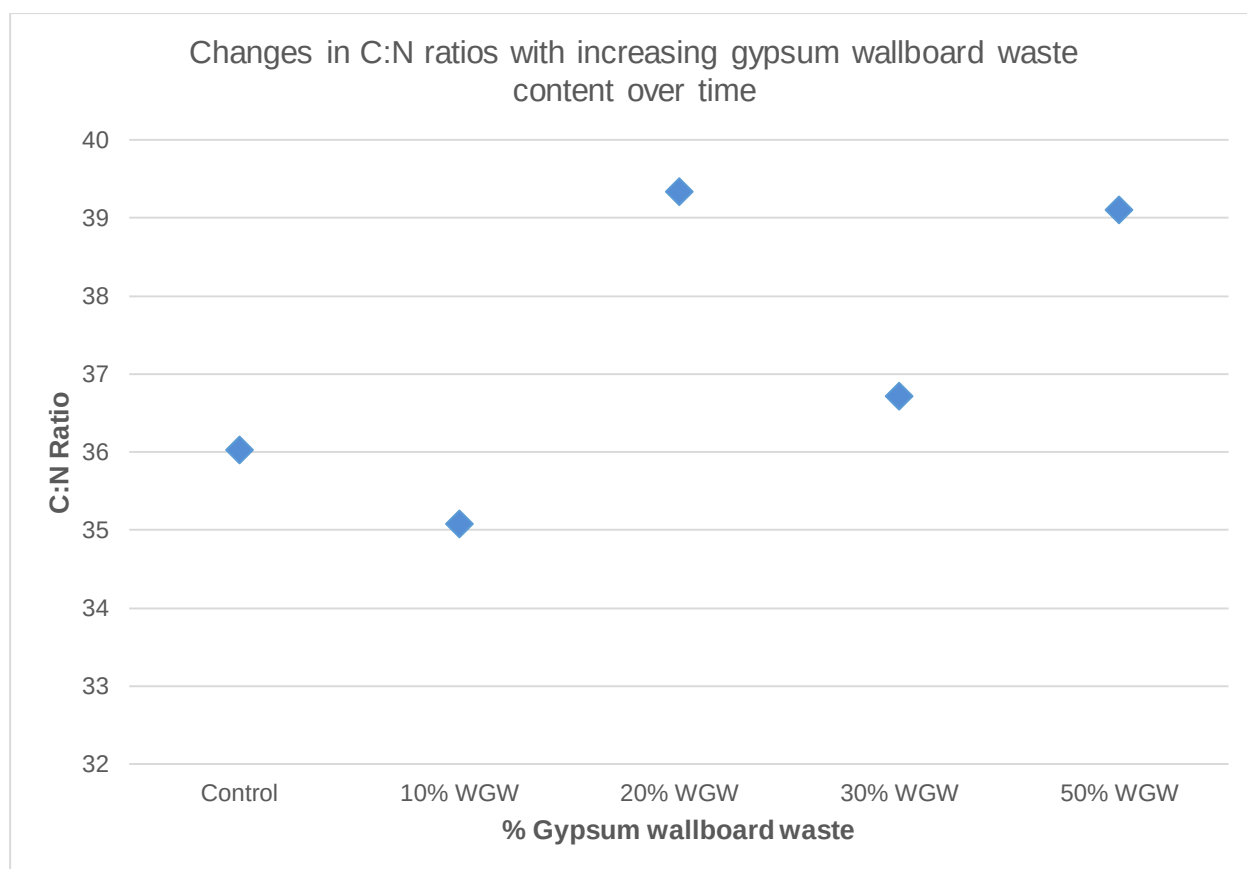


Figure 4-5: C:N ratios with increasing proportions of gypsum wallboard waste in compost.

4.3.2.1.2.5 pH and electrical conductivity (EC)

The initial (Day 1) and final (Day 90) pH and EC-values are shown in Table 4-9

In general, the pH decreased over the 90 day trial. The changes in the initial and final pH of the compost heaps were not significant although a slightly higher change was observed in the control compared to the compost with gypsum wallboard waste (Table 4-8).

Table 4-8: Initial and final pH and EC values.

	Initial pH	Final pH	Initial EC	Final EC
Control	9.04	7.8	0.513	2.11
10% WGW	7.95	7.4	2.53	2.25
20% WGW	7.58	7.4	2.53	2.39

	Initial pH	Final pH	Initial EC	Final EC
30% WGW	7.92	7.4	2.56	2.4
50% WGW	7.9	7.4	2.27	2.16

The pH of the gypsum wallboard waste was 7.35 (Table 4-5). The initial pH of the control was 9.04 and that of the 10%, 20%, 30% and 50% gypsum wallboard waste compost ranged between 7.58 and 7.95 (Table 4-8). The results indicated that the addition of gypsum wallboard waste lowered the pH of the compost from the onset. This is in agreement with the findings of Richards (2013) and Wolkowski (2000). Thus, the presence of gypsum wallboard waste affects pH. The observed reduction in the pH in all the compost heaps can be attributed to the formation of organic acids during decomposition (Rynk *et al.*, 1992) and nitrification processes which release hydrogen ions (Eklind & Kirchmann, 2000; Febrisiantosa *et al.*, 2018; Saludes *et al.*, 2008). Also, the decrease in sodium concentrations as a result of the cation exchange between the sodium and calcium ions and the formation of the SO_4^{2-} ions in the compost decreased the pH (Ahmed *et al.*, 2016). The observed results are consistent with the findings of Saludes *et al.*, 2008, Moustafa *et al.*, 2010, and Febrisiantosa *et al.*, 2018 who also observed a decrease in pH when gypsum from wallboard waste was added to compost. Overall, the pH was within the 7-9 range required for compost (Table 3-5). No direct relationship was observed between the percentage gypsum wallboard waste and the change in pH.

The Electrical Conductivity (EC) of the gypsum wallboard waste prior to composting was 2.21 dS/m (Table 4-5). Adding the gypsum wallboard waste to the compost increased the EC to between 2.27 and 2.53 dS/m across all the gypsum wallboard waste compost (Table 4-8). This suggests that the addition of the gypsum wallboard waste altered the EC of the compost from the onset. In contrast, the initial EC of the control was much lower but increased over time. Since the control was not mixed with the gypsum wallboard waste, this suggests that the ingredients used in the organic matter compost contributed to the increased EC values of the control. In the case of the gypsum wallboard waste compost, gypsum is a salt and is expected to increase the EC value of the compost. Saludes *et al.*, (2008) also found an increase in EC when horse manure was utilised in compost. This is consistent with this study as horse manure was used as one of the organic matter ingredients and could have contributed to the EC content. The acceptable range for EC in compost is 2-4 dS/m (Table 3-5). Therefore, the EC of all the compost heaps was within the required range.

4.3.2.1.2.6 Sodium (Na) content

The results indicated an overall decrease in the sodium content with increasing gypsum wallboard waste (Figure 4-6). Gypsum is moderately soluble in soil, and when exposed to moisture, it

dissolves (Moustafa *et al.*, 2010) and the ions separate into Ca^{2+} and SO_4^{2-} according to the following reaction:



The calcium ions (Ca^{2+}) from the gypsum replace the sodium ions (Na^+) in the cation exchange sites (Ahmed *et al.*, 2016). Increasing amounts of gypsum increase the amount of Ca^{2+} replacing the Na^+ in soils (Sparks, 2003). This is due to the fact that the calcium ions have the ability to flocculate the soil thereby leaching the replaced Na^+ ions as a soluble Na_2SO_4 salt (Ahmad *et al.*, 2013; Ahmed *et al.*, 2016), ultimately reducing the sodium concentrations in the soil. Gypsum is therefore, effective in reducing the salinity levels of compost and in a natural setting, the gypsum wallboard waste will mobilizes the sodium ions to deeper levels of the soil profile, reducing the impact of soluble salts on soils (Day *et al.*, 2019).

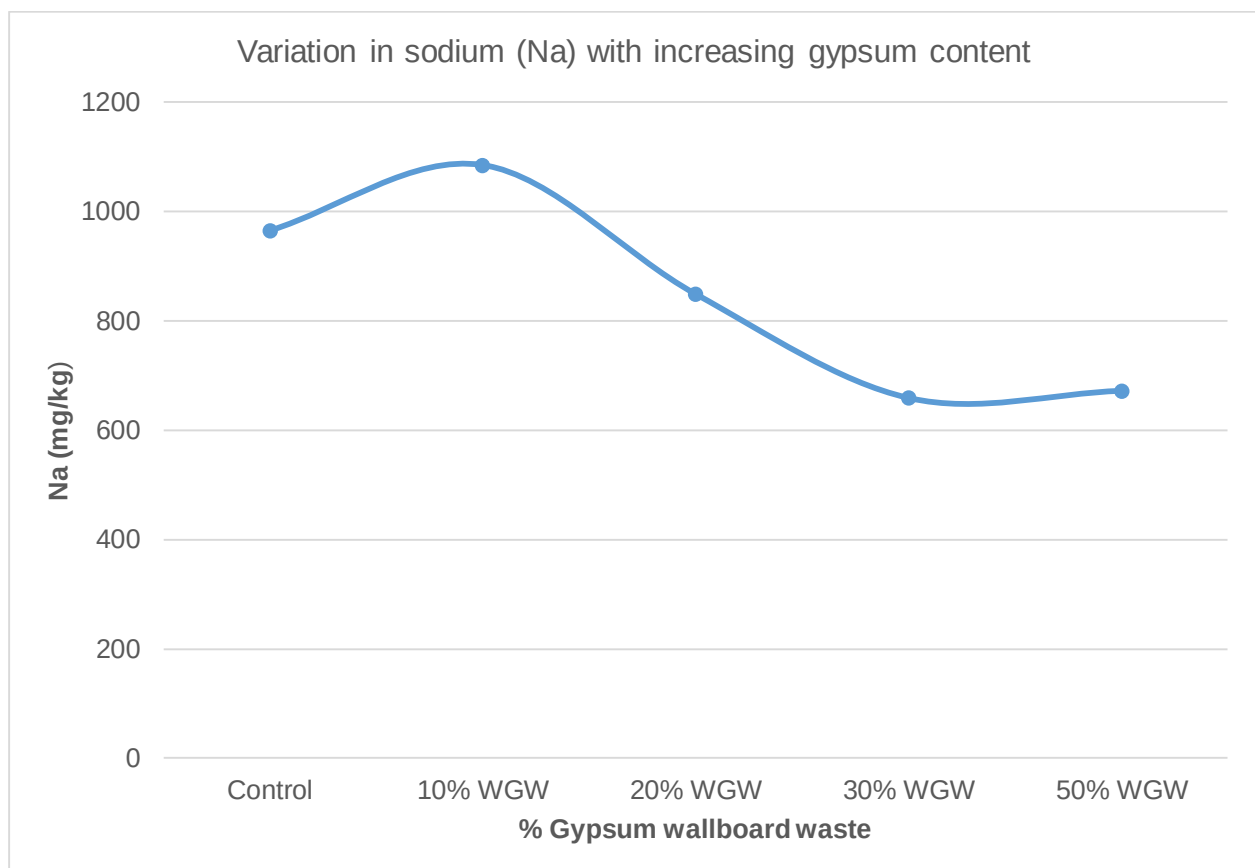


Figure 4-6: Change is sodium content with increasing proportions of gypsum wallboard waste.

4.3.2.1.2.7 Heavy metal content

As discussed in section 3.5.1.4.2, South Africa has not yet developed guidelines on the limits of heavy metals permitted in compost. Therefore, heavy metal content results of all the compost heaps (Table 4-10) were compared to the EU, USA, and Canada guidelines shown in Table 3-6.

The results indicated that the heavy metal concentrations in all the compost heaps were below the threshold stipulated by the international guidelines. A decrease in the Copper (Cu), Molybdenum (Mo), Lead (Pb) and Zinc (Zn) with increasing gypsum wallboard percentages was observed. However, based on the compositional characteristics of the gypsum wallboard waste (Table 4-1), the Copper, Molybdenum, Lead and Zinc concentrations were below detection limit. Therefore, the observed Cu, Mo, Pb and Zn concentrations in the compost heaps originated from the organic matter constituents.

Table 4-9: Heavy metal results of the compost piles (mg/kg).

Metals	Control	10% WGW	20% WGW	30% WGW	50% WGW
Arsenic	BDL	BDL	BDL	BDL	BDL
Cadmium	BDL	BDL	BDL	BDL	BDL
Chromium	BDL	BDL	BDL	BDL	BDL
Cobalt	BDL	BDL	BDL	<3	BDL
Copper	77	82	BDL	53	47
Mercury	BDL	BDL	BDL	BDL	BDL
Molybdenum	15.81	7.61	9.12	BDL	BDL
Nickel	BDL	BDL	BDL	BDL	BDL
Lead	11.07	10.05	9.4	10.06	9
Selenium	BDL	BDL	BDL	BDL	BDL
Zinc	114	117	88	97	83

Adding gypsum to compost decreases the availability of dissolved organic carbon which in turn decreases the phytoavailability of heavy metals in the compost (Lwin *et al.*, 2018). Richards (2013), found that the addition of gypsum wallboard waste in compost, removed quantities of lead by forming insoluble forms of lead compounds such as PbSO₄ (anglesite), which are not available to plants (Garrido *et al.*, 2005; Lin *et al.*, 1995). Gypsum can reduce lead concentrations by 64% through the formation of sulphides in soil. (Vink *et al.*, 2010). Therefore, lead retention caused by the addition of gypsum results in increasing concentrations with increasing gypsum percentages. However, the opposite was observed in this study, suggesting that the reduction in lead concentrations in the compost with increasing percentages of wallboard waste might be due to the dilution effect of gypsum wallboard. Similarly, decreasing zinc and copper concentrations with increasing gypsum content can also be attributed to the dilution effect of the gypsum wallboard waste.

The results discussed in this section indicated that the gypsum wallboard waste was suitable for use in composting. The addition of gypsum wallboard waste dampened the temperatures of the compost when compared to the control, this was as a result of a reduction in microbial activity due to the decreased carbon content of the compost with increasing gypsum content and a reduction in moisture content with time. In addition, the gypsum wallboard waste did not affect the moisture content, but reduced the pH, and EC of the compost from the onset, although they remained within the required limits throughout the experiment. Furthermore, the gypsum wallboard waste did not contribute heavy metals to the compost. Instead, it reduced the concentrations of lead suggesting that the presence of gypsum wallboard waste will reduce the toxicity of harmful metals in compost in addition to reducing the salinity of the compost through facilitating the leaching of sodium ions.

4.3.2.2 Results of experiments to produce a fertilizer from composting gypsum wallboard waste.

The final compost was tested against the requirements of the fertilizer regulations stipulated in the *Fertilizer, Farm Feeds, Agricultural Remedies and stock remedies Act (Act 36 of 1947)* to establish its suitability as fertilizer. The results are presented in Table 4-10: The suitability of the compost for fertilizer production in terms of the requirements stipulated in the fertilizer regulations. Below and are discussed in the sub-sections to Section 4.3.3.2.

Table 4-10: The suitability of the compost for fertilizer production in terms of the requirements stipulated in the fertilizer regulations.

Criteria	Acceptable range	Control	10% WGW	20% WGW	30% WGW	50% WGW
Cadmium (Cd)	<20mg/kg	<6	<6	<6	<6	<6
Chromium (Cr)	<1750mg/kg	<2	<2	<2	<2	<2
Copper (Cu)	<750mg/kg	77	82	60	53	47
Mercury (Hg)	<10mg/kg	<2	<2	<2	<2	<2
Nickel (Ni)	<200mg/kg	<4	<4	<4	<4	<4
Lead (Pb)	<200mg/kg	11.07	10.05	9.4	10.06	9
Zinc (Zn)	<2750mg/kg	114	117	88	97	83
Arsenic (As)	<20mg/kg	<1	<1	<1	<1	<1
Selenium (Se)	<15mg/kg	<1	<1	<1	<1	<1
Boron (B)	<80mg/kg	17	16	16	14	13
Particle Size	100% < 12mm standard sieve	96	90	85	80	70
Ash content	< 670g/kg (dry matter basis)	479.5	511.3	546.7	557.9	630.1
Moisture content	< 400g/kg	568.4	502.4	497.6	475.0	441.8
Infectious/Pathological/Microbial agents	0 viable Ascaris ova / 10g dry sludge	<1	<1	<1	<1	<1
	0 Salmonella organisms / 10g dry sludge	Absent	Absent	Absent	Absent	Absent
	Helmith ova <1 ova / 4g	<1	<1	<1	<1	<1
	Max. 1000 Faecal coliforms/ 10g sludge immediately after disinfection/sterilisation	5150	<3	<4	<4	<4
N	<100g/kg	8.4	8.1	6.7	7.0	5.5
P	<100g/kg	1.2	1.1	0.9	0.9	0.8
K	<100g/kg	2.8	3.3	2.5	2.8	1.9
Sum NPK	<100g/kg	12.4	12.5	10.1	9.9	8.2
Prescribed plant nutrients	>40g/kg	111	122	146	148	206
Calcium		93.9	97.1	106.0	106.4	137.0
Sulphur		6.1	13.7	26.9	30.7	56.3
Magnesium		3.5	3.7	4.2	4.6	4.6
Iron		7.478	7.459	8.383	6.375	8.247
Manganese		0.141	0.136	0.121	0.109	0.115
Zinc		0.114	0.117	0.088	0.097	0.083
Molybdenum		0.01581	0.00761	0.00912	BDL	BDL
Boron		0.017	0.016	0.016	0.014	0.013

4.3.2.2.1 Heavy metals

The heavy metal (As, B, Cd, Cr, Cu, Hg, Ni, Pb, Se and Zn) concentrations were significantly below the maximum limits acceptable for fertilizer in South Africa, implying that the gypsum wallboard waste did not present any harm associated with heavy metals when used as fertilizer (Table 4-10). The boron, copper, lead and zinc concentrations decreased as the gypsum wallboard percentage increased, whereas the concentrations of arsenic, cadmium, chromium mercury, nickel and selenium were below the detection limit for analysis.

Boron, Copper, Lead and Zinc

The boron concentration of the control heap was 17 mg/kg and decreased to 13 mg/kg when 50% gypsum wallboard waste was added. At a pH of greater than 7.2, boron in compost occurs as sodium metaborate (Gupta & Chandra, 1972). In the presence of gypsum, the sodium metaborate reacts to produce sodium sulphate and calcium metaborate. However, the results in this study indicated that both the sodium (Figure 4-6) and boron concentrations (Table 4-11) decreased as the percentage of gypsum wallboard waste increased. Thus, it is more likely that the dilution effect of the gypsum wallboard waste influenced the decreasing boron concentrations observed.

Furthermore, the minimum required concentration of boron in plants is 15 mg/kg, below which boron deficiency in plants will occur (Das *et al.*, n.d). Concentrations between 15 to 100 mg/kg are considered sufficient whereas concentrations above 100 mg/kg are toxic to plants (Das *et al.*, n.d). In this study, the compost heaps with 30% and 50% gypsum wallboard waste showed boron concentration of 14 mg/kg and 13 mg/kg respectively. These concentrations were below the required minimum boron concentration and will therefore produce a fertilizer deficient in boron. As a result, up to 20% gypsum wallboard waste can be added to produce a fertilizer.

The effect of gypsum on lead in compost was explained in detail in Section 4.3.2.1.2.7. The concentration of lead decreased from 11 mg/kg in the control to 9 mg/kg when 50% of gypsum wallboard was added. This is due to dilution effect of the gypsum wallboard waste. Similarly, observations were made for copper and zinc. .

4.3.2.2.2 Ash content

In a natural setting, the ash content represents the solid fraction remaining after organic matter has been degraded. This is the fraction that will be applied as fertilizer. The results from this study indicated that the ash content of the heaps increased as the percentage of gypsum wallboard waste increased, but remained within the 670 g/kg limit required for fertilizer (Table 4-11). Although the ash contents were within the required fertilizer limits, the percentage difference between the limit and the observed ash content decreased from 28% in the control to 18%, 16%

and 5% when 20%, 30% and 50% gypsum wallboard waste was added respectively, suggesting that the gypsum wallboard waste contributed increasing amounts of ash content and that a correlation exists between the percentage gypsum wallboard waste and ash content. The observed results were however, expected because gypsum is non-flammable, and is therefore expected to report to the ash.

In addition, the ash content was inversely proportional to the organic matter content (Figure 4-7), suggesting that the composition of the resultant fertilizer (especially containing 20 to 50% gypsum wallboard waste) will constitute a higher fraction of gypsum and possibly lower amounts of other essential nutrients required by plants due to the lack of adequate organic matter to supply the nutrient..

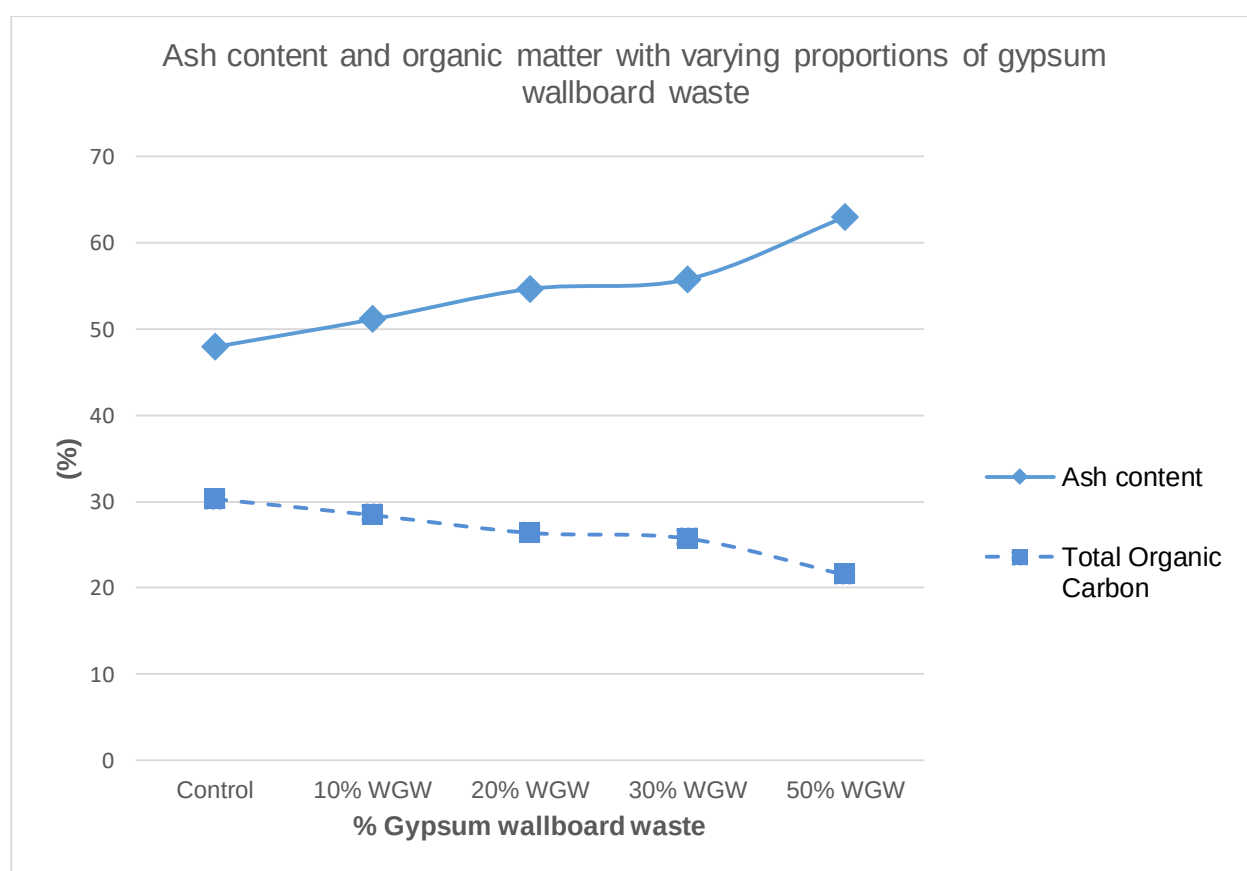


Figure 4-7: Ash content and total organic carbon with increasing gypsum wallboard proportions.

4.3.2.2.3 Particle size

The fertilizer regulations require that the particle size of the fertilizer pass 100% through a 12 mm sieve (Table 4-10). The particle sizes of the heaps were estimated based on visual observations. Based on observations, the percentages of the control, 10%, 20%, 30% and 50% gypsum wallboard waste heaps passing through a 12 mm sieve were 96%, 90%, 85%, 78% and 70% respectively. The noticeable larger size fractions (greater than 12 mm) were lumps of paper pulp

and broken up pieces of the gypsum wallboard and the paper fraction. This could be improved though with greater shredding (pre-processing) of the gypsum board prior to composting. The results indicated that none of the heaps satisfied a 100% pass through a 12 mm sieve and therefore, further sieving with a 12 mm sieve is required for the fertilizer to satisfy the particle size requirements stipulated in the regulations.

4.3.2.2.4 Moisture content

The moisture content of all the compost heaps was above the maximum limit of 400 g/kg required for a fertilizer (Table 4-10). The moisture was highest in the control compost heap (570 g/kg) and decreased as the gypsum wallboard waste percentage increased. As previously discussed, the moisture content is related to the activity of microorganism as they decompose the organic matter (Sudharsan & Kalamdhad, 2015). The heat generated by microbial activity in compost results in the evaporation of moisture over time. Since the compost in this study did not reach maturation stage upon completion of the trial, the moisture content would still be expected to decrease over time. Although the observed moisture content was high, there was a general decrease in moisture content with increasing gypsum wallboard waste content which may be as a result of the ability of wallboard to absorb moisture in compost (Marvin, 2000).

4.3.2.2.5 Infectious/Pathological/Microbial agents

As stipulated in the fertilizer regulations, the infectious/pathological/microbial organisms that must be analysed in a fertilizer include *Ascaris*, *Salmonella*, *Helmith* and *Faecal coliforms* (Table 4-10). The presence of these infectious pathogens is detrimental to humans if the fertilizer is applied to plants meant for animal and human consumption. Also, aquatic life may be affected if the fertilizer containing these pathogens is carried to water bodies.

The results indicate that, *Salmonella* was absent across all the compost heaps, and *Ascaris* and *Helmith* were within the required limits. However, the concentrations of the *faecal coliforms* exceeded five times the limit in the control heap. Maintaining temperatures of above 55°C for at least three days is sufficient to eliminate the pathogens contained within organic matter (Rynk *et al.*, 1992). Based on the temperature profiles in figure 4-1, the composting temperatures of all the compost heaps remained above 55 °C for at least three days. These temperatures should have been sufficient to destroy the pathogens in the compost. However, other factors such as competition for nutrients, production of ammonia and organic acids, and microbial antagonism, can hinder the destruction of *faecal coliforms* during composting (Sunar *et al.*, 2014).

The addition of gypsum wallboard waste drastically reduced the concentration of *faecal coliforms* from 5150/10g to less than 4/10g. It is likely that the introduction of gypsum wallboard waste to the compost, diluted the nutrient content of the compost heaps which reduced microbial activity

as inferred from the decreasing temperature with time and the decreasing carbon contents with increasing gypsum wallboard waste as discussed above (sections 4.3.3.1.2.3 and 4.3.3.1.2.4), causing possible nutrient deficiencies for the microorganism and causing them to die off (O'Brien, 2017).

4.3.2.2.6 Nitrogen (N), Phosphorus (P) and Potassium (K)

The nitrogen, phosphorus and potassium concentrations of all the compost heaps were within the limits required for a fertilizer, and decreased when the gypsum wallboard waste contents increased (Table 4-11). A fertilizer with sufficient nutrients should contain greater than 1% nitrogen and greater than 1.5% potassium and phosphorus combined (Brinton, 2000). The approximate NPK ratios will vary depending on the nutrient requirements of the plants.

Based on the results, the nitrogen content in all the compost heaps was below 1% and the combined potassium and phosphorus content were also less than 1.5%, implying that that fertilizer produced in this study should be supplemented with additional nitrogen, phosphorus and potassium prior to application as deficiencies in nitrogen, phosphorus and potassium will affect the growth of plants (Ayilara *et al.*, 2020; Sullivan *et al.*, 2018). It is important to note that the addition of a nutrient-rich fertilizer will increase the cost of producing compost using gypsum wallboard waste.

Furthermore, the nitrogen, phosphorus and potassium contents decreased as the gypsum wallboard waste increased (Figure 4-8). Traditionally, the concentrations of nitrogen, phosphorus and potassium increase as the organic matter decomposes (Saludes *et al.*, 2008). However, gypsum wallboard waste is not a source of nitrogen, phosphorus and potassium and will therefore, not increase the concentrations of these nutrients in compost and fertilizer. As a result, the decreasing NPK values (though insignificant when comparing the values across the heaps), can be attributed to the declining percentage of organic matter as the percentage of the gypsum wallboard increases (Figure 4-3). Also, the addition of gypsum prevents the leaching of phosphorus through the formation of calcium phosphate minerals (Davidson, 2017; Moustafa *et al.*, 2010). The phosphorus content should therefore increase. However, in this study the opposite was observed. The effect of gypsum on nitrogen was explained in detail in section 4.3.2.1.2.3. Thus, it can be concluded that the gypsum wallboard waste diluted the concentrations of the nitrogen, phosphorus and potassium and produced an inferior fertilizer.

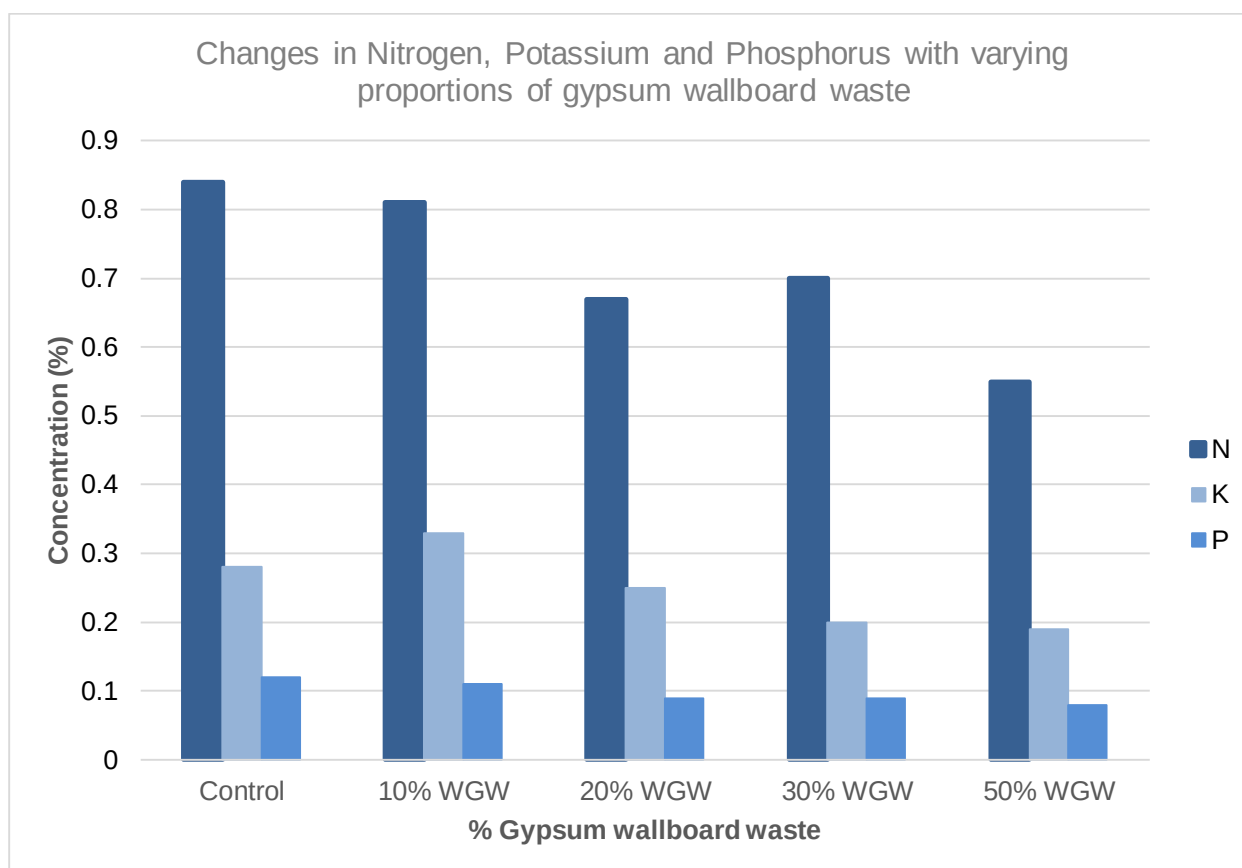


Figure 4-8: Change in nitrogen, phosphorus and potassium with increasing gypsum wallboard waste proportions.

4.3.2.2.7 Plant nutrients

The combined concentrations of the required plant nutrients (B, Ca, Fe, S, Mo, Mn, Mg, Zn) in all the compost heaps were above the minimum limit required ($> 40\text{g/kg}$) (Table 4-10). The concentrations of the plant nutrients increased with increasing gypsum waste contents and ranged from 111 g/kg in the control to 206 g/kg in the heap containing 50% gypsum wallboard waste. As expected, the calcium and sulphur from the gypsum wallboard waste contributed the highest amount towards the observed nutrient content of the heaps.

The sulphur and calcium contents were showed a positive correlation to the percentage gypsum wallboard waste added (Figure 4-9). The calcium content increased from 9.39% in the control to 13.7% in compost with 50% gypsum wallboard waste. Similarly, sulphur increased 8 times compared to the control when 50% gypsum wallboard waste was added. The results were in agreement with Saludes *et al.*, (2008) and Naeth & Wilkinson (2013) who also found a positive relationship between calcium and sulphur gypsum wallboard waste in compost.

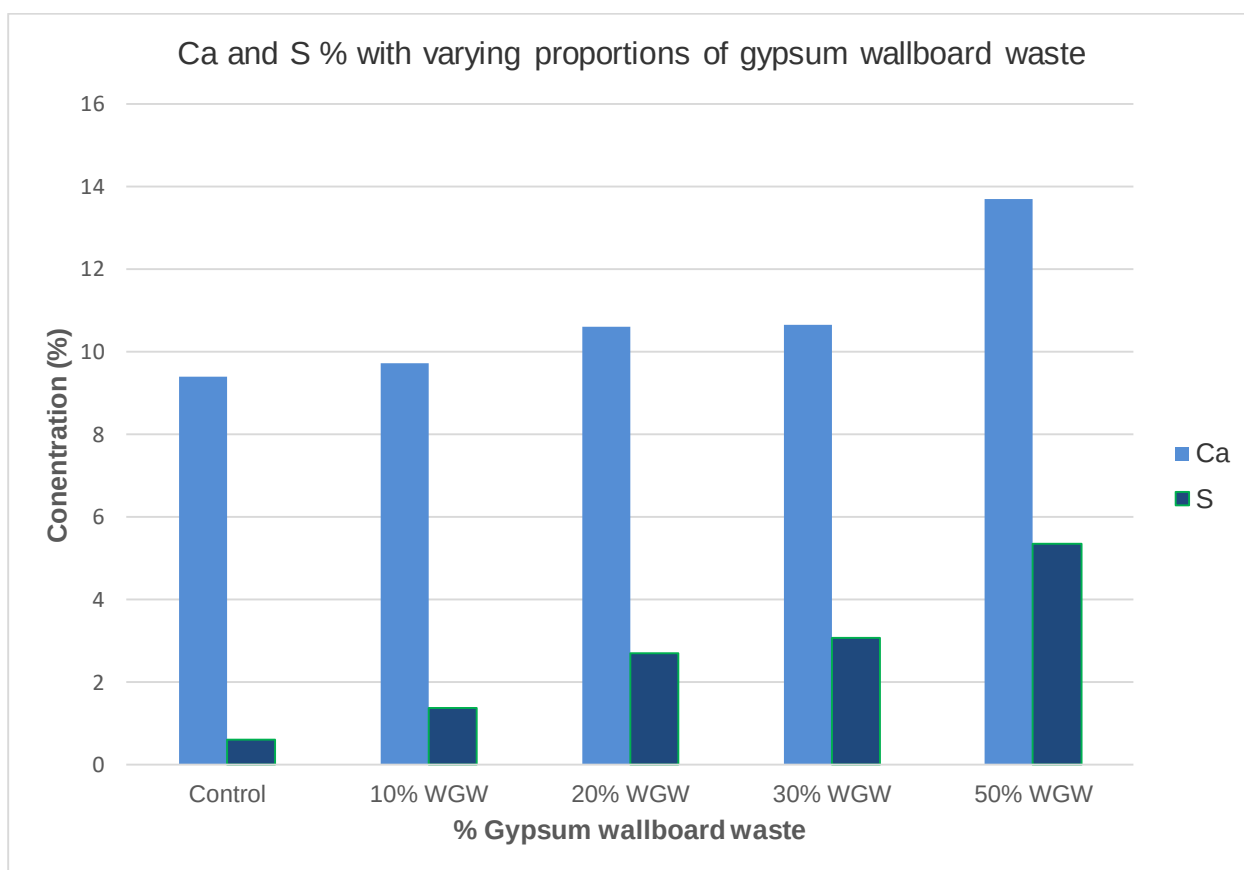


Figure 4-9: Calcium and sulphur content with increasing gypsum wallboard waste proportions.

Furthermore, an increase in magnesium concentration with increasing gypsum wallboard waste content was also observed. The magnesium was also within the required range (i.e. 0.35-0.46%) as indicated in Table 4-10. The results observed are contradictory to the findings of Tubail *et al.*, (2008) and Wolkowski (2008) who observed a decrease in magnesium with increasing gypsum wallboard waste contents. This is because in principle, gypsum is expected to promote the leaching of magnesium through the replacement of Mg^{2+} ions with Ca^{2+} ions in the cation exchange sites (Moustafa *et al.*, 2010). Thus, the magnesium contents are expected to decrease with increasing calcium contents from the gypsum wallboard waste. No direct relationship was observed between iron, Manganese, Molybdenum, Zinc and the gypsum wallboard waste content.

Based on the results discussed in this section, gypsum wallboard waste was suitable for fertilizer production as it did not present any harm associated with heavy metals. Instead, it increased the concentration of essential nutrients such as calcium and sulphur and reduces the concentration of infectious pathogens. However, the resultant fertilizer must be supplemented with nutrient rich fertilizer to meet the nutrient requirements of plants, and up to 20% of gypsum wallboard waste can be added before the fertilizer is deficient in boron nutrients.

4.3.3 Summary

In summary, this study has shown that gypsum wallboard waste can be suitable for use in alternative applications. This is based on the fact that it is non-hazardous according to the SANS 10234 waste classification criteria, suggesting that the gypsum wallboard waste will not pose any physical, health or environmental hazards when applied in alternative uses. In addition, the compositional and physico-chemical properties of the gypsum wallboard waste indicated that the heavy metals concentrations, sulphate content, pH, EC and moisture content of the gypsum wallboard waste were within the required limits for use in alternative uses. This, suggested that the gypsum wallboard waste is suitable for recycling purposes and will not present any harm associated with the presence of heavy metals and sulphate ions, and will not alter the pH and salinity of the alternative process.

The results from the field experiments indicated that the presence of the gypsum wallboard waste dampened the composting temperatures but the moisture content, pH, and EC of the compost remained within the required composting limits. Also, the addition of the gypsum wallboard waste reduced the concentrations of heavy metals in compost which indicated the potential for gypsum wallboard waste to reduce toxic levels of heavy metals concentrations in compost to below lethal levels. Also, the sodium content of the compost was reduced to where gypsum wallboard waste was added in high amounts indicating gypsum's ability to regulate salinity in compost.

The results also indicated that the gypsum wallboard waste was suitable for fertilizer production. However, up to 20% of gypsum wallboard waste can be added to produce a fertilizer before the boron concentrations are reduced to deficiency levels. Also, the fertilizer produced from the gypsum wallboard waste would need to be supplemented with a nutrient rich fertilizer as the NPK values were within the lower ranges of the acceptable limits. The results also showed that the gypsum wallboard waste reduced the heavy metal concentrations to below acceptable levels whilst increasing the calcium and sulphur content of nutrients. This suggested that gypsum wallboard waste added did not present any harm associated with heavy metals and contributed the essential nutrients required by.

4.4 Results related to research objective 3: Investigating the opportunities and challenges associated with wallboard waste in composting and fertilizer production and, investigating the views of wallboard manufacturers toward the use of recycled gypsum from wallboard.

The literature review looked at secondary data sources that described the experience of various stakeholders utilising gypsum wallboard waste, by looking at the challenges and opportunities associated with reusing and recycling gypsum wallboard waste in alternative uses. These data sources included information from various waste management companies (NWGR, 2020),

magazine articles on gypsum wallboard recycling (Gibson, 2011), wallboard manufacturing company websites (Saint Gobain Gyproc, 2017), wallboard waste recycling companies (GRI, 2013) as well as studies or research conducted around gypsum wallboard waste recycling, (Eurogypsum, 2015a) and studies aimed at understanding experiences from stakeholders (Jimenez- Rivero & Navarro, 2017a).

The findings of the literature review were used to conduct interviews to investigate the opportunities and challenges experienced by various stakeholders in the use of gypsum wallboard waste in alternative processes with a focus on composting and fertilizer production, and to investigate the views of wallboard manufacturers in utilising recycled gypsum in their wallboard manufacturing processes. The interviews made use of open ended questions and purposive sampling and the data was analysed through thematic analysis. (Braun & Clarke, 2006).

4.4.1 Results on challenges and opportunities from literature

A summary of the opportunities and challenges associated with the selected alternatives to landfill disposal of gypsum wallboard waste are summarized below. A more detailed account is provided in Section 3.7 of the Literature Review chapter.

Gypsum wallboard manufacturing:

Challenges

- Separation of paper and gypsum; and
- Quality of recycled gypsum.

Opportunities

- Conservation of natural resources (natural gypsum);
- Opportunity to acquire natural gypsum at a cheaper rate;
- Diversion of waste from landfill;
- Reduced energy and transportation costs;
- Achievement of organizational environmental targets and
- Reward points for recycling the waste

Composting of gypsum wallboard:

Challenges

- Maintaining the required composting parameters;
- Controlling leachate generation and odour emissions;
- Lack of awareness; and
- Support from government.

Opportunities

- Diverting waste from landfill;
- Cheap rate for raw material;
- Effective Management of gypsum wallboard waste;
- Motivate a shift from chemical enhancers
- Job creation and support for composting businesses.

Fertilizer production from gypsum wallboard waste compost

Challenges

- Related to the composting process (Section 3.6.3.2.1).

Opportunities

- Source of Ca and S. Sulphur is released over a year after application;
- Reduce negative environmental impacts associated with chemical fertilizer; and
- Cheaper than chemical fertilizer

Section 4.4.2 outlines the results of challenges and opportunities outlined by participants from interviews.

4.4.2 Results on challenges and opportunities from interviews

Respondents were requested to describe their experiences on the challenges and opportunities related to the use of gypsum wallboard waste in composting and fertilizer applications. The results of the interviews are outlined in the sub-sections to Section 4.4.2 of this dissertation.

4.4.2.1 Composting

The use of gypsum wallboard waste in composting is successfully practiced internationally (section 3.5.1.4.2). It was therefore vital to investigate the challenges and opportunities experienced by the interviewed participants where wallboard waste was used composting. The participants interviewed for this research are either aware or have experience using gypsum wallboard waste in composting. From the nine participants, two participants showed an interest in utilising gypsum wallboard waste in their composting processes whilst the remaining seven indicated a lack of interest. The results are discussed below in detail.

4.4.2.1.1 Negative response towards the use of gypsum wallboard

As already mentioned above, seven respondents (78%) indicated a lack of interest in utilising gypsum wallboard waste in their processes. The respondents were not interested in discussing further the issues surrounding the gypsum wallboard waste in composting. It is also important to note that these respondents currently utilise natural gypsum in their composting process.

However, one participant indicated that their International Organization for Standardization (ISO) certification did not permit the use of recycled gypsum or waste in their compost and therefore were not interested. A further three respondents mentioned that they were not interested in utilising gypsum wallboard waste as an additive and did not provide a reason for the lack of interest. The remaining three respondents with experience in trialling gypsum wallboard waste in composting expressed their lack of interest in gypsum wallboard wallboard/plaster quality as they mentioned that it was unsuitable for composting due to the inability of the gypsum to biodegrade, therefore, making the final product appear substandard.

Composting reduces costs, minimises the dependencies on chemical fertilizer, conserves natural resources and benefits plant production (Drechsel & Kunze, 2001). The benefits of gypsum wallboard waste in composting have been thoroughly discussed in detail (Arnold, 2011; Batham *et al.*, 2013; Bernard, 2013; Dave, 1999; Gharaibeh *et al.*, 2014; Marvin, 2000; MTPROG, 2008; Richards, 2013; Townsend & Cochran, 2003; Richards, 2013). Additionally, the results from the composting field experiment in this study also indicated that the gypsum wallboard waste was suitable for use in composting and did not affect the compost parameters if the process is managed properly (section 4.3.2.1.2).

Therefore, the three respondents that did not provide reason why they were not interested in utilising the gypsum wallboard waste, the lack of education and awareness on the benefits of gypsum wallboard waste from manufacturing processes in composting might be a major contributing factor to the resistance towards using gypsum wallboard waste in compost (Ayilara *et al.*, 2020; Jimenez -Rivero & Navarro, 2017a). Thus, it is worth carrying out educational campaigns to educate composters on the benefits of recycling and utilising recycled gypsum from wallboard waste in their processes. Also, processing techniques to ensure the final compost produced from gypsum wallboard waste does not resemble a substandard quality can be researched and implemented (if cost effective). This can help achieve high beneficiation rates of gypsum wallboard waste and also reduce the 90% of waste currently being disposed in South African landfills.

4.4.2.1.2 Positive response towards the use of gypsum wallboard

Two out of nine respondents (22.2%) indicated an interest in utilising gypsum wallboard waste in their composting process, in both powder form and the original state of the wallboard waste. These respondents currently mix gypsum wallboard waste with organic matter to produce sellable compost. However, they mentioned that the material should be clean and uncontaminated with other material such as plastic, rubber, strapping etc. Of importance in this study, both respondents understood the importance of diverting the gypsum wallboard waste from landfill in terms of the

benefits in recycling and reducing the environmental impacts. This is a crucial step towards implementing the waste hierarchy and successfully diverting this waste from landfill.

The opportunities associated with composting gypsum wallboard waste as an alternative were related to the beneficial uses of gypsum as described in section 3.7.3.1. The respondents both mentioned that based on their experience on the use of gypsum, it assisted with drainage, improved soil structure, loosened the final product and loosened soils that were previously compacted as a result of over cropping and flooding. The study found that the mentioned benefits correlate with the findings identified in the literature (Bernard, 2013; Gharaibeh *et al.*, 2014; Weggel *et al.*, 2010).

The challenges of composting gypsum wallboard waste were largely related to operational requirements. Achieving the appropriate proportions of the wallboard waste to organic matter without exceeding the sufficient quantities was mentioned as one of the biggest challenge. This study, however, showed that 50% of gypsum wallboard waste can be incorporated in composting without impacting the required compost parameters. Thus, maintaining the appropriate levels for each of the parameters required in the composting process is essential (section 3.7.3.2.1). Also, the respondents mentioned that sometimes they receive the gypsum wallboard waste contaminated with other material (i.e. plastic, wood etc.) and sometimes the boards received are over-size and cannot be composted as is. This results in their operation incurring costs as they have to pre-process the material at their own cost prior to incorporation. Also, this causes delays in their processes which impacts on their overheads as

Most of challenges identified from the literature (section 3.7.3.2 and 4.4.1) such as the generation of leachate and odours, the lack of adequate space required for composting and the lack of support from government were not of concern in this study. This is because the composting of the gypsum wallboard waste was already being conducted at facilities that are operational and legally compliant with the law. Therefore, the negative environmental factors (i.e. leachate, odours) associated or resulting from composting and the legal requirements prior to conducting the process (i.e. registration, licenses etc.) were already accounted for. Also, the activities are being carried out in facilities with adequate space and are already compliant with the applicable and relevant requirements of the law.

4.4.2.2 Fertilizer production

Seven gypsum containing fertilizer producers were invited to participate, and only two responded (29%). From the two respondents, one indicated a lack of interest stating that the composition of the gypsum wallboard waste was not suitable for the agricultural industry. The other respondent

showed interest in utilising wallboard for fertilizer production. However, they mentioned that the gypsum wallboard waste should satisfy the following requirements:

- Powders with a D50 of minimum <40um with 100% passing 100um screen;
- Heavy metals below the minimum agriculture standard;
- Moisture levels below 12%;
- Supplied as a free flowing bulk powder in 34 mt Tanker lots or in 1mt bulk bags;
- Volumes could be between 200 to 2000 tpm or 12000 pa;
- A gate fee of R700 to R800/mt (excl. VAT) delivered;
- Consistent quality;
- Guarantee of supply;
- Detailed laboratory analysis; and
- Non-contaminated.

Although the challenges of utilising gypsum wallboard waste for fertilizer production were not directly communicated, they were inferred by the researcher based on the above requirements. For example, the gypsum was required to be in powder form. South Africa currently does not possess the technology to separate the paper from the gypsum. This presents a challenge in meeting the above requirements. Furthermore, a gate fee of R700-R800 /mt was expected prior to the acceptance of the powder gypsum for reuse purposes. As already mentioned in section 3.5.2.1.4 above, landfill disposal in South Africa remains a cheaper method for waste disposal with gate fees ranging between R170 and R584 per tonne across the metropolitan municipalities (GreenCape, 2020).

Based on the above, the price for reuse of gypsum is greater than the price for landfill disposal making this option unfeasible. To encourage recycling or reuse of the gypsum wallboard waste, the gate fee for landfills need to be higher than those for recycling (Jimenez-Rivero & Navarro, 2017a). Alternatively, there is a need to promulgate legislation to prohibit the disposal of gypsum wallboard waste in South African landfills or to implement a landfill tax as is the case in the European Union, North and South America (Section 3.4.2.1 above). On the other hand, the field experiments in this study showed that up 20% gypsum wallboard waste can be used to produce a fertilizer of acceptable quality. Thus, the gypsum wallboard waste can be utilised in its original form to generate a fertilizer, a cheaper alternative to converting the gypsum to powder form.

In terms of the opportunities, the study found that the opportunities for utilising gypsum wallboard waste in fertilizer production were similar to the benefits of utilising gypsum in composting. The respondent mentioned that the gypsum did not increase soil alkalinity or acidity, and that it remediated saline soils and removed excess sodium levels in the soil. In addition, the experiments in this study also found that fertilizer produced from gypsum wallboard waste is cheaper than

chemical fertilizers and increased the calcium and sulphur content in addition to destroying infectious pathogens. Furthermore, the associated environmental benefits include the reduction of greenhouse emissions and elimination of soil organisms and cause diseases in humans (Ayilara et al., 2020).

4.4.3 The views of wallboard manufacturers in the use of recycled gypsum from wallboard waste

In addition to investigating the opportunities and challenges, the study investigated how wallboard manufacturers viewed the use of recycled gypsum from wallboard waste in their manufacturing processes.

Two wallboard manufacturers were invited to participate in the interview and two wallboard manufacturers responded (*Note: there are only two wallboard manufacturers in South Africa*). The findings from the interviews were discussed below:

- The cost of recycling is too high (e.g. required a lot of testing and payback takes a while), therefore, it was concluded that the project would not be feasible for the organizations at this time.

The recycled gypsum should meet the specifications of the gypsum used as a raw material, and consistent volumes must be guaranteed (Eurogypsum, 2015b). Therefore, each load of recycled gypsum needs to be tested before incorporating into the wallboard manufacturing process Breslin (2010). This presents cost implications for the parties conducting the recycling (i.e. waste management/ recycling company or wallboard manufacturers). In addition, it is important that an end-market for the recycled gypsum is established (Jeffrey, 2011; Ndukwe & Yuan (2016); Townsend & Cochran 2003). The successful model used internationally (Europe, North America and Asia) involves partnerships between recyclers and manufacturers to ensure sustainability (Gypsum Recycling International, 2013). Thus it is worth replicating a similar model in South Africa to secure an end-market thereby justifying the cost involved in the process.

- Future plans to reuse recycled gypsum into the manufacturing process have been factored in. The volumes of manufacturing waste generated are insignificant compared to the volumes required for the production of new wallboard and therefore, will not make a difference in the manufacturing of new wallboard. However, the recycling of the waste will benefit the environment (through diverting from landfill), improve the image of the company will allow for incentives through the Leadership in Energy and Environmental Design (LEED) program.
- The impact of the gypsum wallboard waste on the environment and the need to divert from landfill is well understood.

The impact of the gypsum wallboard waste on the environment such as the H₂S emissions in landfills is understood, and therefore recycling will reduce these impacts.

- The opportunities associated with utilising recycled gypsum are understood and recognised
- Another finding from the interviews was related to cost-saving. Since gypsum is the main ingredient in the manufacturing of new wallboard, and since recycled material is cheaper than virgin material, acquiring the material at a cheaper rate will benefit organizations.

The results from this study have revealed that South African wallboard manufacturers were interested in utilising recycled gypsum in new wallboard production processes. In addition, they are aware of the cost implications, environmental problems and opportunities related to the recycling and reuse of the gypsum wallboard waste. These include the importance of diverting the waste from landfill, rigorous quality assurance of the recycled material, acquiring raw material at a cheaper rate, improving the company image and earning points from the green building council. However, the lack of the paper-gypsum separating technology is currently the major stumbling block. Other benefits associated with utilising recycled gypsum include preserving landfill airspace and reducing the depletion of natural gypsum and reducing greenhouse gas emission by 9% (Jiménez -Rivero *et al.*, 2016). Based on this findings, there is no reason as to why the recycled gypsum cannot be used in South African wallboard manufacturing companies since this technique is already practiced internationally (Eurogypsum, 2015b).

- Technical specifications and criteria: European guidelines for recycled gypsum vs South Africa

The technical specifications expected by manufacturer 1 for recycled gypsum were similar to the required European guidelines for recycled gypsum (Table 4-11 and Table 4-12), although variations were observed for the gypsum purity and soluble chlorides. In contrast, manufacturer 2 had a higher tolerance of the permitted moisture content than the European requirements and the thresholds for magnesium salt were more stringent than the European standards.

Table 4-11: Comparison of recycled gypsum parameter requirements in South Africa and Europe

Parameter	Unit	Reference standards	GtoG guidelines on gypsum recycling standards	Manufacturer 1	Manufacturer 2
Maximum size	Mm	EN 933-1	15	5 - 15	15
Free moisture	% w/w	VGB-M-701	<10	<10	30
Purity	% w/w	VGB-M-701	>80	>85	

Parameter	Unit	Reference standards	GtoG guidelines on gypsum recycling standards	Manufacturer 1	Manufacturer 2
Total Organic Carbon	% w/w	EN 933-1	<1.5	<1.5	
Magnesium Salts	% w/w	VGB-M-701	<0.1	<0.1	0.01
Sodium salts	% w/w	VGB-M-701	<0.06	<0.06	
Potassium salts	% w/w	VGB-M-701	<0.05	<0.05	
Soluble chlorides	% w/w	VGB-M-701	<0.05	<0.02	
pH	% w/w	VGB-M-701	6-9	6-9	6.7

Furthermore, the thresholds for the heavy metals for manufacturer 1 were more similar to the European guidelines, whereas manufacturer 2 indicated more stringent requirements than the European guidelines (Table 4-12). Both manufacturers 1 and 2 indicated do not utilise asbestos in their processes.

Table 4-12: Heavy metal requirement comparisons in South Africa and Europe

Parameter	Unit	GtoG guidelines on gypsum recycling standards	Manufacturer 1	Manufacturer 2
Arsenic (As)	mg/kg	<4	<4	<1
Beryllium (Be)	mg/kg	<0.7	<0.7	
Lead (Pb)	mg/kg	<22	<22	6.6
Cadmium (Cd)	mg/kg	<0.5	<0.5	0.5
Chromium (Cr)	mg/kg	<25.0	<25	1.7
Cobalt (Co)	mg/kg	<0.4	<0.4	
Copper (Cu)	mg/kg	<14	<14	24
Manganese (Mn)	mg/kg	<200	<200	
Nickel (Ni)	mg/kg	<13	<13	0.5
Mercury (Hg)	mg/kg	<1.3	<1.3	<0.5
Selenium (Se)	mg/kg	<16	<16	<2
Tellurium (Te)	mg/kg	<0.3	<0.3	

Parameter	Unit	GtoG guidelines on gypsum recycling standards	Manufacturer 1	Manufacturer 2
Titanium (Ti)	mg/kg	<0.4	<0.4	
Vanadium (V)	mg/kg	<26	<26	1.7
Zinc (Zn)	mg/kg	<50	<50	3.5
Asbestos	Yes/No	No	No	No
Radioactivity Index (RI)	<0.5	<0.5	Natural gypsum does not have radioactivity	

The results showed that the wallboard manufacturers were interested in utilising recycled gypsum in the manufacturing of new gypsum wallboard. This was not motivated by the generated manufacturing waste as the volumes are minimal compared to the volume of raw material required. Instead, the recycling was motivated by factors such as improving company image, achieving the set environmental targets and earning reward points from the green building council.

The variations in the quality requirements between the South African gypsum wallboard manufacturers are due to their unique production and processing standards and the type of gypsum wallboard they manufacture. Thus, the study has discovered that there is no “one size fits all” in the quality requirements and that the recycling process will need to be adjusted to accommodate the different expected requirements.

The use of recycled gypsum in the manufacturing of new wallboard is widely used in Belgium, Finland, Sweden, the Netherlands, Denmark and the United Kingdom by companies that also exist in South Africa (Eurogypsum, 2015b). Based on the fact that recycled gypsum consists of similar physical and chemical properties (Geraldo *et al.*, 2017; Penheiro & Camarini, 2015; Sayonara *et al.*, 2015), flexural strength (Ahmed *et al.*, 2011; Erbs *et al.*, 2018; Geraldo *et al.*, 2017; Rossetto *et al.*, 2016), and energy requirements (Erbs *et al.*, 2018) as natural gypsum, and the fact that the gypsum wallboard manufacturing companies in South Africa have a global footprint, the similarities between the European guideline and Manufacturer 1 in South Africa indicates the possible success of incorporating recycled gypsum in South Africa. Therefore, should conditions allow, replicating the process in South Africa is possible. Thus, there is no reason as to why new wallboard cannot be manufactured from recycled gypsum.

4.5 Chapter conclusion

The gypsum wallboard waste used in this study was classified as non-hazardous indicating that it will not pose any physical, health or environmental hazards when applied in alternative uses. This was in correlation with international classifications for gypsum wallboard suggesting that it can be applied in similar alternatives as those applied internationally and identified in literature. In addition, the composition and physico-chemical properties of the gypsum wallboard waste indicated that it will not influence the properties of the alternative use because the presence of heavy metals were very low compared to the stipulated thresholds and the neutral pH and low electrical conductivity values suggested that the wallboard waste will not adjust water and soil pH as well as contribute to increased salinity when applied to alternative uses. Thus, the gypsum wallboard waste was potentially suitable for alternative uses.

Furthermore, this study showed that the gypsum wallboard waste dampened the temperature but the moisture content, electrical conductivity, and pH of the compost remained within the required composting parameters. Also, the sodium concentrations and the heavy metals were reduced suggesting that gypsum wallboard waste is capable of reducing the salinity and toxic levels of heavy metals in compost to below lethal level. In addition, this study also showed that the gypsum wallboard waste was suitable for fertilizer production. However, up to 20% of gypsum wallboard waste can be added to produce a fertilizer before the boron concentrations are reduced to deficiency levels. Also, the fertilizer produced from the gypsum wallboard waste was inferior and would need to be supplemented with a nutrient rich fertilizer as the NPK values were within the lower ranges of the acceptable limits. Furthermore, the gypsum wallboard waste drastically reduced the concentrations of pathogens as a result of nutrient deficiency. The concentrations of calcium and sulphur nutrients increased in correlation to the quantity of gypsum wallboard added. This suggested that gypsum wallboard waste supplied the essential nutrients required by plants.

The results from the interviews revealed that 78% of composters were not interested in utilising gypsum wallboard waste in their processes either because of its origin- wallboard/plaster quality, organizational ISO certification or the fact that it makes the final product appear substandard. The results also revealed that gypsum was required in powder form to be accepted for fertilizer production in addition to a gate fee cost higher than the landfill gate fee. This presents challenges because landfill disposal remains a cheaper method of waste disposal in South Africa and the technology required to convert the gypsum into powder form is currently unavailable. Therefore, there is a need for legislative intervention such as landfill restrictions for gypsum wallboard waste and landfill taxes to move this waste up the waste management hierarchy. On the other hand, this study showed that up to 20% gypsum wallboard waste can be used to produce a fertilizer of acceptable quality. Thus, indicating that gypsum wallboard waste can be utilised in its original form to generate a fertilizer, a cheaper alternative to converting the gypsum to powder form.

Furthermore, the study also found that gypsum wallboard manufacturers in South Africa were interested in utilising recycled gypsum in the manufacturing of gypsum new wallboard. However, the manufacturing waste played a small role in driving recycling, due to the fact that the volumes of the waste were minimal compared to the volumes required as raw material in the production of new wallboard. Instead, recycling was motivated by factors such as improving company image, achieving the set environmental targets and earning reward points from the green building council. In addition, the expected quality requirements for recycled gypsum for one gypsum wallboard manufacturer were similar to the requirements of recycled gypsum in European. Since the South African wallboard manufacturing companies have a global footprint, and since the recycling of gypsum wallboard waste is successfully established internationally, this suggested that the gypsum wallboard waste generated in South Africa can also be successfully recycled provided that the expected specifications are met.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Introduction

This study aimed to explore the alternative options to landfill disposal for gypsum wallboard waste. The study made use of a sequential mixed method design through the use of *qualitative* data collection and analysis followed by *quantitative* data collection and analysis to meet its objectives. Conclusions and recommendations, as they relate to the three research objectives are provided in Sections 5.2 and 5.3.

5.2 Conclusions

The conclusions related to the three research objectives are outlined in the following sub-sections:

5.2.1 Conclusions on research objective 1: Evaluating the properties of gypsum wallboard waste

The gypsum wallboard waste used in this study was classified as non-hazardous in accordance with the GHS SANS 10234 classification suggesting that the wallboard waste will not pose any physical, health or environmental hazards when applied in alternative uses. This was in correlation with international classifications for gypsum wallboard which also suggested that it can be used in similar alternatives as those applied internationally and identified in literature.

In addition, the composition and physico-chemical properties of the gypsum wallboard waste indicated that it will not influence the properties of the alternative use because the presence of heavy metals were very low compared to the required limits, suggesting that the gypsum wallboard waste will not present any harm associated with the presence of heavy metals. The neutral pH, low electrical conductivity and low moisture content suggested that the wallboard waste will not adjust pH of the alternative use and will not contribute to increased salinity. Also, the physical state of the gypsum wallboard will allow for easy paper-gypsum separation during recycling. Thus, the gypsum wallboard waste was found to be suitable for alternative use other than landfill disposal (based on its composition and physico-chemical characteristics).

5.2.2 Conclusions on research objective 2: Identifying the alternatives to the disposal of gypsum wallboard waste

The review of literature identified several alternative uses of gypsum wallboard waste including manufacturing of new wallboard, manufacturing of portland cement, manufacturing of ceramics, manufacturing of concrete, and other uses such treatment of waste-water contaminated with heavy metals, agriculture (composting, fertilizer production and animal bedding), improving the drying rate of paint, treatment of acid mine drainage contaminated with heavy metals and the

extraction of elemental sulphur used as raw material in processes generating phosphate fertilizers and sulphuric acid.

Composting and production of fertilizer were identified as the feasible/viable alternatives within the South African context and were further investigated through field experiments. The results showed that the gypsum wallboard waste in composting dampened the temperature of the compost, increased the electrical conductivity, and reduced the moisture content and pH of the compost but did not contribute to the heavy metal contents of the composting process. Instead, sodium and the concentrations of heavy metals were reduced suggesting that gypsum wallboard waste is capable of reducing the salinity and toxic levels of heavy metals in compost to below lethal level.

In addition to composting, this study also showed that the gypsum wallboard waste was suitable for fertilizer production. However, up to 20% of gypsum wallboard waste can be added to produce a fertilizer before the boron concentrations are reduced to deficiency levels. Also, the fertilizer produced from the gypsum wallboard waste would need to be supplemented with a nutrient rich fertilizer as the NPK values were within the lower ranges of the acceptable limits. Of interest to this study, the gypsum wallboard waste drastically reduced the concentrations of pathogens, and increased the concentrations of calcium and sulphur nutrients in correlation to the quantity of gypsum wallboard added. This suggested that gypsum wallboard waste supplied the essential nutrients required by plants in addition to eliminating infectious pathogens in compost that are harmful for human and animal consumption.

5.2.3 Conclusions on research objective 3: Investigating the opportunities and challenges associated with wallboard waste in composting and fertilizer production and, investigating the views of wallboard manufacturers toward the use of recycled gypsum from wallboard.

Opportunities and challenges related to the alternative uses of gypsum wallboard waste were investigated by means of literature review, and through interviews with certain stakeholders (i.e. composters, fertilizer producers and wallboard manufacturers).

The results from the interviews revealed that 78% of composters were not interested in utilising gypsum wallboard waste in their processes either because of its origin- wallboard/plaster quality, organizational ISO certification or the fact that it makes the final product appear substandard. The results also revealed that the challenges associated with the use of gypsum wallboard waste in composting were not related to quality instead they were related to operational processes (i.e. maintaining the composting parameters). The composting experiments in this study successfully showed that the wallboard waste did not affect the composting processes, and the compost produced was of acceptable quality.

Therefore, the negative perceptions around gypsum wallboard waste (potentially due to lack of awareness and education on the use of recycled gypsum or gypsum wallboard waste) is one of the causes hindering the reuse and recycling of the gypsum wallboard waste. Composting of gypsum wallboard waste minimises the dependencies on chemical fertilizer, conserves natural gypsum resources, benefits soil fertility and offers a waste management solution for gypsum wallboard waste that would have otherwise landed in landfill, thus, the benefits of utilising gypsum wallboard in compost outweigh the challenges and should be considered.

The study also revealed that gypsum was required in powder form to be accepted for fertilizer production in addition to a gate fee cost higher than the landfill gate fee. In a country like South Africa where landfill disposal remains a cheaper method of waste disposal and the technology required to convert the gypsum into powder form is currently unavailable, this is, currently, not a feasible and viable option. Therefore, there is a need for legislative intervention such as landfill restrictions for gypsum wallboard waste and landfill taxes to move this waste up the waste management hierarchy as is the case in Europe and the Americas. Field experiments in this study showed that up to 20% gypsum wallboard waste can be used to produce a fertilizer of acceptable quality. Gypsum wallboard waste can be utilised in its original form to generate a fertilizer, a cheaper alternative to converting the gypsum to powder form.

Furthermore, this study also found that gypsum wallboard manufacturers in South Africa were interested in utilising recycled gypsum in the manufacturing of new gypsum wallboard. The manufacturing waste played a small role in driving recycling, due to the fact that the volumes of the waste were minimal compared to the volumes required as raw material in the manufacturing of new wallboard. Instead, recycling was motivated by factors such as improving company image, achieving the set environmental targets and earning reward points from the green building council. The expected quality requirements for recycled gypsum for one gypsum wallboard manufacturer were found to be similar to the requirements of recycled gypsum in Europe. Since the South African wallboard manufacturing companies have a global footprint, and since the recycling of gypsum wallboard waste is successfully established internationally, this suggested that the gypsum wallboard waste generated in South Africa can also be successfully recycled provided that the expected specifications are met.

5.3 Recommendations and areas of future research

The sub-sections below provide practical recommendations related to this study, as well as recommendations for further research.

5.3.1 Practical recommendations related to alternative uses of gypsum wallboard waste

The practical recommendations related to the scope of this study includes:

- Conduct trials to investigate the effect of the resultant compost and fertilizer obtained in this study to determine the impact of the varying amounts of gypsum wallboard on the soil and plants;
- Conduct trials to investigate the type of microorganism that are affected by the presence of gypsum wallboard to determine the impact of gypsum wallboard on the “healthy” bacteria.
- Increased education and awareness on the use of recycled gypsum and gypsum wallboard waste to promote and encourage the use of gypsum wallboard waste in alternative uses.
- Conduct an optimisation study to investigate the amount of gypsum wallboard added and cost of adding nutrient rich fertilizer in order to produce a suitable fertilizer from gypsum wallboard waste.

5.3.2 Areas of future research:

To fully understand the influence and impact of gypsum wallboard waste, the following are worth investigating:

- Conduct trials to separate the paper and gypsum from gypsum wallboard waste.
- Conducting trials to test the use of gypsum wallboard waste on other alternatives not tested in this study.
- Investigate the potential of gypsum wallboard waste from C&D projects in alternative uses.

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APPENDICES

Appendix A: Interview Schedule Guide:

Questions	Composter 1	Composter 2
What does your company do?	We compost various organic material to produce a compost. The compost is sold to end-markets such as garden services, nurseries, landscapers, and homeowners.	We are an organic waste recycling company. We use all kinds of organic waste and turn it into compost.
Do you use gypsum in your processes?	I have never used gypsum in my composting processes before but I have read it can be used. I also know someone who used to work for a gypsum manufacturing organization. They have told me about its benefits. I only started utilising gypsum wallboard waste towards the end of last year.	We done some composting of gypsum boards in recent years
Would you be interested in utilising gypsum wallboard waste?	Yes	Yes we would
Do you think the gypsum wallboard waste will add value to your process?	It will also help the final product to be loose. it will help with the drainage.	Yes. Gypsum in general helps with the breaking of compact soils due to over cropping, flooding etc and improves soil structure.
How much gypsum (per month) due you currently use		At the moment we receive this product occasionally. There is constant flow of it.

What are the cost implications associated with using this gypsum?	It is cheaper than the purchasing raw gypsum	The only additional cost is that the boards need to be grinded into smaller pieces to be able to breakdown within the six week composting period.
Are sufficient volumes always available?	Yes	No
Have you considered utilising or incorporating gypsum wallboard waste in your composting processes?	Yes	Yes we have but that waste stream is not currently sustainable.
What are your views on diverting gypsum wallboard waste from landfill?	It is very important as landfill space is limited and will become more and more expensive when the landfills close to the urban centres reach their life span	We need to divert all organic and recyclable materials from landfill.
What characteristics are you looking for in order for it to be acceptable?	Yes, the gypsum wallboard must be clean and shredded not contaminated at all. Must not contain plastic, strapping and plastic bags	The must clean, not contaminated with other non-organic materials like cement, plastic, rubber, etc.
How much of this waste are you prepared to utilise in your processes?	I am limited to how much organic materials I have on hand to mix in with	Composting is very hands on. You need to know and understand the different waste products and how much of each can be used. Composting is not about adding a whole lot of organics and think you have compost. It's a process that cannot be rushed. You working with live micro-organisms and too much of some waste product, even organic, is not always good for the process. The same will apply with the gypsum.
Are there any other requirements for utilising the gypsum wallboard in your system	I would like to receive the gypsum wallboard waste shredded or in smaller pieces. Must not contain any toxic elements/composition.	No
What volumes would you require on a monthly basis	This would be dependent on the availability of other organic materials	We can use up to 500 tonnes per month.
What form of the gypsum wallboard waste you would require? Powder? Or as wallboard?	Both	Both

What are the challenges and opportunities associated with using the gypsum wallboard waste in your system	At the moment, one of challenges is the size of the board I am currently receiving. I sometimes receive the gypsum wallboard in its original manufactured sizes. Receiving larger chunks of the wallboard means I have to make plans to reduce the material to workable sizes. This is labour intensive and increases handling costs. The other challenge is quality control, one day a load comes shredded, the next load comes with enormous boards that have not been shredded. Some boards come in a pack of say 10 boards still with strappings on. Plastic bags, strapping and cornice corner spacers contaminating the gypsum wallboard. This all has to be sorted by hand increasing handling costs and delaying productivity of the operation. Paint/Waterproofing on some of the gypsum wallboard also inhibits the composting process reducing productivity of the operation. Benefits With regards to benefits, gypsum will help the final product remain loose and also helps with drainage.	The challenges would be of how much (%) of the gypsum boards can be used at once in the process before you step over the line of too much. The benefits is the same as point 4
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Are there any costs associated with testing and analysing the compost to ensure it is within spec? Is this a challenge		Yes and No
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Fertilizer Producers

What characteristics are you looking for in order for it to be acceptable? What are the quality requirements (ranges please)?	Requirements would be as follows: • Powders would need to have a D50 of minimum <40um with 100% passing 100um screen. • Heavy metals and any other contaminants would have to be assured to be below the minimum Agric standard. • Moisture levels below 12%. • Supplied as a free flowing bulk powder in 34mt Tanker lots or in 1mt Bulka bags. • Volumes could be between 200 to 2000tpm or 12000pa. • Required price indications would be in the range of R700 to R800/mt (exc.vat),
Are there any other requirements? Please elaborate	We would only be interested in a consistent and dependable dry source of uncontaminated super fine gypsum powders. You would have to prove that you could supply this into our production starting with a detailed analysis of the waste components included with, or in the Gypsum (there could also be undesirable levels of sodium from the sodium silicate or polyacrylates that could be used in the production of these waste Gypsum boards and panels?)
Challenges and opportunities	Unless the source and storage conditions of this waste material can be controlled, there will be a high risk of exposure to weather and other potential contaminants and this could leave the original dry waste material sodden and contaminated, being very hard and costly to process back into a dry form. A wet slurry process may be better cost option to supply directly into the composting market.

	However caution would need to be ensured with any soil application recommendations that should be through a qualified agronomist for various soil applications due to the risk of over applying with the negative effects of Mg and K shortfalls. As high quality Gypsum can be a good source of both Calcium and Sulphur, without increasing any soil alkalinity or acidity, it would be easy to promote within our various granules. Gypsum is also a useful product used to help remediate saline soils, removing excessive sodium levels.
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Gypsum wallboard manufacturers

Questions	Manufacturer 1	Manufacturer 2
What type of gypsum do you use to manufacture the gypsum wallboard? Is it synthetic or natural?	Natural and Synthetic	Natural
Where is it sourced?	Natural- Imported. Synthetic-Local	Local
Cost implications?	Gypsum mines located in the Northern Cape. However, transportation from Northern Cape to Gauteng is expensive. Railway not ideal due to potential contamination. Also, the gypsum has high salt content. Salt affects the bond between the paper and the gypsum. So currently imports gypsum. Importing is cheaper than transporting by road from the Northern Cape.	
Are sufficient volumes always available?	Yes	Yes
What is the most common board size you produce?	6.4mm (ceilings in homes), 9.5mm (ceiling tiles), 12.5mm (walls), 15mm (hotel).	6mm
The types of boards you produce	Moisture resistant and Fire resistant	Plaster, Moisture, Fire, Noise and tapper board.
How much manufacturing waste do you generate monthly/yearly?	400-500 tonnes/ month	600-700 month
Where is it generated in the manufacturing process?	Burnt, start-up waste, off spec etc	In the middle and the final stage of manufacturing process.
What is the % of manufacturing waste produced from the wallboard stream?	96% production rate, 4% waste	

Are you aware of the impacts of gypsum disposed in landfills?	Yes	Yes
What are your views on diverting the gypsum waste from landfill?	Gypsum wallboard causes H ₂ S odours in landfills. Need to divert to protect the environment and earn points from the Green building community.	Waste Combustion and recycling are one of the best solutions to avoid these impacts to environment
What are your future plans for the gypsum wallboard waste you generate?	Recycle back into the process	Recycling
Have you considered recycling the gypsum wallboard back into your manufacturing process?	Yes. Have tried it before. Payback takes a while	We have tried recycling our own stucco from scrap boards however, this process proved to be more difficult to separate paper and gypsum. In addition, it needs lot of lab test to ensure that it matches the same standard of our recipe.
What characteristics are you looking at in order for it to be acceptable to be recycled? (Please Refer to attached excel spreadsheet)	For wallboard >95%. For plaster 100% purity	Moisture and pH of a certain % of the solution
How much of this waste are you prepared to recycle?	Have trailed 100 tonnes before. 60% is recyclable	
Is the waste enough to add value back to the production process?	Production rate is 95% and manufacturing waste is 5%. The volumes are not enough but we want to do it for the image, environment and Green building.	Yes, although is scrap is still a composition of good stock that we put in there, so having less scrap is saving on manufacturing variance. Yes, Gypsum is our primary raw material, without it there's no production process. The cheaper we can get gypsum the better the savings for the company.
Perceived Challenges/ Opportunities associated with using the recycled gypsum? -	Opportunities- Waste minimisation, company image, alleviate pressure on gypsum natural resources, cost reduction as recycled gypsum costs less than natural gypsum	Challenge: There's very few people in the market that are doing the separation process of plasterboard and stucco, due to lack of those services it becomes a bit costly to recycle. Opportunities: Gypsum is our primary raw material, without it there's no production process. The cheaper we can get gypsum the better the savings for the company provided that the gypsum meets the QC spec, reusing it won't be an issue

Appendix B: Invitation to participate



Faculty of Natural and Agricultural Sciences
North-west University
Potchefstroom Campus
Private Bag X6001
Potchefstroom
2520

Dear Sir/Madam

Re: Request for voluntary survey participation on the following research topic:

Exploring gypsum wallboard waste disposal alternatives

My name is Rudzani Muedi. I am a Masters student from the Faculty of Natural and Agricultural Sciences, specializing in Waste Management at the North-West University. I am carrying out a research that seeks to establish the alternative uses of gypsum wallboard waste in South Africa. In order to answer the research question, the study aims to explore the alternative options to landfill disposal of gypsum wallboard waste. The study aims to achieve this by investigating the alternative uses of gypsum wallboard waste suited for the South African environment as well as establish the opportunities and challenges associated with these alternatives. In addition, the study aims to investigate the interest levels of various stakeholders in diverting this material from landfill.

The study has identified fertilizer production from gypsum wallboard waste as one of the alternatives. For this reason, I wish to understand the interest levels of fertilizer producers in incorporating gypsum wallboard waste into the composting processes. I would like to conduct an interview with you which will take 30mins to 45mins of your time. The information obtained from the interview will be used for the purpose of the dissertation. I assure you that your identity and that of your company or firm will be left anonymous. For further information on the research you can contact my supervisor Dr Claudine Roos at claudine.roos@nwu.ac.za

Yours Sincerely

Rudzani Muedi

Appendix C: Interview consent form



Name of Researcher: Rudzani Melba Muedi

Project Title: **Exploring gypsum wallboard waste disposal alternatives**

Aim of Research: To explore the alternative options to landfill disposal of gypsum wallboard waste

Objectives of the Research:

- Research objective 1: Evaluating the physico-chemical properties of gypsum wallboard waste
- Research objective 2: Identifying the alternatives to the disposal of gypsum wallboard waste.
- Research objective 3: Investigating the views of wallboard manufacturers with regards to gypsum wallboard waste recycling and, the opportunities and challenges associated with wallboard waste in composting and fertilizer production.

Please tick in the box after each statement to which you wish to consent.

1.	I have read and understood the information sheet provided to me regarding the above mentioned title and I have had the opportunity to consider the information contained therein.	
2.	I have been made aware of the purpose of the study.	
3.	The interview will take approximately 45 minutes to 1 hour	
4.	My participation in this project is voluntary. I may withdraw and discontinue participation at any time without penalty.	
5.	I have a right not to answer any questions that makes me uncomfortable or puts me in a risky position	
6.	I understand that the researcher will not identify me by name in any report using information obtained from this study, and that my confidentiality as a participant in this study will remain secure.	
7.	The researcher will provide me with a copy of the final writing included in the project so I can have the opportunity to verify them.	
8.	I agree to be interviewed for the purpose of the project mentioned above.	

SAFETY DATA SHEET

Section 1: Identification

Waste Name: Gypsum Board**Chemical Name/Synonyms:** Gypsum wallboard/Sheetrock/Drywall**Waste Generator:** N/A**Emergency contact person:** N/A**Emergency contact number:** N/A**Waste origin:** Manufacturing processes of ceiling boards

Section 2: Hazard(s) Identification

Hazard Classification: Not classified as hazardous in terms of SANS 10234**Signal Word(s):** N/A**Hazard Statements:** N/A**Precautionary Statements:** Precautionary statements provided to assist with safe handling and use.

P260: Do not breathe vapours

P264: Wash eyes thoroughly after handling

P270: Do not eat, drink or smoke when using this product

P281: Use personal protective equipment as required

P305+P351+P338: IF IN EYES: Rinse cautiously with water for several minutes. Remove contact lenses, if present and easy to do. Continue rinsing

P391: Collect spillage

P501: Dispose of contents/container in appropriate waste skips

Section 3: Composition/ Information on Ingredients

The gypsum board waste stream consists of the below mentioned ingredients, which may be present at or below their indicated concentrations respectively.

Chemical Name	Synonym	CAS#	Conc. %
Silicon Dioxide (Amorphous)	112945-52-5		3.62
Calcium Sulphate	7778-18-9		31.29
Phosphorous Oxide	1314-56-3		0.90
Strontium Oxide	1314-11-0		0.17

Section 4: First-Aid Measures

General Advice: When consulting a physician. Show this safety data sheet to the doctor in attendance.

After skin contact: Take off contaminated clothing and shoes immediately. Wash off with plenty of soap and water. Obtain medical advice if irritation persists or later develops.

After eye contact: Check for and remove contact lenses. Hold eyelids open and rinse thoroughly with plenty of water for at least 15 minutes. Obtain medical advice.

After inhalation: If irritation develops or persists, call for medical assistance.

After swallowing: Never give anything by mouth to an unconscious person. Rinse mouth with water. DO NOT induce vomiting.

PPE for First Aid Responders: Wear protective clothing, gloves, and eye protection.

Section 5: Fire-Fighting Measures

Extinguishing media: Use extinguishing medium suitable to surrounding environment.

Potential Products of Combustions: Oxides of silicon, oxides of sulphur, and oxides of calcium.

Protective Equipment/ Precautions for fire fighters: Wear self-contained breathing apparatus for firefighting as necessary.

Section 6: Accidental Release Measures

Personal precautions: Response and clean-up crews must be properly trained.

Measures for environmental protection: Prevent further leakage or leakage if safe to do so. Do not let product enter drains. Discharge into the environment if permitted.

Measures for cleaning/collecting: Large Spill: Collect spilled waste manually and place into appropriate receptacle ensuring measures are taken to suppress dust formation, noting that any materials used during the clean-up reflects the same hazards as the gypsum board waste stream. **Small Spill:** As per large spill

Measures for cleaning/collecting: Large Spill: None

Section 7: Handling and Storage

Precautions for Safe Handling: Handle in accordance with good industrial hygiene and safety practice. The personal protection and controls identified in Section 8 of the SDS should be used as appropriate

Precautions for Storage: Apply relevant license conditions and or National Waste Storage Standards, as relevant.

Compatibility Issues: Strong oxidising agents.

Section 8: Exposure Controls/Personal Protection

	Component	Source	Limit (mg/m3 unless otherwise stated)
Exposure limits	Silicon Dioxide (Amorphous)	OSHA	10 (TWA)
	Calcium Sulphate	ACGIH	10 (TWA)
Engineering Controls	Clean up contaminated areas		
Personal Protective Equipment	Eye Protection: Safety glasses or goggles.		
	Skin Protection: Gloves and clothing covering body as determined by a risk assessment.		
	Respiratory Protection: Suitable respiratory equipment to be selected under guidance by the relevant occupational health and safety authority.		

Section 9: Physical and Chemical Properties

Form: Solid

Colour: Brown

Odor: Not determined

Odor threshold: Not determined

pH: 7.35

Melting point/melting range: Not determined

Boiling point/boiling range: Not determined

Flash point: Not determined

Evaporation rate: Not determined

Flammability: Not flammable

Upper/lower flammability or explosive limits: Not determined
Partition coefficient: n-octanol/water: Not determined
Decomposition temperature: Not determined
Auto ignition temperature: Not determined
Solubility in/Miscibility with water: Not determined
Viscosity: Not determined
% Volatiles: Not determined

Section 10: Stability and Reactivity

Reactivity: Not subject to polymerisation under normal conditions.
Chemical stability: Stable under normal conditions.
Conditions to avoid: Incompatible materials
Incompatible substances/ materials: Strong oxidising agents.
Hazardous decomposition products: Oxides of silicon, oxides of sulphur, and oxides of calcium.

Section 11: Toxicological Information

Acute toxicity:
Potential routes of exposure/potential health effects: Dermal, inhalation, and eye contact
Skin: N/A
Eye: N/A
Inhalation: N/A
 Constituent / Ingredient Toxicity (Gypsum Board): LD₅₀ Oral:> 5000mg/kg and Dermal:> 5000 mg/kg
 LC₅₀ Inhalation > 20 mg/l
Ingestion: N/A
Carcinogenic effects: N/A
Reproductive toxicity: N/A
Irritancy of the Waste: N/A
Sensitization: N/A
Specific Target organ Toxicity: N/A

Section 12: Ecological Information (non-mandatory)

Constituent Ecotoxicity: LC₅₀ > 100 mg/l EC₅₀ > 100mg/l
Mobility: Not determined
Biodegradation: Not determined
Bioaccumulation: Not determined
Other adverse effects: None

Section 13: Disposal Considerations (non-mandatory)

As assessed in terms of the South African National Standard for the Assessment of Waste for Landfill Disposal (GN R 635 of 23 August 2013).
Potential Landfill Prohibition / Restrictions: As assessed under GN R 635 of August 2013.
Treatment Prior to Disposal: Not Determined

Section 14: Transport Information (non-mandatory)

Waste Classification: Not Classified
UN Number:
UN Shipping Name:
Packaging Group:
SANS 10228/ Transport Hazard Classes
Marine Pollutant:
Special Instructions:
Labelling Required: No label required under SANS 10228

Section 15: Regulatory Information (non-mandatory)

Safety, Health and Environmental Legislation /
 Standards / Guideline

Comments / Applicability

National Environmental Management Act, 1998 (Act 107 of 1998)[NEMA]	Principles, aims and objectives from environmental management in South Africa.	
National Environmental Management: Waste Act, 2008 (Act 59 of 2008)[NEM:WA]	Principles, aims and objectives for sound waste management practices in South Africa. Provides for, <i>inter alia</i> , the definition of 'waste'	
National Waste Classification and Management Regulations (GN R 634 of 23 August 2013)	Covers the requirements for waste management, classification and assessment for disposal to landfill of waste in South Africa.	
National Standard for the Assessment of Waste for Disposal to Landfill (GN R 635 of 23 August 2013)	Covers the requirements for the assessment of waste for disposal to landfill; where disposal is relevant.	
National Standard for the Disposal of Waste to Landfill (GN R 636 of 23 August 2013)	Covers the requirements (incl. prohibitions) for the disposal of waste to landfill; where disposal is relevant.	
SANS 10228 (The identification and classification of dangerous goods for transport)	Standard cover the identification of dangerous goods that are capable of posing significant risk to health and safety or to property and the environment; where such is linked to transport requirements for the transport of such goods.	
SANS 10232 (Transport of Dangerous Goods – Emergency Information Systems)	Covers the requirements for emergency information systems, placards and emergency information documents relevant to incidents involving dangerous goods.	
SANS 10234 (Globally Harmonised System of Classification and Labelling of Chemicals)	Covers the classification of hazardous substances, including waste, for their safe transport, use at the workplace or in the home according to their health, environmental and physical hazards, for example, acute toxicity and flammability.	
National Water Act, 1998 (Act 36 of 1998)[NWA]	Promotes the protection of water resources in the National interest.	
Occupational Health and Safety Act, 1993 (Act 85 of 1993)[OHSA], as amended	Provides for the health and safety of persons at work.	

Section 16: Other Information

Physical Hazards		Health Hazards		Environmental Hazards	
Explosives	X	Acute Toxicity: Oral	X	Acute Toxicity – Acute	X
Flammable Gases	X	Acute Toxicity: Skin	X	Acute Toxicity – Chronic	X
Flammable Aerosols	X	Acute Toxicity: Inhalation	X		
Oxidizing Gases	X	Skin Corrosion/Irritation	X		
Gases Under Pressure	X	Serious Eye Damage/Eye Irritation	X		
Flammable Liquids	X	Respiratory Sensitization	X		
Flammable Solids	X	Skin Sensitization	X		
Self-Reactive Substances	X	Germ Cell Mutagenicity	X		
Pyrophoric Liquids	X	Carcinogenicity	X		
Pyrophoric Solids	X	Toxic To Reproduction	X		
Self-Heating Substances	X	Specific Target Organ Toxicity – Single Exposure	X		

Substances That, On Contact With Water, Emit Flammable Gases	X	Specific Target Organ Toxicity – Repeated Exposure	X			
Oxidizing Liquids	X	Aspiration Hazard	X			
Oxidizing Solids	X					
Organic Peroxides	X					
Corrosive To Metals	X					

Appendix E: Ethics Approval letter



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Senate Committee for Research Ethics

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ETHICS APPROVAL LETTER OF STUDY

Based on approval by the **Faculty of Natural and Agricultural Sciences Ethics Committee (FNASREC)**, the Faculty of Natural and Agricultural Sciences Ethics Committee hereby **approves** your study as indicated below. This implies that the North-West University Senate Committee for Research Ethics (NWU-SCRE) grants its permission that, provided the special conditions specified below are met and pending any other authorisation that may be necessary, the study may be initiated, using the ethics number below.

Study title: Exploring gypsum wallboard waste disposal alternatives

Study Leader/Supervisor: Dr C Roos

Student: RM Muedi

Ethics number:

N	W	U	-	0	1	3	0	6	-	2	0	-	A	9
Institution				Study Number					Year			Status		

Status: S = Submission; R = Re-Submission; P = Provisional Authorisation; A = Authorisation

Application type: Single

Risk Category: Minimal

Commencement date: 01/02/2020

Expiry date: 01/04/2021

Approval of the study is initially provided for a year, after which continuation of the study is dependent on receipt and review of the annual (or as otherwise stipulated) monitoring report and the concomitant issuing of a letter of continuation.

Special in process conditions of the research for approval (if applicable):

- The following documentation are archived by FNASREC and should be complete and kept up to date:
 - Research proposal
 - Signed approval from the scientific committee indicating the proposed risk category
- All researchers involved in the study should submit signed NWU code of conduct statements annually.
- All researchers of low risk studies should submit proof of relevant ethics training every two years.
- All researchers that take part in activities that pose a safety and security threat to the researchers or the environment should submit a risk assessment form annually.
- All research involving human interaction should follow best ethical practise and keep documents as proof. This includes informed consent, questionnaires, incorporation of risk-benefit, and responsible data management.
- Any research at governmental or private institutions, permission must still be obtained from relevant authorities and provided to the FNASREC. Ethics approval is required BEFORE approval can be obtained from these authorities.

General conditions:

While this ethics approval is subject to all declarations, undertakings and agreements incorporated and signed in the application form, the following general terms and conditions will apply:

- *The study leader/supervisor (principle investigator)/researcher must report in the prescribed format to the FNASREC:*
 - *annually (or as otherwise requested) on the monitoring of the study, whereby a letter of continuation will be provided, and upon completion of the study; and*
 - *without any delay in case of any adverse event or incident (or any matter that interrupts sound ethical principles) during the course of the study.*
- *The approval applies strictly to the proposal as stipulated in the application form. Should any amendments to the proposal be deemed necessary during the course of the study, the study leader/researcher must apply for approval of these amendments at the FNASREC, prior to implementation. Should there be any deviations from the study proposal without the necessary approval of such amendments, the ethics approval is immediately and automatically forfeited.*
- *Annually a number of studies may be randomly selected for an external audit.*
- *The date of approval indicates the first date that the study may be started.*
- *In the interest of ethical responsibility, the NWU-SCRE and FNASREC reserves the right to:*
 - *request access to any information or data at any time during the course or after completion of the study;*
 - *to ask further questions, seek additional information, require further modification or monitor the conduct of your research or the informed consent process;*
 - *withdraw or postpone approval if:*
 - * *any unethical principles or practices of the study are revealed or suspected;*
 - * *it becomes apparent that any relevant information was withheld from the FNASREC or that information has been false or misrepresented;*
 - * *submission of the annual (or otherwise stipulated) monitoring report, the required amendments, or reporting of adverse events or incidents was not done in a timely manner and accurately; and / or*
 - * *new institutional rules, national legislation or international conventions deem it necessary.*
- *FNAS-REC can be contacted for further information or any report templates via Roelof.Burger@nwu.ac.za 018 299 4269*

The FNASREC would like to remain at your service as scientist and researcher, and wishes you well with your study. Please do not hesitate to contact the FNASREC or the NWU-SCRE for any further enquiries or requests for assistance.

Yours sincerely,



Prof Roelof Burger
Chairperson Faculty of Natural and Agricultural Sciences Ethics Committee (FNASREC)

Appendix F: Compost Results

Compost sieve test results

10% WGW (50L)	1L	>25 mm	90% Gypsum	20% WGW (50L)	2L	>25 mm	75% Gypsum
	5L	>8mm< 25 mm	35% Gypsum		6L	>8mm< 25 mm	60% Gypsum
	48L	< 8 mm	20% Gypsum		45L	< 8 mm	35% Gypsum
30% WGW (50L)	2L	>25 mm	100% Gypsum	50% WGW (50L)	8L	>25 mm	100% Gypsum
	9L	>8mm< 25 mm	80% Gypsum		9L	>8mm< 25 mm	80% Gypsum
	41.5L	< 8 mm	50% Gypsum		42L	< 8 mm	50% Gypsum

Appendix G: Results of the compost analysis

Lab Nommer	Verwysing	Beskrywing	N *	Ca	Mg	K	Na	S	P	Fe	Mn	Cu	Zn	B	pH	Calc. C *	C:N *	Moisture *	Ash *
Lab Number	Reference	Description	%	%	%	%	mg/kg	%	%	mg/kg	mg/kg	mg/kg	mg/kg	mg/kg	pH units	%	-	%	%
OM6-5099	IW2020	0383	0.55	13.70	0.46	0.19	672	5.36	0.08	8247	115	47	83	13	7.4	21.51	39,10:1	44.18	63.01
OM6-5100	IW2020	0377	0.81	9.71	0.37	0.33	1085	1.37	0.11	7459	136	82	117	16	7.4	28.41	35,08:1	50.24	51.13
OM6-5101	IW2020	0378	0.67	10.60	0.42	0.25	849	2.69	0.09	8183	121	60	88	16	7.4	26.36	39,34:1	49.76	54.67
OM6-5102	IW2020	0379	0.70	10.64	0.46	0.20	659	3.07	0.09	6375	109	53	97	14	7.4	25.70	36,72:1	47.50	55.79
OM6-5103	IW2020	0380	0.84	9.39	0.35	0.28	965	0.61	0.12	7478	141	77	114	17	7.8	30.26	36,03:1	56.84	47.95

Appendix H: Measured Temperature Readings

Date	Base Heap	10% Wallboard	20% wallboard	30% wallboard	50% wallboard	Ambient Temperature
14-Feb-20	52	39	37	36	33	29
17-Feb-20	56	54	50	50	44	29
18-Feb-20	59	57	50	51	48	27
19-Feb-20	66	58	54	53	49	27
20-Feb-20	66	57	54	52	50	29
21-Feb-20	66	60	58	56	50	28
24-Feb-20	66	61	62	62	57	26
25-Feb-20	64	60	62	60	57	26
26-Feb-20	64	59	60	58	55	28
27-Feb-20	64	59	60	57	56	29
28-Feb-20	64	60	61	61	55	27
2-Mar-20	64	60	63	61	57	17
3-Mar-20	63	60	61	59	56	24
4-Mar-20	63	59	60	58	56	27
5-Mar-20	64	60	57	57	54	28
6-Mar-20	63	60	60	58	54	26
9-Mar-20	62	58	59	57	52	28
10-Mar-20	62	58	58	57	54	28
11-Mar-20	62	59	58	55	54	28
12-Mar-20	63	57	59	57	53	26
13-Mar-20	62	57	59	56	52	25
16-Mar-20	62	56	59	56	53	26
17-Mar-20	62	57	59	56	53	21
18-Mar-20	62	57	59	55	52	23
19-Mar-20	59	52	56	55	51	28
20-Mar-20	47	38	38	36	35	28
23-Mar-20	56	43	43	42	40	23
24-Mar-20	58	42	42	42	42	27
25-Mar-20	56	41	42	40	39	29
26-Mar-20	56	37	52	40	43	27
27-Mar-20	56	37	40	40	43	24
30-Mar-20	56	37	36	37	42	22
31-Mar-20	58	47	36	38	42	24
1-Apr-20	53	50	45	45	44	26
2-Apr-20	55	48	44	45	45	18
3-Apr-20	54	45	43	45	45	20
6-Apr-20	51	45	41	44	45	26
7-Apr-20	51	45	41	42	45	27
8-Apr-20	51	41	40	42	45	22
9-Apr-20	49	44	40	42	45	20
10-Apr-20	54	44	41	43	40	21
15-Apr-20	50	44	35	40	43	21
16-Apr-20	50	40	37	40	42	22
17-Apr-20	47	38	37	38	41	23
20-Apr-20	47	42	36	40	40	25
21-Apr-20	47	39	34	37	37	26
22-Apr-20	51	43	35	39	37	25
23-Apr-20	49	37	35	39	38	23
24-Apr-20	44	35	33	35	36	22
27-Apr-20	50	39	36	40	39	19
28-Apr-20	50	39	31	34	36	15
29-Apr-20	43	35	31	33	37	17
30-Apr-20	45	34	31	35	33	20
1-May-20	53	41	39	37	35	23
4-May-20	40	34	27	31	33	23
5-May-20	40	32	26	29	31	22
6-May-20	46	34	28	33	31	24
7-May-20	42	30	27	31	32	22
8-May-20	44	31	27	29	30	23
11-May-20	44	33	29	33	31	23
12-May-20	40	30	27	28	32	23
13-May-20	43	31	29	30	31	23
14-May-20	45	37	29	29	30	22

Correlation Analysis of the compost heaps temperature profiles

	<i>Control</i>	<i>10% Gypsum wallboard waste</i>	<i>20% Gypsum wallboard waste</i>	<i>30% Gypsum wallboard waste</i>	<i>50% Gypsum wallboard waste</i>	<i>Ambient Temperature</i>
<i>Control</i>	1					
<i>10% Gypsum wallboard waste</i>	0.9280029	1				
<i>20% Gypsum wallboard waste</i>	0.9411486	0.95047359	1			
<i>30% Gypsum wallboard waste</i>	0.9299868	0.972210682	0.980152	1		
<i>50% Gypsum wallboard waste</i>	0.9148575	0.944248971	0.96004	0.973082	1	
<i>Ambient Temperature</i>	0.4881511	0.474499203	0.497254	0.459345	0.41261	1