Optimising Pulp and Paper Mill Sludge Through Alternate End of Life Pathways: Enabling the Transition Towards Circularity Within the Pulp and Paper Industry

By

Yusuf Faizel Omarjee

Submitted in fulfilment of the requirements for the degree of
Master of Science in Engineering,
School of Civil Engineering,
Faculty of Engineering,
University of KwaZulu-Natal

June 2022

Supervised by: Professor Cristina Trois
Co-supervised by: Dr Noredine Mahdjoub

Preface and Declaration

I, Yusuf Faizel Omarjee hereby declare that the research completed is my own work, except where otherwise stated. All citations, references and borrowed ideas have been duly acknowledged in text. The contents of this work is a result of my own research, results reported are due to investigations by myself, and that it has not been previously submitted by me for a degree at this or any other university or institution. This dissertation is submitted in fulfilment of the requirements for the Master of Science in Engineering degree in the School of Civil Engineering, in the College of Agriculture, Engineering and Science at the University of KwaZulu-Natal

Furthermore, I, Yusuf Faizel Omarjee, confirm that I utilised the WROSE Model in data analysis and providing recommendations. It is understood and accepted that the WROSE Model (Waste to Resources Optimisation and Scenario Evaluation) is a licensed trademarked Waste Management Support Tool developed by Professor Cristina Trois at the University of KwaZulu-Natal. I undertake not to disclose and/or reproduce and/or publish and/or utilise any part of the WROSE Model, now and in the future, in part or full, including input and/or output data from this study outside of this document without consent, in writing, from Professor Cristina Trois, or a person appointed or elected by the University of KwaZulu-Natal.

[redacted]

Yusuf Faizel Omarjee

____

Professor Cristina Trois

____

Dr Noredeine Mahdjoub

Abstract

Globally the pulp and paper industry (PPI) is regarded as one of the most polluting industries in terms of land, air and water pollution, requiring large quantities of process waters. PPI's process fibres of different origins i.e. virgin fibres, recycled fibres and non-wood fibres. The source of fibre and manufacturing processes employed determines the quantities and composition of wastes generated. Currently most PPIs, globally follow a linear economic model in which wastes generated are landfilled and is not sustainable as we strive towards a shared goal of carbon neutrality. Limited renewable natural resources and landfill airspace are facing increased demands with the latter being non-renewable. Common waste management methods of pulp and paper mill sludge (PPMS) include incineration prior to landfilling, and by enabling a transition towards a circular economy will facilitate the addition of economic value to 'wastes' generated. Adopting circularity facilitates the utilisation of alternate pathways by maximising the benefits posed by such resources, simultaneously reducing quantities of waste requiring landfilling. Increased levels of sustainability can be achieved through mitigating the ever-increasing demands placed on limited natural resources through reuse and recycling efforts.

This research which was a desktop study focused on alternate waste management approaches on PPMS, exploring of alternate end-of-life pathways facilitating landfill diversion, and increase circularity within the PPI. The pathways explored are relevant globally and within a South African context such as the use of PPMS as a soil conditioner and compost, conversion into an energy pellet, anaerobic digestibility, reuse within the pulp and paper industry and mineral based products and as a landfill cover material. They could be used proactively in anticipation of extreme climatic conditions posed by climate change in efforts of reducing our vulnerability to such risks. Circularity within the PPI will allow for the conservation resources like water, soils and wood. Results from this study highlighted the viability of sustainable integrated waste management of the PPI. Pathways explored allow for the PPI shifting away from the cradle-to-grave and towards a cradle-to-cradle approach of the PPI's wastes. The results also displayed great potential in integrated waste management systems with benefits posed to economic, social and environmental spheres.

Key words:

Pulp and paper industry (PPI), paper mill sludge, organic waste, sustainability, circularity, waste management, landfill diversion, climate change

UNIVERSITY OF KWAZULU-NATAL
INYUVESI YAKWAZULU-NATALI

List of Figures

List of Tables

List of Abbreviations

PPI – pulp and paper industry

PPMS – pulp and paper mill sludge

DPMS – deinking paper mill sludge

WROSE^{TM} – Waste to Resource Optimisation and Scenario Evaluation Model

FVC – forestry value chain

GDP – gross domestic product

NSSC – neutral sulphite semi chemical

EPR – extended producer responsibility

AOX – adsorbable organo-halogens

COD – chemical oxygen demand

BOD – biological oxygen demand

MBR – membrane bioreactor

LSP –low sludge production process

SRT – sludge retention time

HRT – hydraulic retention time

RAS – return activated sludge

HFO – heavy fuel oil

IRO – ion refined oil

WAO – wet air oxidation.

SCWO – super critical water oxidation

CEC – cation exchange capacity

SOC – soil organic carbon

C:N ratio – carbon /nitrogen ratio

ENSO – el nina southern oscillation

1. Introduction

The pulp and paper industry (PPI) is one of the greatest polluter industries globally and is water intensive. PPI's contribute significantly towards growth of the global economy (Makgae, 2011). In manufacturing of pulp and paper products, virgin materials and recycled fibres are processed, subsequently generating large quantities of wastes requiring sustainable waste management (Makgae, 2011).

Different paper grade requirements require production processes having differences with variations present between mills, consequently, residuals vary in amounts and composition (Poykioa et al., 2018). Composition of solid wastes generated i.e., pulp and paper mill sludge (PPMS) is majorly affected by the type of materials processed, manufacturing process utilised and technologies used in wastewater treatment.

PPMS are complex mixtures of chemically modified wood fibres, inorganic solids and chemicals added during manufacturing processes (Ghinea et al., 2014). PPMS is an active organic material classified as hazardous (Ghinea et al., 2014), posing advantages and disadvantages PPMS generated from wastewater treatment processes accounts for the largest volume waste stream (Ghinea et al., 2014), and concept of sustainability and striving towards achieving higher levels of sustainability, being applied to PPI's due to its polluter status.

PPMS is an organic waste, and constant research in developing alternative methods which are viable economically and environmentally, in reducing, recycling and reusing of this waste. Efficient waste management plays a critical role not only in reducing the impact of wastes generated from an economic standing, but also from an environmental and social standing (Gibril et al., 2018).

Current waste management practices include incineration to alleviate energy demands and landfilling. These practices can be disadvantages, since incineration can lead to net energy losses, and landfilling which is not a sustainable and further compounded by transportation, and tipping costs and the negative impacts associated on social and environmental health. Another factor being stringent environmental regulations present in South Africa which bans the landfilling of wastes with moisture contents greater than 40% (Lundqvist, 2020). Therefore, sustainable methods must be considered in waste management of PPI's.

A rapidly increasing world population led to increased demands on paper and related products, with demands projected to significantly increase over the next 50 years by between 46% to 78% above existing levels (Desmond & Asamba, 2019). This led to heightened focus on alternate uses of PPMS through valorisation approaches which will not only eradicate challenges associated with disposal, but redirect the waste stream in the manufacturing of value-added products. Such waste management approaches enable the transition towards a circular economic model whilst simultaneously increasing sustainability of the industry.

It is vital to characterise the physical and chemical properties of PPMS which allows for an accurate assessment of impacts and towards finding alternative waste management practices. Through the sustainable utilisation this waste material will counter demands placed on limited natural resources. This research aims to determine alternate waste management pathways of PPMS enabling landfill diversion of this material.

1.2 Key Research Questions

- To determine the different origins of solid wastes generated in PPI's and their compositions.
- Quantify and compare the impacts associated with current waste management practices and alternative methods towards determining the best available technology/method that ensures sustainability as we transition towards circularity.
- To determine and evaluate possible scenarios of PPMS valorisation that allows for environmental, social and economic benefits being posed to PPI's.

1.3 Research Objectives

1. Determine the quantities and composition of solid wastes generated in PPI's through;
1. Processing fibres differing in origin
2. Different manufacturing processes employed i.e. Mechanical, thermos-mechanical and chemical processes.
3. Characterize the PPI's solid waste streams
4. Optimise the various solid waste streams
5. Determine viable alternate pathways towards efficient and effective solid waste management approaches to mitigate;
    A. Increased demands on limited renewable natural resources
    B. Reduce amounts of greenhouse gasses emitted from PPI's
    C. Reduce the effects posed by enhanced climatic systems such as the ENSO system prevalent in South Africa resulting directly from the accelerated rate of climate change
6. Divert wastes from landfilling and conserve landfill air space
7. Explore alternate end of life pathways for solid wastes generated in PPI's
8. Using the WROSE Model to determine the best scenarios of alternate pathways for solid wastes, increasing circularity.

1.4 Rationale

This research will include characterising of PPI's solid waste focusing on PPMS, and explore alternate-end-of-life-pathways based on the physical and chemical nature of this material, enabling greater circularity in this industry

It is vital to successfully divert PPI waste from landfilling, to establish systems of alternate pathways for such wastes. This research has great potential in contributing significantly in reducing the quantities of PPI waste requiring landfilling and facilitating the transition to circularity

1.5 Research Design and Methodology

This research followed a mixed methods approach which has been divided into 3 phases towards addressing the aims and objectives set out

Phase 1: This phase includes an overview of pulp and paper industries. Literature focussed on included solid wastes generated, how different parameters would affect the composition of solid wastes generated with emphasis on PPMS. The literature further analysed PPI's found within South Africa in respect to the climatic conditions and applicable legislation. This phase also includes the methodology and methodological approach used during the course of this study.

Phase 2: This phase includes alternate uses of PPMS facilitating landfill diversion. This chapter analyses sustainable waste management practices allowing for the optimisation of PPMS through the concepts of circularity. There are four alternate pathways viable to the PPI within South Africa and was critically analysed. There following seven alternate pathways was analysed regarding their applicability to PPMS. The viability of the alternate pathways was used in the WROSE Model ™ in determining the best possible scenarios conducive to increasing circularity within the South African PPI. This chapter also includes examples of PPI's globally which have been successfully implemented alternate pathways for their PPI's solid wastes, and furthermore, this chapter critically looked at the factors leading to polarisation between the global north and south in respect to their adoption of circular principles when it comes to solid wastes.

Phase 3: This chapter includes the conclusion based on this research. The conclusion focussed on contemporary issues effecting South Africa, and the potential in sustainable waste management approaches could result in net benefits within the environmental, social and economic spheres of life. Conclusions were also drawn up regarding the fulfilment of the aims and objectives set out. Recommendations were also made on improving current waste management practices and mitigate limitations hindering the successful implementation of such alternate pathways.

PHASE 1: LITERATURE REVIEW

2.1 Sources of Raw Materials in the Pulp and Paper Industry

Production of paper and paperboard surpasses 400 million tonnes per annum globally, and majority of paper originating from trees, 55% virgin pulp, 38% recycled fibres and 7% from non-wood sources (Latha et al., 2018).

Yearly increases in demands in amounts of wood as a raw material required for processing is resultant of population growth and consequent increased consumption and demand for paper and paper related products and almost every location globally has seen increased demands (Latha et al., 2018).

Different types of wood with different characteristics are utilised in PPI's and can be differentiated into three separate groupings i.e. softwoods, hardwoods and residues from mechanical processing of wood which include sawmill and sawdust (Bhojvaid, 2004; Mabee, 2001).

Table 1 Highlighting differences between hardwood and softwood trees

Aspect	Hardwood	Softwood
Botanical classification	Angiosperm	Gymnosperm
Leave type	Broad leaves, deciduous or evergreen	Conifers, needle or scale like evergreens
Pore type	Porous	Non-porous
Conduction and transport of water	Vessel cells (Pores in transversal surface)	Tracheid
Mechanical support	Fibres (Wood cells)	Tracheid
Storage food reserve	Living cells (Ray and longitudinal parenchyma)	Living cells (Longitudinal parenchyma)
Reproduction seed	Flowering seed – dicotyledon	Naked seed - monocotyledons

Adapted from (Pérez et al., 2002)

2.1.1 Softwoods

Softwoods are preferred in the production of 'strong paper' due to the length of fibres present and also used as a reinforcement in other paper products (Mabee, 2001). Low density softwoods dominated by thin walled fibres such as spruces, firs and pines are the preferred choice of wood in the production of paper requiring enhanced bonding related characteristics such as surface and tensile strength (Bhojvaid, 2004).

Higher tear strength when using denser softwoods is essential for paper requiring high bending stiffness (Mabee, 2001). Radiata pine is cultivated throughout South America, South Africa and New Zealand can be described as holding an intermediate position between the low density and high-density softwoods (Mabee, 2001). Pulps sourced from softwood forests contain a large proportion originating from the tops of mature trees and thinning's (Bhojvaid, 2004). This results in the pulp containing a higher proportion of juvenile wood compared to a mature tree. Juvenile wood has smaller fibres with a lower density than a mature tree.

During mechanical pulping of softwoods, fibre characteristics of the different wood species processed are not retained as in many of the processes, a large portion of fibres are broken into smaller fragments and elements (Antons et al., 2018). The amount of fragmentation occurring depends on wood density, as wood of a lower density yields higher quality pulp (Saeed et al., 2017).

2.1.2 Hardwoods

Hardwoods are the preferred choice in the production of printing papers (Mabee, 2001). This is due to fibres present having small dimensions as depicted in the figure below, allowing for the presence of high amounts of fibres per a unit mass of pulp. This proves advantageous in formation of characteristics such as a smooth surface, uniformity and opacity which are important factors in the production of printing paper (Latha et al., 2018; Mabee, 2001).

Eucalyptus and acacia pulps were found to have the highest amount of fibres present per a mass area, almost double the amount present in commonly used birch and aspen pulps (Bhojvaid, 2004). Short hardwood fibres are favoured for tissue paper production. Short fibres allow for greater tactile softness in the final product (Bhojvaid, 2004).

Hardwood pulps are generally based on mixtures of hardwoods sourced from North America with tropical hardwoods from Africa and Indonesia. This allows for mixes containing portions of dense species having thick walled fibres resulting in poor strength, but high bulking characteristics (Bhojvaid, 2004). In mixed tropical hardwoods there are species processed having long fibres present allowing for improved strength characteristics of the produced pulp (Antons et al., 2018).

Hardwoods like birch is preferred in semi-chemical pulp, and utilised in the corrugated layer of corrugated board (Antons et al., 2018). This is due to a high xylan content allowing the pulp to attain a desired level of stiffness (Cote, 1968).

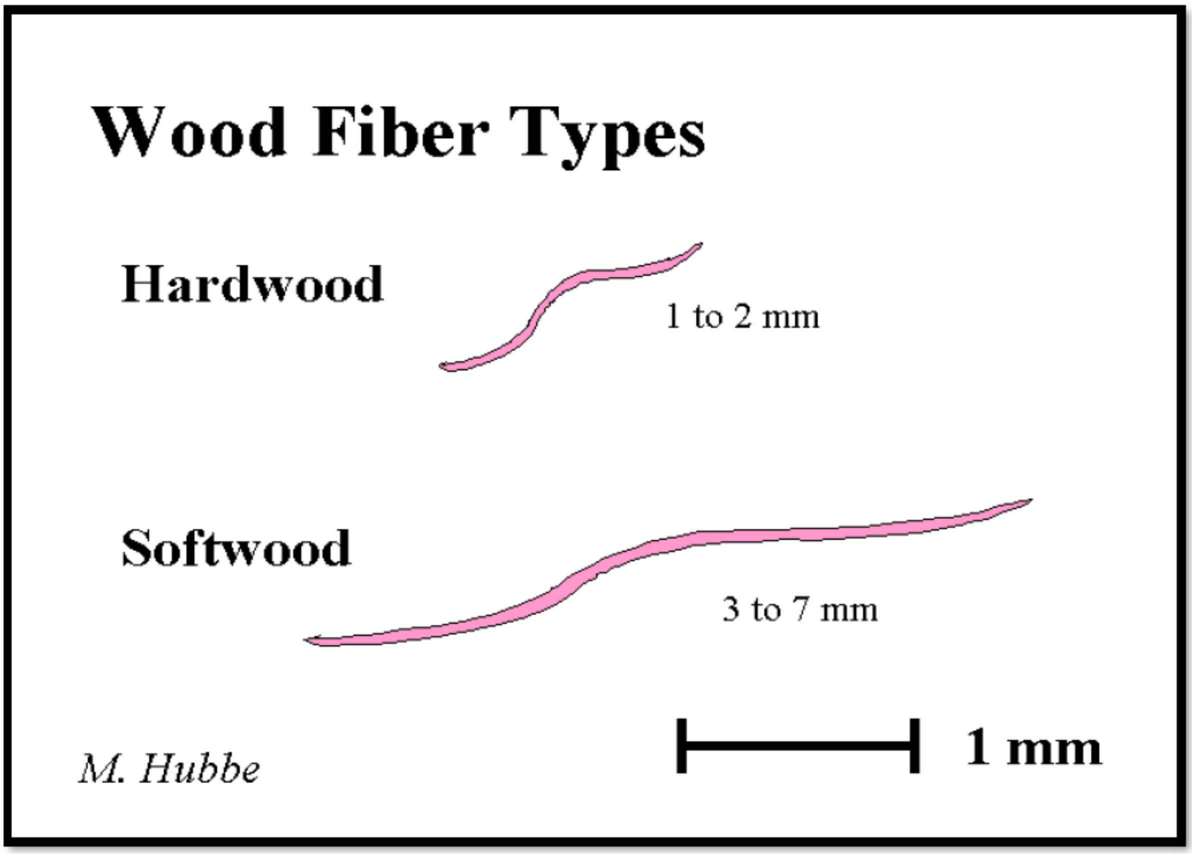

Figure 1 Illustration showing differences in fibre lengths between hardwood and softwoods (Hubbe & Grigsby, 2019)

2.1.3 Residues from Mechanical Wood Processing

Residues from mechanical processes in sawmills results in two types of residues obtained i.e. sawdust and chips (Mabee, 2001). These materials are utilised as raw materials for pulp or as a source of fuel. Competition for these materials by the wood panel industry such as producers of fibreboard and particleboard is advantageous as lower quality residues are accepted (Sood & Sharma, 2019).

2.1.3.1 Sawmill Chips:

Sawmill chips can be described as a residue consisting mostly of sapwood and older parts of the trunk with longer, coarser and thicker walled fibre than the rest of tree (Mabee, 2001). Mills usually processing softwoods utilise it in products requiring high bulk and tear strength (Bhojvaid, 2004).

2.1.3.2 Sawdust:

Sawdust is poorer quality material compared to sawmill chips because many fibres are cut with the saw resulting in reduced average lengths of fibres which is depicted in the image below (Wai & Lilly, 2002). Countering the problem of shortened fibres, mills use thick saw blades allowing for longer fibres with fewer fibres been cut (Antons et al., 2018). Modified pulping equipment is required as the material has great potential in plugging and clogging strainers (Bhojvaid, 2004).

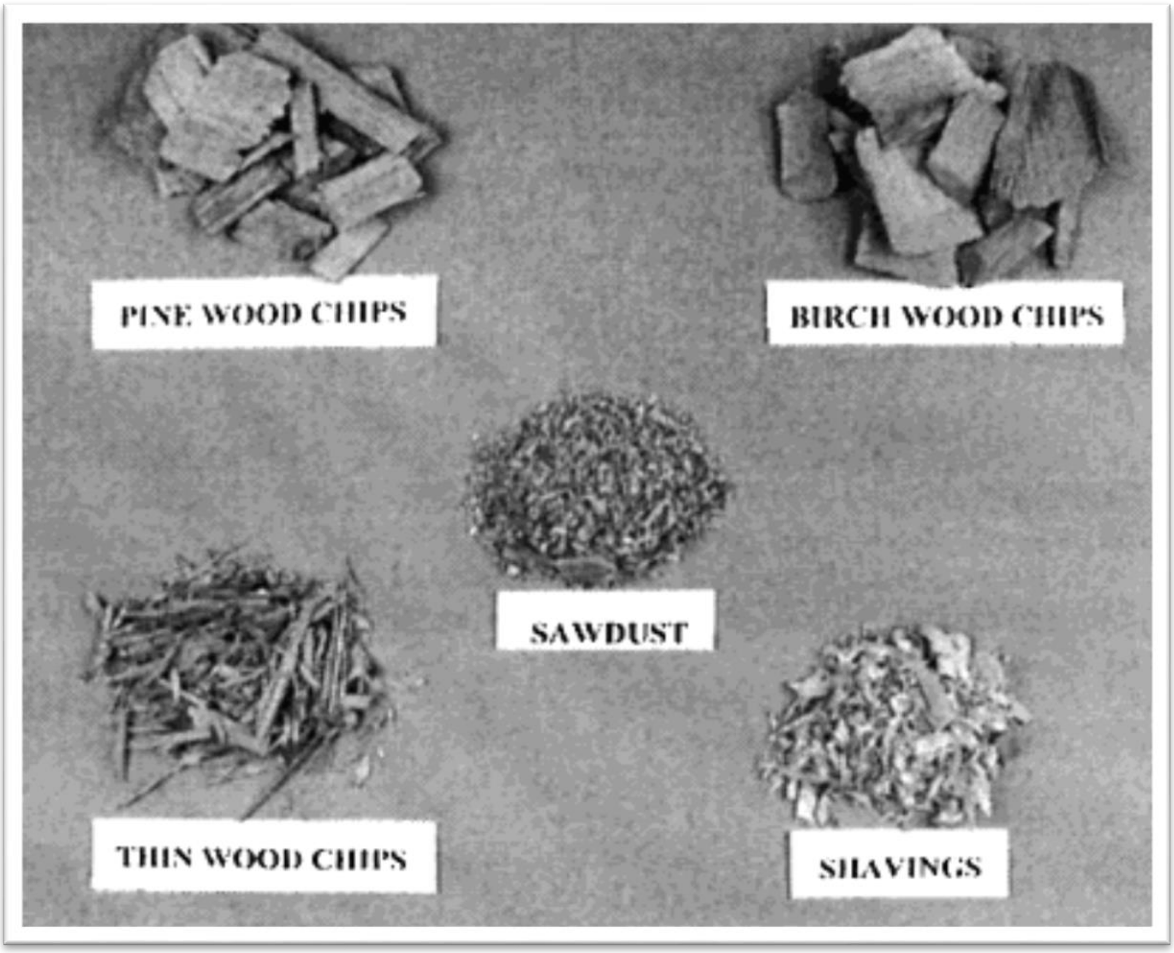

Figure 2 Illustration depicting different residues from mechanical wood processing (Ramiah, 1970)

2.2 Occurrence and Availability of Wood Resources

2.2.1 Natural Forests

Natural forests are the most important source of pulp. Natural softwood resources occur in a belt along the northern hemisphere covering parts of North America, Northern Europe and Russia. Globally, 30% of softwood stocks are found in North

America, while Russia has approximately 50% of softwood stock but faces limitations in utilising this resource as majority remains inaccessible due to infrastructural and economic reasons.

Naturally growing hardwood stock is twice the size of softwood stock. Most hardwood is found in Latin America, Africa and Southeast Asia cumulatively holding 80% of hardwood resources. Significant proportions of these resources should be restricted in attempting to achieve ecological preservation and sustainability in forest resources.

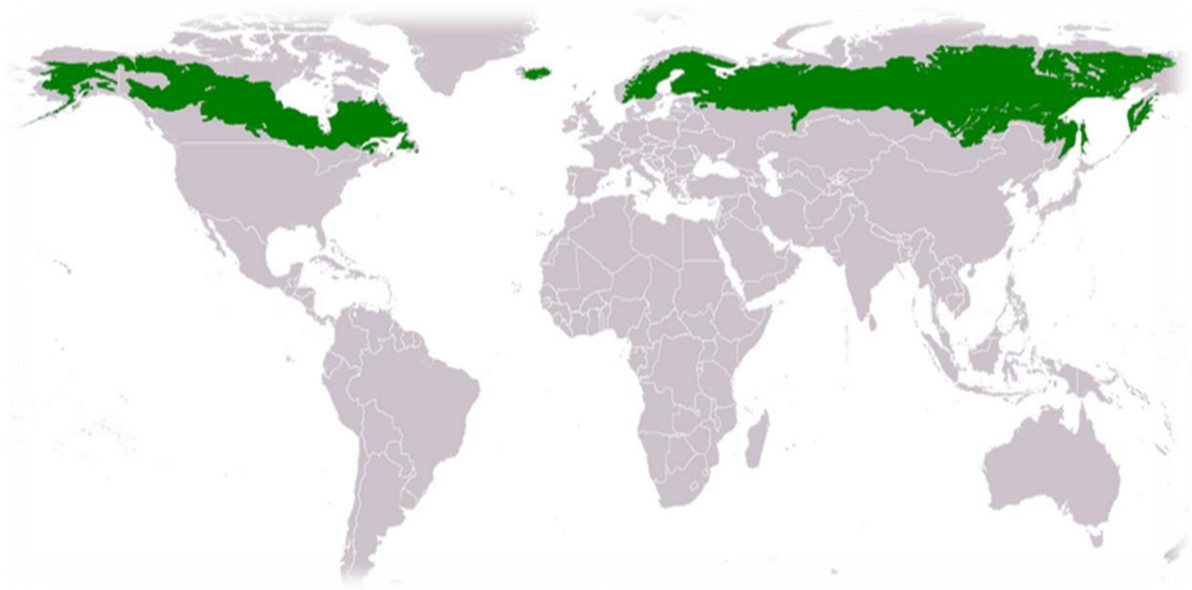

Figure 3 Illustration depicting the softwood belt found in the northern hemisphere (Malkocoğlu & Özdemir, 2006)

2.2.2 Wood Plantations

Wood plantations cover 140 million hectares, of which 20 million hectares comprised of fast-growing plantations during the 90's. These plantations were generally found in the tropics and southern hemisphere. Species commonly cultivated in fast-growing plantations include eucalyptus, pinus and acacia, and the most cultivated pine species being *Pinus radiata*. Fast growing plantations have great potential in areas like genetic modification and bioengineering, allowing for improvements in characteristics and yield.

2.2.3 Mechanical Wood Processing (Sawmills)

Globally, there are regions with a balance between pulp and mechanical wood processing industries with operations mutually dependant on one another (Bhojvaid, 2004). Residues from mechanical wood processes like wood chips and sawdust are an important source of pulp for PPI’s (Saeed et al., 2017). In the event of imbalances, these industries will compete for the same resources or the mechanical wood processing industry will face difficulties finding viable alternatives for the residues generated (Saeed et al., 2017).

Another important factor is utilising wood as a source of fuel (Latha et al., 2018). Estimates have shown consuming wood as a fuel source could be higher than that of PPI’s. Wood used as a fuel source and in PPI’s is not a directly overlapping resource (Latha et al., 2018). This highlights the importance in developing fast growing wood plantations of higher efficiencies (Latha et al., 2018).

2.3 Wood Chemistry

Woods composition can be chemically classified into three polymer groups, of which two groups i.e. cellulose and hemicellulose are closely related polymers, and jointly referred to as cellulosics and holocellulose (Sandberg et al., 2012). Alphacellulose, commonly referred to as cellulose and comprised of pure chains P-D-glucose

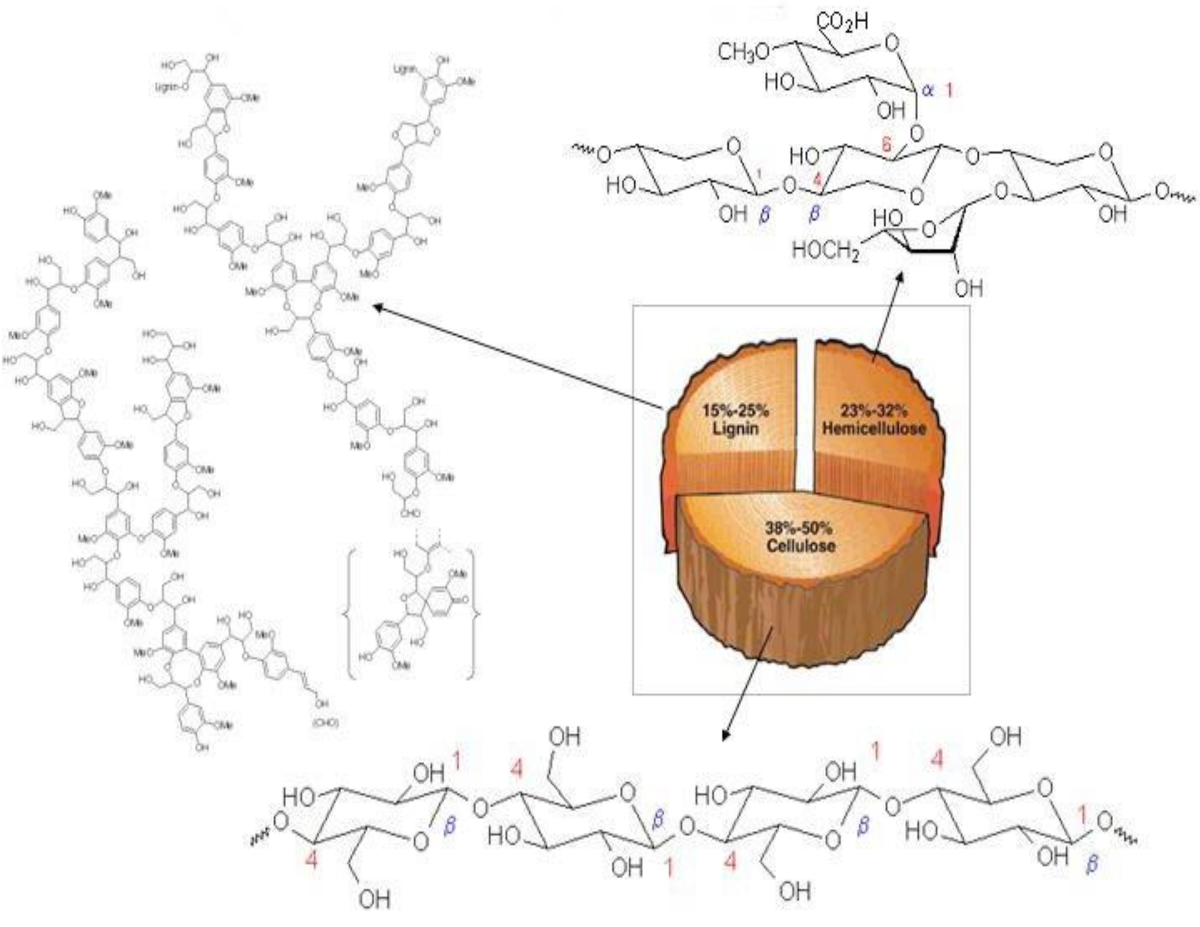

Figure 4 Illustration showing the components and chemistry of wood i.e. cellulose, hemicellulose and lignin (Pérez et al., 2002)

2.3.1 Alphacellulose

Alphacellulose or cellulose, is the structure simplest to manipulate during industrial processes (Antons et al., 2018). By mass an average sample of wood contains around 50% of cellulose (Antons et al., 2018). Greatest concentrations of cellulose are found along the secondary cell wall of the wood fibres allowing for woods rigid structure (Mahmood & Mahmood, 1984)

The basic structure of an alphacellulose molecule is described by taking the form of a narrow long chain, where D-glucose units are joined in 1,4 j3-linkage (Boonstra et al., 2007). These glucose molecules combine resulting in formation of a disaccharide unity referred to as cellobiose (Boonstra et al., 2007). As thousands of units of cellobiose molecules join resulting in the creation of a strand of alphacellulose

Alphacellulose molecule has polymerization of approximately 14 000 glucose units (Boonstra et al., 2007). Alphacellulose molecules have an absolute chemical formula of H(C6Hlo05), OH where it can be inferred that the carbon content of an alphacellulose molecule is around 44% of the total mass (Boonstra et al., 2007). Alphacellulose is insoluble in water, decomposes easily and non-toxic.

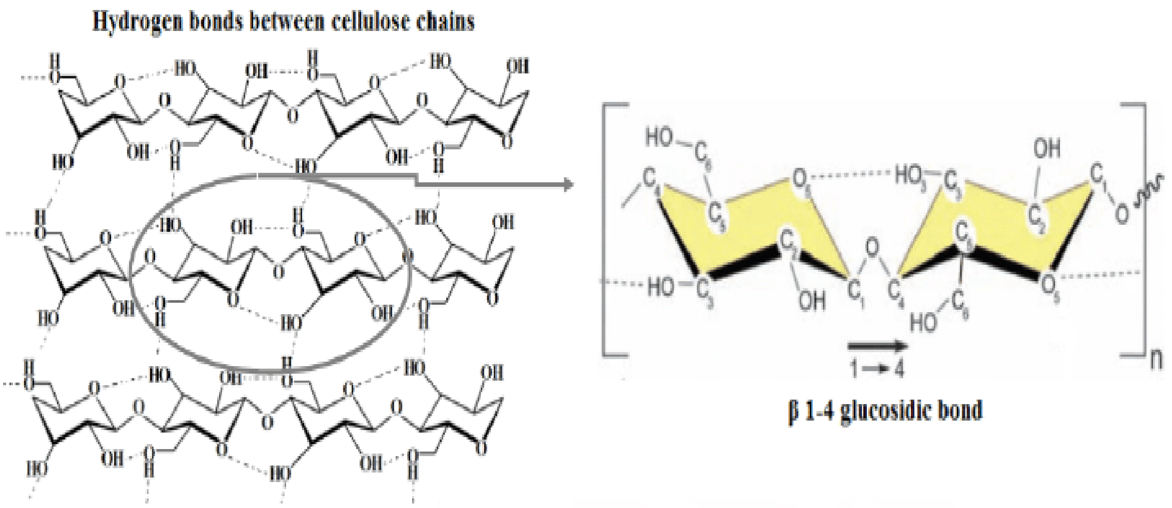

Figure 5 Illustration depicting the chemical structure of alphacellulose (Boonstra et al., 2007)

2.3.2 Hemicellulose

Hemicellulose, a compound of greater complexity compared to a simple chain of alphacellulose (Mabee, 2001). Many acids and monomers present in the macromolecule, assortment of compounds provide numerous available bond sites which are extended in a non-linear manner resulting in the creation of a branched structure of hemicellulose (Boonstra et al., 2007). No specific structure has been defined due to positions of different compounds which cannot be predicted. Consequently, responses of hemicellulose in wood chemical engineering is unpredictable, and working with hemicellulose is difficult with a significant effect on the suitability of fibres in papermaking (Latha et al., 2018).

Hemicellulose is smaller than alphacellulose in respect to its structure. Generally, displaying a degree of polymerisation between 100 to 200 units of carbohydrates (Boonstra et al., 2007). Large variations can be seen in hemicellulose in respect to its size and structure as different monomers present results in changes to the overall molecule (Boonstra et al., 2007).

By mass, 20% of the total mass of wood is attributed to hemicellulose groups (Chaouch et al., 2010). Hardwoods and softwoods differ significantly in the fraction of hemicellulose present, with differences in hardwoods and softwoods displayed when undergoing pulping processes is attributed to their unique structural properties (Chaouch et al., 2010).

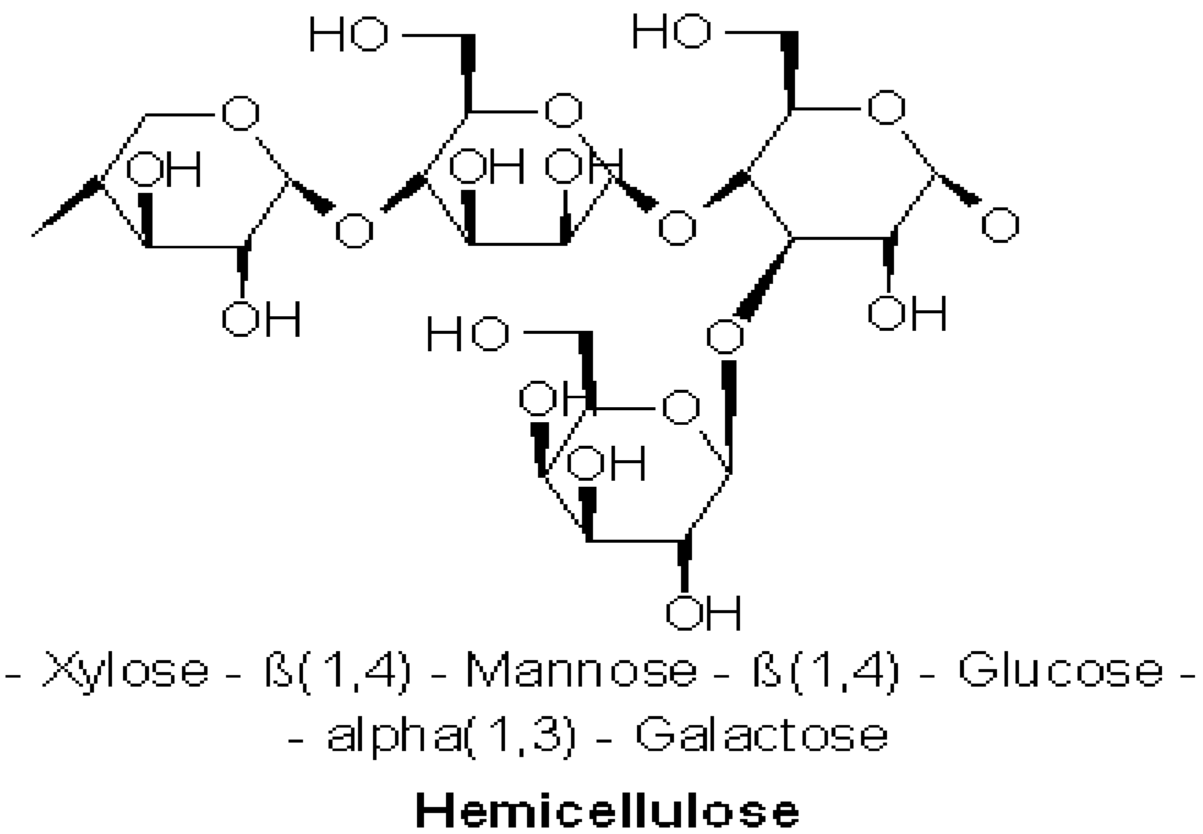

Figure 6 Illustration of the chemical structure of hemicellulose (Chaouch et al., 2010)

Softwoods have better responses to pulping compared to hardwoods due to simple chemical and morphological structures (Chaouch et al., 2010). Variability in hemicellulose results in an absolute chemical formula highly improbable in determining, by analysing amounts of the various components allow for a mean chemical formula being determined. Therefore, carbon content of hemicellulose ranges around 44% in softwoods and 38% in hardwoods of the total mass of hemicellulose (Boonstra et al., 2007).

2.3.3 Lignin

Lignin is the most complex macro polymer of wood. Lignin differs from alphacellulose and hemicellulose because it is not fibrous in form and composed of mostly aromatic compounds (Mabee, 2001). Lignin is an incorporation of three phenylpropane groups and their derivatives (Bajpai, 2016). Its combinations are in a number of ways resulting in a large amorphous molecule. This molecule usually appears light brown in colour, but there are different processes such as Kraft pulping which causes it becoming black (Latha et al., 2018).

Lignin allows for binding of different fibrous components present in wood, enhancing the strength and cohesiveness (Mabee, 2001; Bajpai, 2016) Lignin is undesirable by the PPI because it hinders production of paper of a high quality and also transfers its colour onto the white tone of cellulosic matter present (Latha et al., 2018)

The three phenylpropane groups form building blocks of lignin. These groups, similar to each other with a distinguishing factor which is the presence or absence of methoxy groups around the phenolic ring (Douyong et al., 2012). The structure of lignin facilitates a variety of bonding sites that can be invoked during macromolecules construction. Many intermediate structures are produced depending on availability of sites resulting in production of an unpredictable polymer (Douyong et al., 2012). The lignin molecule usually constitutes approximately 20% of the total mass of wood (Boonstra et al., 2007).

2.3.4 Extractives and Trace Elements

Extractives and trace elements are components present in wood but not intrinsically part of the matrix of wood (Mabee, 2001). Their presence is explained by the fact that trees are a living organism and a component of ecosystems. Extractable chemicals present in wood can be linked with the living tree and have no function in the structure such as fibres and tracheids (Welzbacher et al., 2011). Extractives account for the smallest proportion of the total mass of wood.

The extractives, globally has seen growing importance in the quest for chemical and pharmaceutical products. Extractive chemicals include tannins, sugars, acids, resins, terpenes, gurns and waxes (Welzbacher et al., 2011) and extractives constitutes between 1–5% of the total mass of wood (Boonstra et al., 2007).

2.4 Manufacturing Processes in Pulp and Paper Industries

Globally, PPI’s can be broadly classified by the different methods they employ in the manufacture of paper i.e. thermo-mechanical, semi-chemical and chemical methods of pulping.

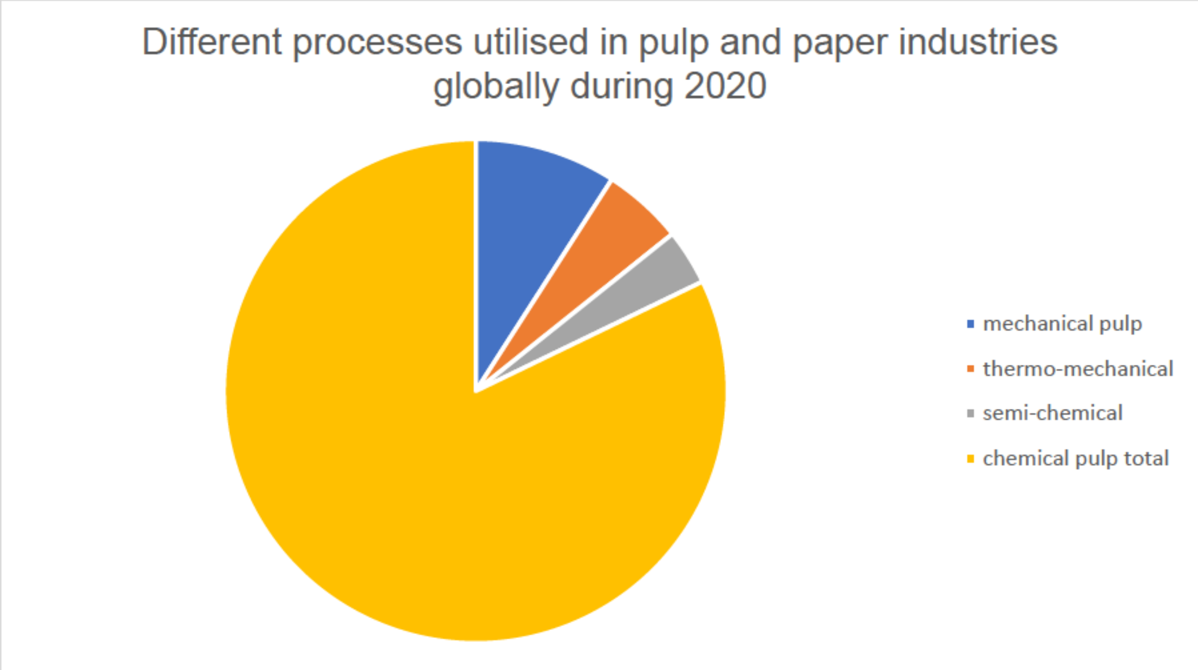

Figure 7 The different mechanical and chemical processes employed in PPI globally in the year 2020 (United Nations, 2020)

2.4.1 Mechanical Pulping

Classification of pulps from mechanical pulping are of three categories i.e. groundwood pulp, refining pulp and chem-mechanical pulp (Bajpai, 2015). Within mechanical pulping processes of groundwood and refining pulp, grinding and refining occur at raised temperatures to soften lignin allowing bonds between the fibres to break (Bajpai, 2015).

The most important refiner process within mechanical processes is thermomechanical pulping (Bajpai, 2015) in which pulp is steamed at high temperatures prior to refining. This allows softening of lignin and partially removing outer layers of fibres, subsequently exposing cellulosic surfaces for inter-fibres bonding (Bajpai, 2015; Latha et al., 2018).

Thermomechanical pulps are usually stronger than groundwood pulps (Bajpai, 2015) and usually utilised as furnish in cardboards, printing papers and tissue paper. Thermomechanical pulping process softwoods due to inferior strength qualities of the pulp opposed to using hardwoods as their fibres cannot form fibrils during refining but separate into short fibres and debris (Abd el Sayed et al., 2020). Hardwood pulps from thermomechanical processes are usually utilised as fillers in other paper production processes (Abd el Sayed et al., 2020).

Utilising chemicals during thermomechanical processes is common such as the addition of hydrogen sulphite prior to refining processes which causes partial sulphonation of lignin in the middle lamella of wood (Chen et al., 2016). This enhances swelling properties of wood whilst reducing the glass transitioning temperature of lignin allowing for liberation of fibres becoming easier during subsequent refining of the pulp (Chen et al., 2016).

Pulps from mechanical processes are weaker than chemical processes, but costs are reduced when utilising mechanical processes (Latha et al., 2018). Mechanical processes yield between 80-95% and account for more than 20% of all virgin fibres processed (Bajpai, 2015). Extremely high energy demands are a huge limitation facing thermo-mechanical processing

2.4.2 Semi-Chemical Pulping

Semi-chemical pulping is described by mild chemical treatments to pulp prior to mechanical refining (Bajpai, 2015; Bajpai et al., 1999). Most pulps used in semichemical pulping are of hardwoods generally yielding between 65-82% (Bajpai, 2015). Semi-chemical pulp accounts for 4% of all virgin materials processed in PPI's (Latha et al., 2018).

Semi-chemical pulping has a crucial process which is the neutral sulphite semichemical process (NSSC) in which partial chemical pulping of wood chips occur with the use of a solution of buffered sodium sulphite and treated with disk refiners for complete fibre separation (Arshiya et al., 2020). Lignin in the middle lamella region undergoing sulphonation causes partial dislocation allowing for weakening of fibres prior to mechanical defibration (Chen et al., 2016). NSSC pulp are generally used in unbleached products requiring increased strength or stiffness (Sandberg et al., 2012).

Integrating NSSC pulping in a Kraft mill (further discussed in 2.4.3.1) usually occurs as a means of chemical recovery. This is achieved through facilitating processing of sulphite spent liquor which provides the necessary chemical constituents such as sodium and sulphur with Kraft liquor, during Kraft processes (Chen et al., 2016).

Table 2 Differences in pulp properties between mechanical and chemical pulping

	Chemical Pulping	Mechanical Pulping
Yield	40-55%	85-95%
Strength	High amount of fibres that are intact	Low amount of fibres due to damage of fibres
Bulk	Low bulk with greater flexibility of fibres	High bulk with reduced flexibility of fibres
Optical	Darker but permits bleaching	Brighter with increased resistance to bleaching
Drainage and Dewatering	Efficient due to long fibres and fewer fines	Reduced due to shorter fibres and many fines

Adapted from (Bajpai et al., 1999)

2.4.3 Chemical Pulping

Chemical pulping dissolves lignin in fibre walls and inter-fibre matrix material, allowing for bonding of fibres via hydrogen bond formations between cellulosic surfaces during manufacturing processes (Bajpai, 2015; Chen et al., 2016). Chemical pulping is achieved through cooking or digesting of materials processed and is further divided into two different processes i.e. sulphate process known as the Kraft process, and sulphite process (Bajpai, 2015; Chen et al., 2016).

2.4.3.1 Kraft Process (Sulphate Process)

The Kraft process, an evolution of the preceding soda process which used sodium hydroxide with additions of sodium sulphide (Chen et al., 2016). The Kraft process utilise a range of pulps in producing packaging papers and boards with requirements of high strength. Within the Kraft process, wood chips are cooked with caustic soda to produce a brown stock that is washed with water in removing black liquor, and thereafter used in chemical and energy recovery (Smith, 2011). Kraft processes dominate PPI's due to high efficiencies in chemical recovery and a product with high strength characteristics. Kraft processes account for up to 75% of all pulps produced currently (Bajpai, 2015; Chen et al., 2016). Different grades of pulp are produced in the Kraft process with yields depending on quality and grade of the final product (Abd el Sayed et al., 2020). Unbleached pulp, characterised by a dark brownish colour and utilised in packaging products, and occasionally further cooked to achieve greater yields whilst retaining a higher degree of lignin (Abd el Sayed et al., 2020). Bleached pulps usually are made into white papers (Arshiya et al., 2020).

Kraft processing technology was introduced during the 1980's, undergoing constant research and development with extensive modifications carried out on this process (Bajpai, 2015). Much focus is on improving quality of pulp, reduced production costs by increasing energy efficiencies, reducing environmental impacts and recovery of wood value added products which allow for greater degrees of sustainability (Smith, 2011). Technologies used in Kraft processes include black liquor impregnation, partial liquor exchange and low cooking temperature (Chen et al., 2016) allowing controlled adjustments to cooking conditions by allowing preparation of all process liquors outside of the tank (Chen et al., 2016).

Reducing amounts of organic materials in effluents especially in areas with a high population relying on filtering water from rivers and waterbodies as a source of drinking water (Smith, 2011). During the 1980's, after polychlorinated dioxins and furans were detected in PPI's effluents led to rapid developments towards alternative environmentally safe bleaching processes in reducing organic matter present in effluents (Smith, 2011). Initially, PPI's intended to replace all chlorine containing compounds allowing for a chlorine free bleaching process (Smith, 2011). This was achieved easily by utilising sulphite pulps due to their bleach-ability and led to many Kraft mills converting to elemental free chlorine bleaching, opposed to totally free chlorine bleaching, as it deteriorated the quality of pulp (Soliman et al., 2017). Acknowledgement of elementally free chlorine bleaching as a component of the best available technology available as investigations have shown elementally chlorine free bleaching been almost completely free of dioxins and substances with potential to bioaccumulate (Smith, 2011).

2.4.3.2 Sulphite Process

Sulphite processes utilise aqueous sulphur dioxide and a base such as ammoniums, calcium, magnesium and sodium (Bajpai, 2015; Bajpai et al., 1999; Chen et al., 2016). The base directly impacts the different processing options available within the sulphite process directly impacting processes involved in chemical and energy recovery and water use requirements (Smith, 2011). The most used sulphite process is magnesium sulphite pulping and in some cases the use of sodium as a base. The use of such bases allows greater degrees of chemical and energy recovery (Chen et al., 2016; Latha et al., 2018). Ligno-sulphonates generated during cooking of liquor is utilised as raw materials in producing different chemicals, seen as value added products (Soliman et al., 2017).

Different chemicals attack and aid the removal of lignin, producing brighter pulps which are easier to bleach, but weaker compared to pulps of sulphate processes (María et al., 2019). Sulphite processes yield between 40-50% (Bajpai, 2015; Chen et al., 2016). Limitations facing sulphite processes being species sensitive to successful processing as the process is intolerant to resinous woods containing tannins and furnishes containing bark. Sulphite processes produces bright pulps easy to bleach, and greater amounts of bleached pulps of lower resistance to refining processes (Antons et al., 2018). High flexibility of this process compared to sulphite processes which is successful when conducted in highly alkaline cooking liquor (Antons et al., 2018; Sood & Sharma, 2019).

The complete pH range can be utilised in sulphite pulping through changing dosages and compositions of chemicals allowing for its use to produce a variety of pulps of different qualities with a larger range of applications (Sood & Sharma, 2019). Sulphite processes are differentiated according to the pH used. Primary sulphite pulping processes are acid bi-sulphite, bi-sulphite, alkaline sulphite and neutral sulphite (Bajpai, 2015; Chen et al., 2016)

Table 3 Differences between sulphate (Kraft) and sulphite pulping

	Kraft Pulping	**Sulphite Pulping**
Cellulose Fibres	Produce weak cellulose fibres	Produce stronger cellulose fibres
Efficiency	Low	High
Environmental Impact	Greater environmental impacts	Less environmental impacts
Stability	Sodium sulphate is very stable and unreactive towards many oxidising agents	Sodium sulphite is very unstable and can get decomposed by weak acids

Adapted from (Chen et al., 2016)

2.5 PPI Solid Waste Streams

2.5.1 Waste Generated in PPI

Different solid wastes and sludges are generated during production stages of PPI's (Arshiya et al., 2020; Bajpai, 2015; Latha et al., 2018; Smith, 2011). Main sources of wastewater treatment sludge are from pulping, papermaking and deinking processes (Abd el Sayed et al., 2020; Smith, 2011). Globally, different rates and amounts of waste generated in PPI's because of different recycling rates found in each region (Blanco et al., 2004). First world countries with vast timber resources can have lower recycling rates than third world countries due to exporting much of the paper produced and a low amount of recovered paper (Monte et al., 2009).

Many plants and mills have internal processes operating treating different types of wastes which results in reduced amounts of solid waste (Ochoa de Alda, 2008; Smith, 2011). An example of this is wood waste including sawdust, woodchips and bark are incinerated with the ash remaining being solid waste requiring landfilling, the same concepts can be applied to incineration of sludge (Bajpai, 2015; Ochoa de Alda, 2008; Smith, 2011).

PPI's in the same geographic area will generate different amounts of solid waste (Ochoa de Alda, 2008). A mill processing virgin materials differ in amounts of sludge from a mill processing secondary fibres because of the unrecyclable filler proportion in secondary fibres (Zhang et al., 2010). Composition of sludge differs and is dependent on the material processed and different processes involved (Bajpai, 2015; Monte et al., 2009; Smith, 2011).

Table 4 Sources of solid wastes in PPI's

Sources	Type Of Solid Waste	Waste Characteristic
Wastewater Treatment Plant	Sludge	• Organic fraction composed of wood fibres and secondary sludge • Inorganic fraction composed of clay, calcium carbonate and other materials • 20-65% solids content
Caustic Processes	Dregs and mud	• Green liquor dregs are composed of insoluble materials and non-reactive metals
Boiler (Power)	Ash	• Inorganic compounds
Mill (Paper)	Sludge	• Fiber and clay wastes that includes biodegradable organics such as fibers, organics and cellulose

Adapted from (Bajpai, 2015)

2.5.2 Generation of Wastewater Treatment Sludge

2.5.2.1 Primary and Secondary Sludge:

Sludge is differentiated into two categories i.e. primary and secondary sludge (Bajpai, 2015; Monte et al., 2009; Smith, 2011). Primary sludge is a fibre rich material formed during the mechanical cleaning of the wastewater (Bajpai, 2015). Secondary or biological sludge is produced through different treatments of activated wastewater including organic and inorganic wastes and described as a combination of fibres, bacterial cells and other waste (Bajpai, 2015; Monte et al., 2009; Smith, 2011)

Table 5 Characterisation of primary sludge

pH	7.39
Total solids (%)	80
Volatile solids (%)	57.94
Ash content (%)	54.06
Total COD (mg/L)	64000
Lignin (%)	5.68
Hemicellulose (%)	6.53
Cellulose (%)	32.49

Adapted from (Monte et al., 2009)

Primary sludge is easier than secondary sludge to dewatering, as secondary sludge comprises of excess biomass from different biological treatment processes (Ghribi et al., 2016). Treatment plants usually include consecutive primary and secondary treatment processes (Monte et al., 2009; Smith, 2011). Secondary treatments are based on biological treatment of wastewater and performed in activated sludge systems, aerobic lagoons and anaerobic treatments (Monte et al., 2009). Majority suspended solids present in wastewater entering treatment processes is transferred to wastewater treatment sludge (Rashid et al., 2006). Organics in wastewater sludge is comprised of bark, fibre and wood residuals, and inorganics include mostly sand (Ghribi et al., 2016).

Organic materials which are soluble are converted into carbon dioxide, water and biomass through the use of microorganisms in activated sludge which is vital to the processes of biological wastewater treatment (Rashid et al., 2006). Sludge from biological processes are known as activated sludge, biosolids and biological sludge. High contents of microbial protein make handling becoming difficult (Ghribi et al., 31 2016; Smith, 2011). Primary and biological sludge usually are combined in achieving adequate dewatering prior to landfilling (Bajpai, 2015; Monte et al., 2009).

Table 6 Characterisation of biological (secondary) sludge

pH	6-7.6
Total solids (%)	1.0 – 2.0
Volatile solids (% of TS)	65 - 97
Total COD (mg/L)	11 000
Nitrogen (% of TS)	3.3 – 7.7
Phosphorous (% of TS)	0.5 – 2.8
Iron (g/kg TS)	0.33 – 2.2
Heating value (MG/kg TS)	22 - 25

Biological sludge can be incinerated in alleviating energy demands, but the low solid content affects the capacity of steam able to generate leading to operational problems (Bajpai, 2015; Latha et al., 2018). They can be landfilled, but has a high potential to leaching due to minerals present and the subsequent contamination of groundwater (Smith, 2011). Biological sludge can also be applied to agricultural land as a mulch or soil improving fertilizer (Blanco et al., 2004; Monte et al., 2009) only if there is no presence of chlorinated organic compounds (AOX) or adsorbable organo-halogens since these compounds are extremely toxic to flora and fauna (Smith, 2011). PPI's using elemental chlorine will have these compounds present in their solid wastes and effluents (Bajpai, 2015; Monte et al., 2009; Smith, 2011).

2.5.2.2 Deinking Sludge

Deinking sludge is generated when producing fibre from recycled paper (Bajpai, 2015). Deinking processes increases the brightness and cleanliness of the material produced (Bhojvaid, 2004). Deinking process are usually incorporated in the production line (Bhojvaid, 2004). Deinking sludge is primary sludge that underwent primary treatment of deinking effluent (Antons et al., 2018). Deinking effluent passes through the same mechanical filters and cleaners as primary sludge, but is much dirtier than primary sludge, difficult to handle and usually kept separate (Antons et al., 2018; Monte et al., 2009).

Commonly used methods in deinking paper products are floatation deinking and mechanical cleaning (Arshiya et al., 2020). Flotation deinking is widely used in which additions of chemicals during floatation such as surfactants causes an enhanced hydrophobic ink characteristics and flocculants causes congregating of ink particles (Arshiya et al., 2020; Monte et al., 2009). Other methods include froth flotation which deletes ink particles, and wash deinking in the removal of small particles, coating materials, inks and fillers (Arshiya et al., 2020). These methods are combined in the production line towards achieving higher removal rates of unwanted materials. Sludge from deinking processes are categorised into organic and inorganic matter (Chaouch et al., 2010; Smith, 2011). Organic matter includes bark and fibre, and inorganic matter includes carbonate, calcium, kaolin and titanium dioxide originating from different chemicals and coating materials used in production of paper (Chaouch et al., 2010; Monte et al., 2009; Smith, 2011)

2.5.3 Composition of Sludge

Different wastes are generated during different stages of production within PPI's and solid wastes includes wood residues, primary sludge, biological sludge, deinking sludge and ash (Bajpai, 2015; Blanco et al., 2004; Chen et al., 2016; Monte et al., 2009; Smith, 2011). Primary wastes produced in PPI's consist of different sludge types specific to materials processed and manufacturing processes, and these factors influences the amounts of waste generated (Bajpai, 2015; Smith, 2011). A mill processing recovered fibres generate 4-6 times more waste than mills processing virgin materials (Antons et al., 2018; Bajpai, 2015; Chen et al., 2016; Monte et al., 2009; Zhang et al., 2010).

Impurities usually end up as waste (Monte et al., 2009). Majority waste materials include rejects, sludge's and ash (Arshiya et al., 2020) which are divided into coarse rejects, light and fine rejects, and sludge. Sludge is dependent on the origin of processed material and manufacturing process involved, and are differentiated into deinking, primary and biological sludge (Arshiya et al., 2020; Chaouch et al., 2010; Zhang et al., 2010). Rejects are impurities from recovered paper such as staples, metal pieces, glass, lumps of fibre and plastic (Bajpai, 2015; Blanco et al., 2004; Smith, 2011)

Table 7 Composition of dry matter content in solid waste streams

	Contents
Primary Sludge	• fibres • fillers • coating clay • calcium carbonate
Biological Sludge	• calcium carbonate • copper • micro-organisms • fibres, proteins
Deinking Sludge	• cellulose fibres • calcium carbonate • kaolin • ink
Coarse Rejects	• recyclable fibres • wet strength fibres • plastics • wood • metals
Fine Rejects	• cellulose • plastics • hair

Adapted from (Bajpai 2015,2019, Monte et al 2009)

Many factors including raw materials used, technology utilised, manufacturing processes, chemicals used and wastewater treatment employed directly affects the composition of sludge making its composition site specific (Abd el Sayed et al., 2020; Bajpai, 2015; Monte et al., 2009). Deinking processes generates the greatest amount of sludge with origins from recycling mixed office wastepaper that potentially contains high amounts of fillers, inks, clay, adhesives and fibres (Abd el Sayed et al., 2020). The resulting sludge has low heating values due to high levels of calcium carbonate, clay and ash contents of up to 48% (Bajpai, 2015; Bajpai et al., 1999; Blanco et al., 2004; Chen et al., 2016; Monte et al., 2009; Smith, 2011). PPI's generate different amounts of sludge which varies distinctly in composition (Kuokkanen et al., 2008; Monte et al., 2009). Sludge with a high ash content has a reduced heating value directly affects waste management and end of life pathways (Blanco et al., 2004; Monte et al., 2009; Smith, 2011) and utilising sludge in energy recovery will not be viable to alleviate the mills energy demands (Blanco et al., 2004; Monte et al., 2009; Smith, 2011)

Table 8 Comparison of different sludge types in their ash content (% weight), organic content (% weight) and heat value (MJ/kh)

Sludge Source	Ash Contents (Wt%)	Organic Content (Wt%)	Heat Value (MJ/Kh)
Primary Sludge (Source: Virgin Materials)	5.69	94.31	20.1
Primary Sludge (Source: Recycled Fibres)	35.28	64.72	14.2
Secondary Sludge (Source: Recycled Cellulose)	32.77	67.23	16.5
Deinking Sludge	40.7	59.3	12.2

Adapted from (Blanco et al., 2004)

Sludge is characterised in determining the best waste management practice. Characterisation is based on heating value, loss of ignition, moisture and ash content, pH, viscosity, and particle and fibre length distribution (Bajpai, 2015; Chen et al., 2016; Kuokkanen et al., 2008; Smith, 2011). Many researchers have shown deinking sludge having the highest ash content, and almost half comprised of incombustible inorganic matter and the lowest carbon content when compared to primary and biological sludge (Adu et al., 2018; Chiang et al., 2016; Kuokkanen et al., 2008). The use of deinking sludge is unsuitable as a fuel in alleviating energy demands of the plant.

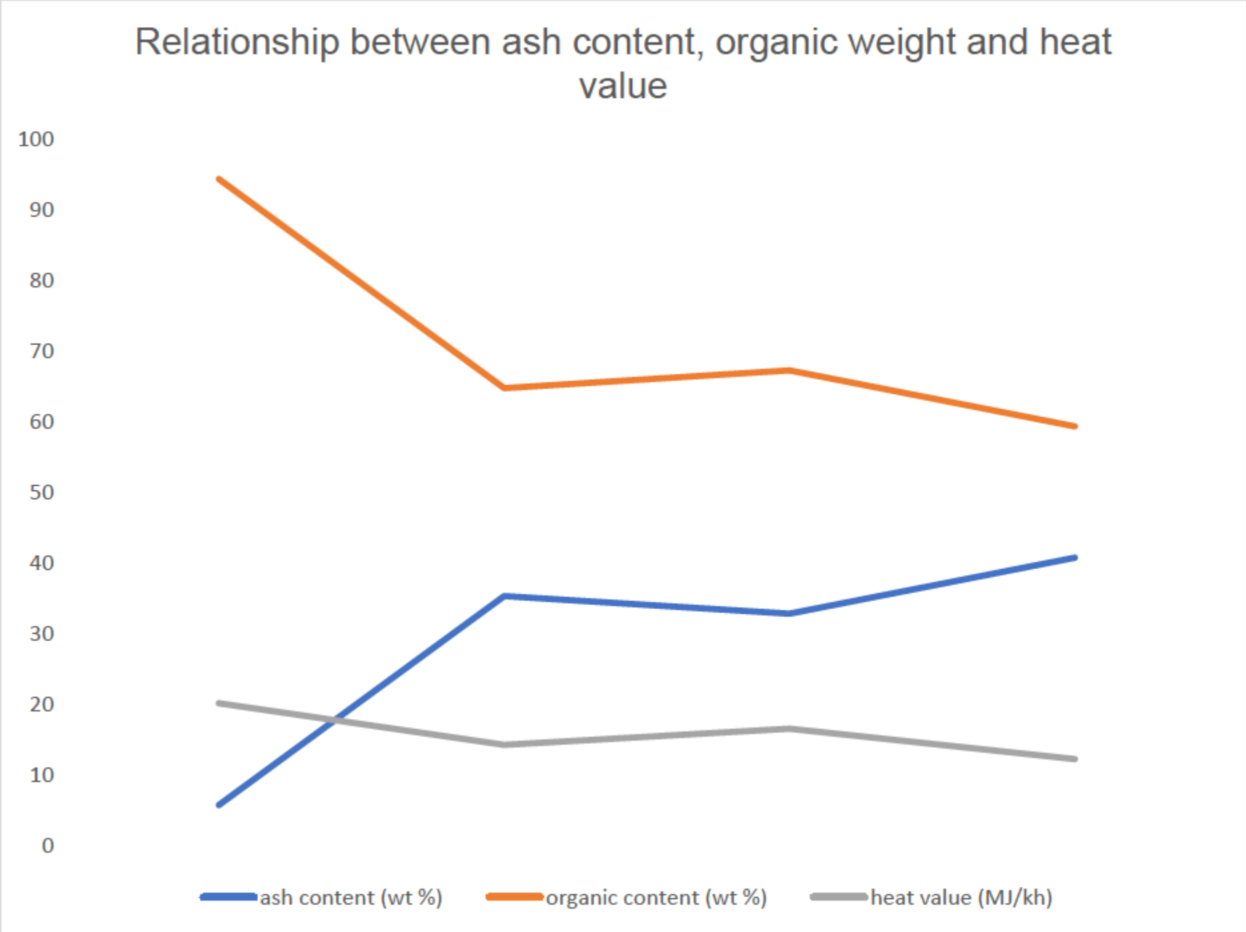

Figure 8 Relationship between ash content (% weight), organic content (% weight), and heat value (MJ/kh) Adapted from (Arshiya et al., 2020; Bajpai et al., 1999; Kuokkanen et al., 2008)

Sludge is distinguished into two main types in relation to their ash content i.e. highash and low-ash sludge, high-ash having greater than 30% ash in dry weight and lowash with less than 30% of ash in dry weight (Bajpai et al., 1999; Kuokkanen et al., 2008; Monte et al., 2009). High-ash sludge originates from processing recycled fibre and also resultant of chemical flocculation used in mills (Kuokkanen et al., 2008; Soucy et al., 2014). Low-ash sludge is described by primary and biological sludge produced in PPI's (Adu et al., 2018).

Primary and deinking sludge is a mixture composed of short cellulosic fibres, inorganic fillers and residual chemicals that dissolved in water during different production stages (Mabee, 2001). Biological sludge has different nutrients present including N, P, K, Ca and Mg (Bajpai et al., 1999; Marche et al., 2003). The amount of nutrients in biological sludge is affected and varies in relation to the levels of microbial decomposition that occurred during biological treatment and the manufacturing process employed (Chiang et al., 2016; Marche et al., 2003).

Table 9 Macronutrients in wastewater treatment plants in PPI's

Macronutrient (g/kg)	Range	Median
Nitrogen – Processing virgin materials	0.51 – 9.0	2.7
Nitrogen – Processing recycled materials	6.2 – 87.5	23.3
Phosphorous – Processing virgin materials	0.01 – 4.0	1.6
Phosphorous – Processing recycled materials	0.42 – 16.7	4.2
Potassium	0.12 – 10	2.2
Calcium	0.28 – 2.10	14.0
Magnesium	0.2 – 19.0	1.55
Sulphur	0.2 – 20.0	4.68

Carbon-nitrogen ratios of biological sludge significantly fluctuate according to the type of paper produced, manufacturing processes involved and raw material processed (Bajpai et al., 1999; Chen et al., 2016; Zhang et al., 2010). Primary sludge largely comprises of organic matter in cellulosic form and wood fibres (Rashid et al., 2006) and usually contain between 0.1-0.3% of nitrogen in dry weight and a carbon ratio in excess of 110:1. Biological sludge contains fine materials and fibres which were not removed during primary treatment with the organic material remaining decomposed and consumed by bacteria in the water (Douyong et al., 2012). Heavy metals in sludge have known potential risks to human health and the environment when present in high concentrations (Blanco et al., 2004; Monte et al., 2009; Smith, 2011). These metals are usually retained in soils for extended periods. Heavy metals in sludge are contaminants that originates from chemicals added during pulping processes or absorbed from soil via roots into the tree (Smith, 2011)

Table 10 Comparison between municipal sludge and biological sludge from pulp and paper industries

	Municipal Sludge	Biological Sludge (PPI)
Total Dry Solids (Total Solids %)	0.8 – 1.2	1.0 – 2.0
Volatile Solids (% Of Total Solids)	59 – 68	65 – 97
Nitrogen (% Of Total Solids)	2.4 – 5.0	3.3 – 7.7
Phosphorous (% Of Total Solids)	0.5 – 0.7	0.5 – 2.8
Iron (G/Kg Total Solids)	0	0.33 – 2.2
Ph	6.5 – 8.0	6.0 – 7.6
Heating Value (MJ/Kg Total Solids)	19 - 23	22 – 25

2.6 Sludge Pre-treatments

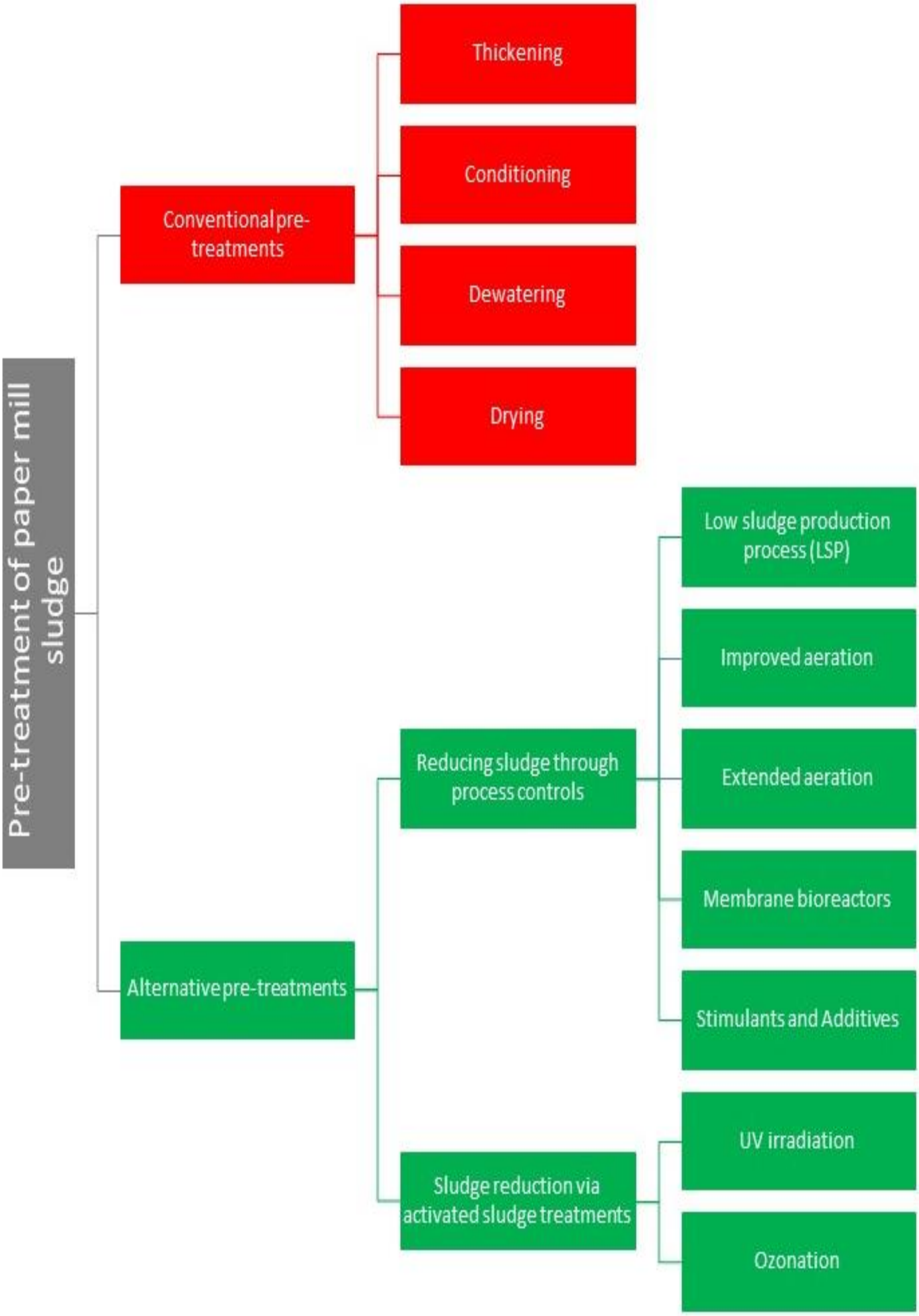

Figure 9 Illustration showing different pre-treatment pathways PPMS can follow. Adapted from: (Deviatkin, 2013; Galić et al., 2021; Karchiyappan & Venkatachalam, 2015)

2.6.1 Conventional Pre-Treatment of Sludge

Wastewater effluents and solid wastes are regarded as a key area of major environmental concern facing PPI's, which have extremely water intensive production processes with many regions globally being water scarce (Granström & Montelius, 2014). Pre-treating of solid wastes generated require different pre-treatments methods in ensuring maximum resource recovery and increased valorisation of solid wastes in achieving higher rates of sustainability (Kaur et al., 2020). Chemical and physical conventional pre-treatment processes of sludge are thickening, conditioning, dewatering and drying (Antons et al., 2018; Arshiya et al., 2020; Bajpai et al., 1999; Chen et al., 2016). There are also of pre-treatment methods that include the use of microorganisms and enzymes. Dewatering biological sludge is crucial in determining volume of solid waste requiring management (Bajpai, 2015; Bajpai et al., 1999; Monte et al., 2009; Smith, 2011).

2.6.1.1 Thickening

Thickening is the first step of conventional sludge pre-treatments. Commonly used technologies are gravity thickeners and rotary sludge thickeners (Wang et al., 2007). Other available technologies which are widely used include belt presses, dissolved air flotation clarifiers (DAF) and gravity table thickeners (Wang et al., 2007). Dry solids content (DSC) increases as sludge passes through the clarifier with increases of between 0.4 – 7.0% (J. Bayr et al., 2013). Biological sludge with excess biomass has a greater resistance to dewatering and the dry solids content is usually is not more than 3.5% (Bajpai, 2015; Bajpai et al., 1999; Bayr et al., 2013; Chen et al., 2016). Higher efficiencies in sludge thickening of between 11-14% is achieved with the use of a floatation unit (Bayr et al., 2013). The most efficient way of thickening is achieved with a belt thickener which results in the dry solid content increasing up to 15% (Bayr et al., 2013). Biological sludge can achieve a dry solids content of 2% with a gravity thickener and 4% with a floatation thickener (Bayr et al., 2013).

Advantages of gravity thickeners is a simple operational process, low operating costs and a degree of storage for sludge (Monte et al., 2009). Energy consumption is also low and the water content of sludge is reduced (J. Bayr et al., 2013). Gravity thickening, is achieved with large circular tanks which sludge is pumped in that has a slowly rotating rake mechanism. This facilitates breakages and disjointing of sludge particles resulting in increased settling and compaction on the bottom of the tank with reductions up to 92% in volume can be achieved (J. Bayr et al., 2013; Wang et al., 2007). Disadvantages are reduced dewatering capabilities and large space requirements when compared to available current technologies. This resulted in the limited use of gravity thickeners in PPI's (Bajpai, 2015; Bajpai et al., 1999; Monte et al., 2009; Smith, 2011)

2.6.1.2 Conditioning

An objective of conditioning is increasing water repulsion properties of sludge and is achieved by changing the forms of water bonds (Elliott & Mahmood, 2007). Thermal or reactant treatment processes are common methods used in PPI (Elliott & Mahmood, 2007). Reactant treatment known as chemical treatment, and optimum results are achieved when a combination of polyelectrolyte and an inorganic salt are used (Deviatkin, 2013). Aluminium oxides, lime and ferric chloride are combined and used as an inorganic salt (Deviatkin, 2013). During reactant treatment, reagents are added into a flocculation tank containing sludge causing smaller particles coagulating into larger groups that is easier to dewater (Veluchamy & Kalamdhad, 2017). The method used to coagulate is dependent on the reagent used (Deviatkin, 2013), with reagent costs affected with local markets. Therefore, reagents or combination of reagents used is site specific (Veluchamy & Kalamdhad, 2017).

Wet air oxidation or heat treatment are ways of implementing thermal treatment of sludge (Elliott & Mahmood, 2007). Heat treatment is a method of treatment from the numerous different thermal processes available. As sludge is heated, water present in the cell structure escape allowing easier dewatering (Chen et al., 2002). Thermal treatment has higher efficiencies compared to chemical conditioning, but costs of thermal treatments are far greater (Chen et al., 2002). Conditioning sludge is done to cause alterations of the floc structures resulting in increased stiffness and incompressibility allowing water being easily drained through filtration (Chen et al., 2002). Conditioners have the following functions; improving dewatering properties, enhancing performance and reducing the specific filtration resistance (J. Bayr et al., 2013). This allows for an increased solids content. The Four mechanisms that chemical conditioners are added to sludge i.e. compressing the electrical double layer, neutralise charges, retain precipitates and the bridging effect (Chen et al., 2002). This is done to reduce stability of flocs facilitating aggregation and precipitation, consequently producing a dense tighter sludge cake allowing for greater water removal (Chen et al., 2002).

2.6.1.3 Dewatering

The ability to dewater is a determining factor in amounts of solid waste requiring waste management, and costs associated with disposing solid waste directly depends on the volume of waste (Elliott & Mahmood, 2007). Common technologies used in dewatering sludge include vacuum filters, belt filter presses, centrifuges and pressure filters (Elliott & Mahmood, 2007). Vacuum filters is one of the earliest mechanical technologies used (Rusten et al., 1999).

Wastewater treatment or primary sludge is easiest to dewater due to their high fibre content and low percentage of ash (Elliott & Mahmood, 2007). Biological sludge is difficult to dewater due to presence of biological systems (Elliott & Mahmood, 2007). The hardest sludge to dewater is primary sludge comprised of ground wood fines (Elliott & Mahmood, 2007). Sludge is usually tertiary and quaternary mill rejects from different processes containing good quality fibres with a high economic value. Increasing biological sludge causes a decreased dewatering ability and dry solid contents of sludge cake (Deviatkin, 2013). Dewatering combined sludge is an issue facing PPI's, specifically in mills processing recycled materials.

Belt presses and centrifuges are commonly used technologies in pre-treating sludge due to its costs and operational efficiencies (Meyer et al., 2018). Higher efficiencies are achieved by centrifuging inorganic conditioned sludge and lower efficiencies with organic sludge due to the nature of organic sludge (Meyer et al., 2018). A dry solids content between 15-35% can be achieved and directly dependent on the type of sludge and different flocculants used in conditioning, whereas sludge processed through a belt filter achieve dry solids contents between 20-36% (Meyer et al., 2018). Capital costs of centrifuges are low but costs in operating centrifuges are expensive due to the specific requirements of chemical agents and an energy intensive process requiring intensive maintenance in its operation (Elliott & Mahmood, 2007). A major issue with centrifuges is the generation of supernatants of poor quality is the accumulation of fines within the treatment system and subsequent vulnerability of centrifuges becoming plugged with pieces of bark (Hartong et al., 2007).

The most dominant technology in dewatering sludge is pressure filters (Hartong et al., 2007) with efficiencies of between 30-35 % dry solids in combined sludge cake (Meyer et al., 2018). Conditioning sludge prior to dewatering is a requirement. Biological sludge under pressures of 200-250psi with the use of conditioning agents can achieve efficiencies between 35-40 % of dry sludge cake solids (Veluchamy & Kalamdhad, 2017). Pressure filters is a batch operation process and operators required paying attention to detail and the short lifespan of the belt proved disadvantageous (Veluchamy & Kalamdhad, 2017) resulting in the development of continuously operating processes with disadvantageous been mechanical complexity and increased maintenance issues.

2.6.1.4 Drying

Dewatered sludge has a moisture content allowing for disposal, but places limitations on incineration and energy recovery (Navaee-Ardeh et al., 2006). This makes drying a vital stage of pre-treatment prior to energy or material recovery (Bajpai, 2018; Hovey, 2016). A common method utilised to dry sludge is the use of flue gasses generated from combustion processes (Hovey, 2016). Other methods with high efficiencies used include rotary dryers and fluidised bed dryers (Hovey, 2016).

In a rotary dryer, sludge and air are fed into the same end, and air is passed over a heater installed inside the dryer. The rotary dryer is set at an incline that slowly rotates facilitating sludge coming into contact with heated air allowing sludge to dry whilst moving towards the discharge end (Hovey, 2016). Rotary dryer dries sludge through direct contact or indirect contact with the use of drying agent (Hovey, 2016).30

Another commonly utilised method includes fluidized bed dryers. This technology allows for quick uniform drying of sludge at low temperatures whilst utilising waste heat energy from production processes (Pandey et al., 2019). Inert materials are heated prior to coming in contact with sludge resulting in its drying. Once sludge is dried, particles become lighter causing them overflowing into a cooler (Pandey et al., 2019).

2.6.2 Alternative Treatments Applicable to Sludge

Conventional treatments of sludge have objectives in reducing the amounts of sludge and include thickening, conditioning, drying and dewatering. Alternative sludge reduction techniques available have a higher degree of sustainability. Two alternative methods include process changes causing reduced amounts of sludge generated, and post treatment of waste activated sludge resulting in reduced amounts of wastes requiring disposal (Karchiyappan & Venkatachalam, 2015). These two methods are broadly classified as i.e. Reducing sludge through process changes and sludge reduction via return activated sludge treatment

2.6.2.1 Reducing Sludge Through Process Changes

Changes to operational processes results in variations in the amounts of sludge generated (Karchiyappan & Venkatachalam, 2015). Activated sludge processes are modified to produce reduced amounts of sludge through changing the system design and operating parameters. Bacteria found in long sludge aged systems propagate slower than those of shorter sludge aged systems (Karchiyappan & Venkatachalam, 2015) and resultant of differences in amounts of cellular energy used in cell maintenance and energy used in cellular reproduction (Mtui, 2012). Process changes analysed were low sludge production process (LSP), improved aeration, extended aeration, membrane bioreactors (MBR's) and additions of biostimulants and additives.

2.6.2.1.1 Low Sludge Production (LSP) Process

The LSP, a modification of the activated sludge process, has two stages in establishing a microbial food chain in reducing amounts of sludge generated (Mtui, 2012). The first stage has a short residence time between 3-5 hours with no recycling of sludge promoting growth of dispersed bacterial cells with a main function to remove soluble BOD (Mtui, 2012). The second stage has a longer retention time (SRT) designed for predation by filter feeders like protozoans and rotifers which consume bacteria from the first stage subsequently convert surplus sludge into energy, water and carbon dioxide (Mtui, 2012).

The LSP is based on principles of energy loss through biomass conversions from lower to higher trophic levels (Mtui, 2012). Consuming bacteria causes energy loss to physiological processes and maintenance of microorganisms requiring energy. Higher life forms consume greater amounts of energy leaving less available for anabolic processes in the production of biomass (Mtui, 2012). Biomass production and energy loss have an inverse relationship, and maximising energy loss allows significant reductions by minimising biomass production (Karchiyappan & Venkatachalam, 2015).

This approach using two tropic levels to reduce biomass formation can be implemented as a suspended growth as in the case of activated sludge, or as an attached growth in the case of trickling filter processes able to carry an ecosystem of greater diversity emphasising a larger metazoan population present compared to activated sludge processes (Galić et al., 2021). Sludge generated with trickling filters are less than the activated sludge processes, and attributed to the use of a multiple tropic level approach allowing for maximum energy loss whilst reducing formation of biomass (Galić et al., 2021; Mtui, 2012).

Modifications to the LSP include the addition of an inert media suspended in the first stage and is known as the biofilm activated sludge (BAS) process (Yu et al., 2013). Additions of nutrients at low quantities enhances rapid growth of polysaccharide producing bacteria that attaches onto the media (Yu et al., 2013). In the following stage, bacteria and polysaccharides formed in previous stages are consumed, and operates similarly to the predatory stage in the LSP process (Mtui, 2012).

BAS process, when compared to the LSP process, has minimal addition of supplemental nutrients, reduced discharged nutrients and production of sludge with improved properties making it advantageous (Yu et al., 2013). Limitations of BAS technology is high capital costs associated with the media (Yu et al., 2013).

2.6.2.1.2 Improved Aeration

Improved aeration, an approach in reducing the production of sludge by improving aeration allowing for higher concentrations of mixed liquor suspended solids in the aeration basin, consequently increasing the retention time SRT (Navaee-Ardeh et al., 2006). Conventional aerating equipment restricted the use of this approach with limitations in the transfer of oxygen. This approach requires sufficient amounts of dissolved oxygen in the system in meeting requirements of the bacteria present (Navaee-Ardeh et al., 2006). Larger bacterial flocs show greater resistance in the transfer of oxygen. It is hypothesised that increasing concentrations of oxygen within liquid will allows the floc to undergo a deeper diffusion of oxygen, increasing aerobic volume of the floc that facilitates deficits in the organic substrate (Navaee-Ardeh et al., 2006).

Monod kinetics, which deals with the growth of microorganisms, show decreases in substrate concentration allowing a greater degree on cellular maintenance instead of growth, that facilitates reduced growth rates and reducing the production of sludge (Karchiyappan & Venkatachalam, 2015; Mtui, 2012). Current modifications include devices that generate high shear within the air mixing zone causing a reduced air 44 bubbles size breaking flocs into smaller flocs (Navaee-Ardeh et al., 2006). Reduced air bubble size and smaller flocs allow for a higher surface area to volume ratio resulting in increased efficiencies of oxygen and nutrient uptake (Navaee-Ardeh et al., 2006).

2.6.2.1.3 Extended Aeration

The plug-flow activated sludge process is similar to the extended aeration process, but a primary difference being the extended aeration processes operating in the endogenous respiration mode where organisms oxidise portions of their own cellular mass requiring longer aeration times with lower rates of organic loading (Galić et al., 2021). Theoretically, no excess sludge would be generated during extended aeration since the growth rate and decay of new and existing cells are equal (Galić et al., 2021). Through utilising the extended aeration process reduces the amounts of sludge requiring waste management, large cost savings in electricity and dewatering, and sludge having reduced odour potential with higher stability

2.6.2.1.4 Membrane Bioreactors (MBR)

An alternate technology in reducing sludge, that allows for reduced generation of sludge by increasing the sludge age (Karchiyappan & Venkatachalam, 2015). Differences between MBR's and the biological sludge process is elimination of secondary clarifiers in which separation of sludge and supernatant occur through the use of membrane processes such as ultrafiltration (Galić et al., 2021; Karchiyappan & Venkatachalam, 2015).

Generally, almost complete separation of liquids and solids occur in MBR's where ultrafiltration obliterates biomass and hydraulic retention times allowing for MBR's utilised for biomass of high concentrations (Galić et al., 2021). Longer retention times in MBR's facilitates greater growth of microorganisms found higher in the food chain which consumes bacterial cells allowing for reduced biomass formations (Galić et al., 2021).

Use of MBR's with mixed liquor suspended solids promotes 'cell-lysis' which is the decomposition of the cell membrane and cell cryptic growth, also the formation, growth and release of intra cellular products which causes decreased sludge been generated (Mtui, 2012). The cell wall degradation is a rate limiting step in MBR's (Karchiyappan & Venkatachalam, 2015). MBR's allow reductions in sludge generated and attributed to two factors i.e. a large proportion of metazoans and protozoans which are retained by the membranes and feed on bacteria, and an MBR is able to retain bacteria that is preyed upon by predatory organisms (Galić et al., 2021; Karchiyappan & Venkatachalam, 2015; Mtui, 2012).

2.6.2.1.5 Biostimulants and Additives

Biological matter in activated sludge increases rates of degradation of biological matter, and also with additions and use of biostimulants (Bajpai, 2014; Karchiyappan & Venkatachalam, 2015). These products shown to enhance metabolism promoting enzymes and stimulatory nutrients (Mtui, 2012). Majority of biostimulants which were used successfully, were patented and composition being confidential.

Bio-augmentation is the continuous additions of biomass that is genetically engineered into a treatment system (Mtui, 2012). Unfavourable conditions for natural growth within the system led to requirements of continual reseeding of organisms into the treatment system (Gorajova et al. 2021). Most genetically engineered biomass has low anabolic rates and a subsequent decrease in sludge generated (Galić et al., 2021).

Paranitrophenol, a biostimulant shown to uncouple the oxidative phosphorylation cycle (ADP-ATP cycle) which is the final stage of cellular respiration where most energy is released. By uncoupling this cycle through the use of paranitrophenol cause reductions on production of sludge up to 50% (Ávila-Pozo et al., 2021).

2.6.2.2 Sludge Reduction via Return Activated Sludge (RAS) Treatment

Return activated sludge exposed to conditioning agents are shown having a reduction to the overall production of biological sludge in conventional biological sludge processes (Karchiyappan & Venkatachalam, 2015). Exposing the recyclable fraction of settled biological sludge to conditions that partially reduces it to a non-viable fraction, allowing for decreased requirements in removing surplus sludge from the system through sustaining a constant amount of mixed liquor suspended solids within the aeration basin (Kaur et al., 2020). RAS treatments analysed were ultraviolet irradiation and ozonation.

2.6.2.2.1 Ultraviolet (UV) Irradiation

Exposing return activated sludge to UV light within a contact chamber in efforts to reduce biological sludge generation (Kaur et al., 2020). Studies show PPI effluents which underwent ultraviolet irradiation had reduced sludge yields of between 14-18% (Karchiyappan & Venkatachalam, 2015). Return activated sludge which passed through an ultraviolet chamber with quartz tubing allow for a fraction of return activated sludge becoming non-viable and simultaneously release the contents of the bacterial cells during the aeration stage (Galić et al., 2021; Kaur et al., 2020). This type of conditioning allows for the release of nutrients like nitrogen and phosphorous that could potentially be recycled, and a reduced amount of filamentous bacteria makes 46 this advantageous (Mtui, 2012). Other benefits include minimised capital and operating costs (Yu et al., 2013).

2.6.2.2.2 Ozonation

Ozonation is the solubilisation of bacterial cells in activated sludge and the subsequent decomposition of the solubilised material facilitating the formation of carbon dioxide and water through processes of aerobic biological oxidation (Kaur et al., 2020). Reducing sludge of specific amounts require treating three times that amount with ozone, dependent on the level of sludge treatment. Reducing excess sludge can to any specified ratio can be achieved with the potential of no excess sludge produced (Kaur et al., 2020). Ozonation is achieved by exposing ozone to a portion of mixed liquor suspended solids from the aeration basin and after following an adequate contact time, the mixed liquor suspended solids is returned to the aeration basin (Karchiyappan & Venkatachalam, 2015).

2.7 Waste Recovery

2.7.1 Thermal Processes

Waste recovery, allows for increased sustainability and a transition towards a circular economy. various recovery options are available for wastes generated including different thermal processes like combustion, pyrolysis, steam reforming, wet air oxidation (WAO), super critical water oxidation (SCWO), and gasification (Lancaster & Xu, 2009). Other available options for resource and energy recovery include composting, land reclamation, production of construction materials like cements and insulating materials, and the conversion to fuel components (Fytili & Zabaniotou, 2008). Sludge from wastewater treatments in PPI's require processing prior to recovery (Lancaster & Xu, 2009). Deinking and mixed sludges are generally drier than primary and biological sludge as the amounts of lignin affects abilities of sludge to dewatering, high levels of lignin shown to be easier to dewater (Bajpai, 2015; Bajpai et al., 1999; Latha et al., 2018).

The end use of wastes generated is dependent on their physical, chemical and microbiological characteristics (Lancaster & Xu, 2009). An example of sludge used as a filler in concretes require storage until processing making it vital during storage in avoiding chemical, physical and microbiological decomposition (Lancaster & Xu, 2009). Different indicators used as parameters in decomposition include solids content, water absorbance, viscosity, compressibility, combustion residue, fibre length distribution, chemical composition and leeching of compounds into the water (K. DuraiSwamy et al., 1991). Technologies utilised in waste recovery are described below. 47 Primary factors influencing selection and implementation of specific technologies depends on local infrastructure and competition with other industries in respect to residues, costs and local policies.

2.7.1.1 Pyrolysis

Pyrolysis, also known as destructive distillation (Lou et al., 2011). In this process, application of indirect heat allows for volatiles being captured. Heated organic waste under anaerobic conditions results in production of fuels in gaseous and liquid phases and a residue that is solid and inert generally being carbon (Lou et al., 2011). This is an alternative to incineration and landfilling, that requires a waste stream that is consistent to produce fuel product. Pyrolysis facilitates the decomposition of organic matter between temperatures of 400–800 degrees Celsius with indirect heat under anaerobic conditions simultaneously capturing volatiles (Bajpai, 2015; Bajpai et al., 1999).

Indirect heat allows decomposition of PPMS into a combinations of solid charcoal, water, soluble organics like methanol and acetic acid, water insoluble groups and noncondensable gasses like hydrogen, methane and carbon monoxide (Reckamp et al., 2014). A requirement of long exposure times in optimising production of water insoluble groups, specifically production of char (Reckamp et al., 2014). No combustion can occur and oxygen is not allowed to enter. This technology was developed and modified to treat wastes having a high carbon contents such as wood, petroleum and plastic wastes (Pandey et al., 2019).

Heating time, reaction time and operational temperatures are optimised and dependent on the desired product (Czernik & Bridgwater, 2004). At reduced temperatures and heating rates allows this process to produces chars with high heating values, if the sludge processed was highly organic allows its utilisation as a fuel or activated in producing activated carbon (Czernik & Bridgwater, 2004). Conversely, high heating rates and temperatures greater than 500 degrees Celsius with short residence times causes the production of bio-oils with yields of 70-75% biooils (Czernik & Bridgwater, 2004). Materials remaining after pyrolysis of deinking sludge can be reused in manufacturing of paper (Lou et al., 2011).

Fast pyrolysis processes is achieved with use of fluidized bed boilers, circulating fluidized bed boilers and rotating cone reactors (Devi, 2013). Pyrolysis of PPMS facilitates energy and materials recovery. Energy recovery by utilising bio-oils produced and materials recovery by recovering remaining solids from this process (Czernik & Bridgwater, 2004). Requirements include a dry solids content of PPMS being greater than 80% (Lou et al., 2011).

During fast pyrolysis, cellulose and hemicellulose degrade and converts (Pandey et al., 2019). At temperatures greater than 300 degrees Celsius, carbohydrate polymers de-polymerise into short chain sugars which are dehydrated slowly and the following reactions facilitate formations of unsaturated polymer intermediates which are condensed in char formation (Devi, 2013; Reckamp et al., 2014). High heating rates used to achieve higher temperatures, and de-polymerisation reactions results in liberation of volatile products such as bio-oils (Reckamp et al., 2014). Breaking the carbon-carbon bond occurs at high temperatures causes formation of gas products (Reckamp et al., 2014). Oils produced in pyrolysis are products of thermally cracking cellulose and include an assortment of organic oxygenates, lignin fragments and polymeric carbohydrates, hemicellulose and lignin derivatives from the biomass processed (Chung et al., 2009).

Table 11 Comparison of physical properties of pyrolysis oil (bio-oil) with petroleum based heavy fuel oil (HFO)

Physical Property	Pyrolysis Oil (Bio-Oil)	Heavy Fuel Oil (HFO) – Petroleum Based
Moisture Content (% Wt)	15 – 30	0.1
Specific Gravity	1.2	0.94
Ph	2.5	-
Elemental Composition (% Wt)		
Carbon	54 – 58	8.5
Hydrogen	5.5 – 7.0	11
Oxygen	35 – 40	1.0
Nitrogen	0 – 0.2	0.3

Adapted from (Bajpai 2010,2014)

Pyrolysis oils are highly acidic making them corrosive with high concentrations of water making it highly unstable, but are ideally suited to substitute fossil fuels in heat and power generation with applications like boilers and furnaces (Chung et al., 2009). These oils can be upgraded to transportation fuels and have an energy density four times greater than the material processed posing a range of advantages with respect to logistics (Chung et al., 2009).

Table 12 General overview of pyrolysis oil (bio-oil) applications

Pyrolysis oil (bio-oils)	Applications
Heat	• Boiler co-firing
Power	• Diesel engine micro-turbines
Fuels	• Upgrading hydrogen
Chemicals	• Resins • Fertilizers • Acetic acid • Flavors • Adhesives

Adapted from (Bajpai, 2010)

Pyrolysing organic wastes facilitates meeting renewable energy targets through the displacement of fossil fuels (Fytili & Zabaniotou, 2008). Increased materials recovery is achieved via pyrolysis compared to incineration with the only usable product being heat, whereas if pyrolysed prior to incineration results in products including bio-oils, chars and gasses (Fytili & Zabaniotou, 2008). Biochar can be used as a fuel or used as feedstock's in other applications. The use of biochar as soil amendments has seen increased attention, and described as agent of carbon sequestering and climate mitigation through use as a soil amendment, described as a carbon sink allowing carbon sequestration (Blanco et al., 2004; Smith, 2011).

2.7.1.2 Incineration or Combustion

Incinerating rejects and residues in combination with power generation is a common waste management practice (Lancaster & Xu, 2009). It can be implemented with nearly all sludges. Specific characteristics of PPMS such as high moisture and ash contents results in its incineration leading to energy deficits in the energy balance (Lancaster & Xu, 2009).

Technology successfully utilised in thermal oxidation of PPMS are fluidized bed boilers, by employing this technology to produce steam in power generation whilst decreasing dependence on fossil fuels (Fytili & Zabaniotou, 2008). This allowed fluidized bed boilers becoming an ultimate solution in disposal of wastes generated in

PPI processes. Chlorine contents of some rejects have ramifications such as corrosion and air contamination from chlorine containing compounds (Smith, 2011) and in mitigating such problems are ash rinsing technologies. This technology proves effective in significantly removing or diluting heavy metals and chlorine, resulting in decreased chlorine concentrations within accepted levels for agricultural applications (Lancaster & Xu, 2009; Monte et al., 2009) Other than reducing fossil fuel dependence, a significant advantage is a reduced amount of material requiring landfilling of between 80-90% (Fytili & Zabaniotou, 2008). Final ash disposal is dependent on qualities of ash, as some ash may be landfilled and others utilised in the construction industry producing value added products (Blanco et al., 2004).

2.7.1.3 Gasification

Gasification is an established technology in recovery of energy from waste, but has a limited application in PPI's (Sikarwar et al., 2016; Bajpai, 2017). Gasification, a thermal process where combustible material fed is transformed to inflammable gasses and inert materials utilising air or oxygen (Sikarwar et al., 2016). This process is conducted at high temperatures between 900-1100 degrees Celsius with air, and 1000-1400 degrees Celsius with oxygen (Molino et al., 2015; Sikarwar et al., 2016).

Gasification allows reductions in volumes of flue gasses as water and carbon dioxide formed participates in the reaction. Use of pure oxygen allows for no nitrogen been produced (Sikarwar et al., 2016). Pyrolysis is considered a part of the gasification process with differences being pyrolysis is conducted under anaerobic conditions. These processes can be implemented in combination (Molino et al., 2015). Chemical differences between gasification and pyrolysis is the operational temperatures and controlling oxidation by air or oxygen (Heidary, 2017). Gasification processes are separated into stages or zones, where each can be optimised to produce gasses (Heidary, 2017).

Gasification converts materials that are carbon based into hydrogen and carbon monoxide by utilising heat under combinations of either steam, nitrogen or oxygen within a reaction vessel. Other than producing carbon monoxide and hydrogen, remaining syngas contains nitrogen with trace amounts of methane, other hydrocarbons, particulates, tar and carbon dioxide (K Durai-Swamy et al., 1991). Syngas can be utilised in various ways such as feeding into internal combustion engines to generate electricity, converted to liquid fuels via catalytic Fischer-Tropsch process, combusted to produce heat energy and the production of different chemicals (Kahmark & Unwin, 1996; Yongwu et al., 2012). Efficiencies depends on various parameters like moisture content of feedstock, fusion temperatures of ash, feeding systems design and the degree of mixing and separation of feedstock (Molino et al., 2015).

Requirements include feedstock preparation to moisture contents between 10-20% prior to entering the feeding system (Zainal et al., 2001). Variations in the design of feeding systems and syngas composition are resultant of physical characteristics of feedstock and pressures within the gasifier (Zainal et al., 2001). Recovered energy as steam is reused in drying of feedstock (Molino et al., 2015).

Recent innovations led to the development of plasma gasifiers where the plasma torch is the primary source of heat (Mountouris et al., 2008). Gas is passed through an electric arc resulting in dissociation of gas molecules creating significantly high temperatures (Mountouris et al., 2008). Limitations facing plasma gasifiers are high costs associated with this technology and compared to traditional gasifiers and consumes a greater amount of parasitic energy (Mountouris et al., 2008).

Different types of gasifier designs are available commercially, but applicability to PPMS are limited to fixed bed, fluidized bed and plasma (Ouadi et al., 2013). During gasification, physical and chemical changes occur to PPMS. Major limitations on gasification of PPMS is reducing water contents to the required levels (Yongwu et al., 2012)

Gasification is characterised by 4 stages or zones i.e. the drying, pyrolysis, throat or oxidation, and reduction zone (Molino et al., 2015; Sikarwar et al., 2016). Dried sludge is fed into the gasifier chamber and undergoes the first step of the process. In this zone, sludge moves downwards and moisture is evaporated by heat from other zones (Molino et al., 2015). The drying rate is dependent on surface area of feedstock, recirculation velocity, relative humidity of gasses, temperature gradients between feedstock and heated gasses, and internal diffusivity of feedstock moisture (Molino et al., 2015). Sludge fed with moisture contents smaller than 15% will lose all moisture in this zone (Molino et al., 2015). This is followed by the pyrolysis zone, where permanent degradation of feedstock occurs as sludge moves out of this zone utilising energy generated from incomplete oxidation of the pyrolysis product (Molino et al., 2015). At 250 degrees Celsius, volatiles are released and conversion of 60-70% of sludge into a liquid fraction comprised of; water, tar and oils in gaseous phase, assortment of hydrocarbons, and unreacted ash and char (Nzihou & Stanmore, 2013). Gaseous phase comprised of; carbon dioxide, carbon monoxide and hydrogen. Pyrolysis generally occurs at temperatures between 350 – 500 degrees Celsius (Nzihou & Stanmore, 2013).

The next stage is the throat or oxidation zone (Molino et al., 2015). Volatiles produced during pyrolysis is partially oxidised in an exothermic reaction causing rapid temperature increases to around 1100 degrees Celsius, surplus heat generated is utilised in drying and pyrolysis reactions (Molino et al., 2015). Oxidation of volatiles is rapid causing available oxygen becoming consumed before diffusing the chars surface and will not undergo combustion (Nzihou & Stanmore, 2013). To reduce amounts of tar produced, oxidising the organic fraction is vital to form low weighted molecular products. Products of the throat zone include; carbon monoxide, carbon dioxide, hydrogen, water, high chain hydrocarbon gasses and residual tars and char (Nzihou & Stanmore, 2013). Products are fed into the final stage, the reduction zone, where chars are converted to gasses by the use of heated gasses from previous zones (Molino et al., 2015). The gasses are reduced allowing the formation of carbon monoxide and hydrogen at larger proportions (Nzihou & Stanmore, 2013). Gasses enter at temperatures between 1000-1100 degrees Celsius and exit around 700 degrees Celsius (Molino et al., 2015).

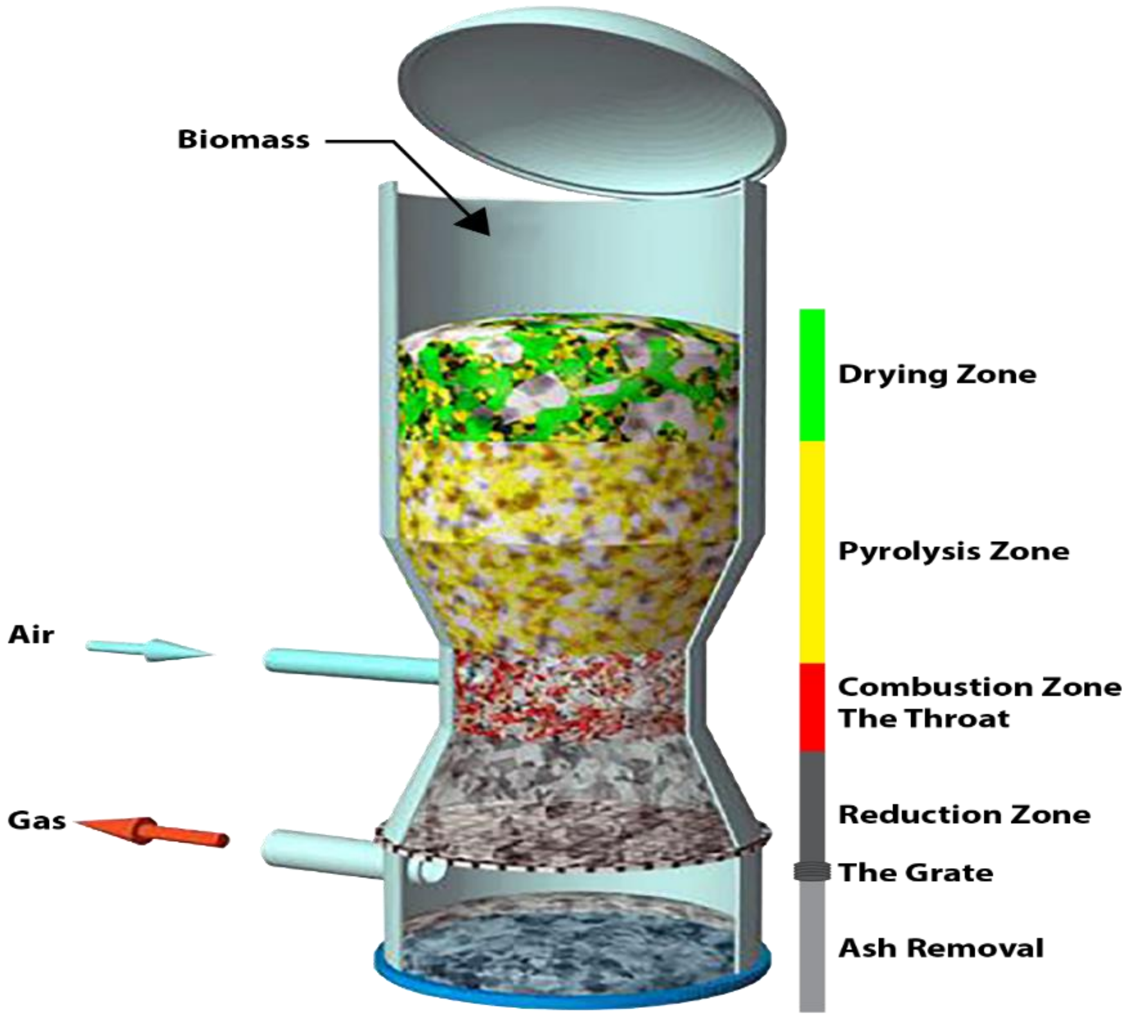

Figure 10 Schematic showing the four processes within gasification of biomass (Calvo et al., 2013)

Difficulties faced in gasification of sludge's is formation of tars and ash slagging (Monteiro Nunes et al., 2007). The presence of tars is undesirable and indicates low gasification efficiencies with increased difficulties associated in cleaning syngas where it generally fouls and clogs tubes and pipes of equipment used (Monteiro Nunes et al., 2007). Tar is removed either by primary methods occurring within the gasifier or secondary treatments occurring outside the gasifier (Monteiro Nunes et al., 2007).

Gasification popularity increased due to the numerous advantages utilising this technology and include volume reductions in flue gasses, pollutant concentrations lower than incineration, and higher energy efficiencies compared with other technologies (Kimura et al., 2006). Gasification is shown to be a practical waste management option for PPMS with potential of a net energy gains. Environmental advantages of gasification are a reduced potential of harmful emissions (Kimura et al., 2006).

The processes involved have abilities in removing undesired compounds via scrubbing, which at a later stage would have formed harmful pollutants during combustion (Kimura et al., 2006). Similarities between gasification and incineration as both methods facilitate conversion of sludge into non-hazardous by products (Lancaster & Xu, 2009), and differences arise from different conversion mechanisms, chemical reactions, and characteristics of by-products (Lancaster & Xu, 2009). Gasification proves advantageous in versatility as the syngas, which has a variety of uses with lower costs involved with cleaning (Chiang et al., 2013).

2.7.1.4 Wet Air Oxidation

Wet air oxidation (WAO) is characterised by "oxidation of organic and inorganic substances in an aqueous solution or suspension by means of oxygen or air at elevated temperatures and pressures in the presence or absence of catalysts" (Luck, 1999). In this process, organic liquid or solid contaminants are extracted into water and come into contact with an anoxidant under favourable conditions facilitating their destruction (Luck, 1999). This occurs in the aqueous phase with temperatures between 150-330 degrees Celsius and pressures between 1-22 MPa with the use of pure or atmospheric oxygen (Luck, 1999).

Water is crucial as it works as a catalyst to the reaction and a hydrolysis reactant (Luck, 1999). Oxidation will occur in an aqueous environment and water acting as a reaction medium for dissolved oxygen with different organic and oxidisable components (Luck, 1999; Sharma et al., 2015). Radicals from oxygen and water attack organic compounds which form organic radicals. These free radicals are a vital factor in WAO chemistry (Chung et al., 2009). Chemistry of WAO is characterised with formations of carboxylic acids, carbon dioxide and water (Debellefontane, 2000). The acids are generally acetic, formic and oxalic acids which are degraded and removed in biological post treatments and cost effective (Lancaster & Xu, 2009).

WAO is an attractive technology in the treatment of sludge, due to its high concentration of organic matter (Debellefontane, 2000). Environmentally considered a viable technology since nitrous oxide, sulphur dioxide, hydrochloric acid, dioxide, furans and fly ash are not produced (Lancaster & Xu, 2009). Increased efficiencies in reducing toxic organics as WAO converts up to 99% of toxic organics into end products that are harmless (Lancaster & Xu, 2009). Compounds unable to completely oxidise results in formation of intermediate compounds constituting upto 25% of the organic matters original mass and includes small carboxylic acids (Debellefontane, 2000).

The temperatures utilised determine the type of application. Low temperature oxidation between 100-200 degrees Celsius is used to condition PPMS and municipal sludge (Sharma et al., 2015). Medium temperatures between 200-260 degrees Celsius is used to treat ethylene spent-caustics and industrial wastes (Sharma et al., 54 2015). High temperature oxidation between 260-320 degrees Celsius is used in destruction of sludge and treatment of industrial wastewaters (Sharma et al., 2015). At high temperatures, complete destruction of PPMS, municipal sludge and organic sludge is predicted (Hii et al., 2014). Requirements include maintaining water in its liquid phase and conducted in aqueous phase at elevated pressures (Hii et al., 2014). Pressurization increases oxygen concentrations which increases rates of oxidation (Debellefontane, 2000).

Efficiencies of this process depends on operational parameters like temperatures, pressures, air supply and the feedstock solid concentration (McCallum et al., 2021). Rates of oxidation can increase by raising reaction temperatures between 120-350 degrees Celsius, and pressures between 1-27MPa (McCallum et al., 2021). This process requires an external oxygen supply (Debellefontane, 2000). Dewatering is not required as a sludge of 1% dry solid content can be used as feedstock, this allows for decreased operational costs by increasing the consistency of sludge, a high solids content keeps the process self-sustaining (McCallum et al., 2021).

When comparing to incineration, WAO is free of air pollution, ash production is reduced and does require dewatering when used as a feedstock (Blanco et al., 2004; Monte et al., 2009). Production of high strength liquors is disadvantageous as a treatment plant with increased aerational capacity is required (Chung et al., 2009). The produced liquor can have a BOD of between 40-50% translating to a 30-50% increased BOD loading in the treatment system (Chung et al., 2009)

2.7.1.5 Super Critical Water Oxidation

Super critical water oxidation (SCWO) is a modification of the WAO process in which operational temperatures are increased past waters critical temperatures in an aqueous medium with the use of an oxidant of either oxygen or hydrogen peroxide (Antal et al., 2000). This is an innovative method, with processes resulting in the effective destruction of organic wastewaters and sludge (Bajpai, 2017; Fytili & Zabaniotou, 2008). During SCWO, chemical properties of water changes and acquires new chemical properties when heated to between 400-600 degrees Celsius past the critical temperature of 374 degrees Celsius, and compressed past the critical pressures of 22 MPa (Antal et al., 2000)

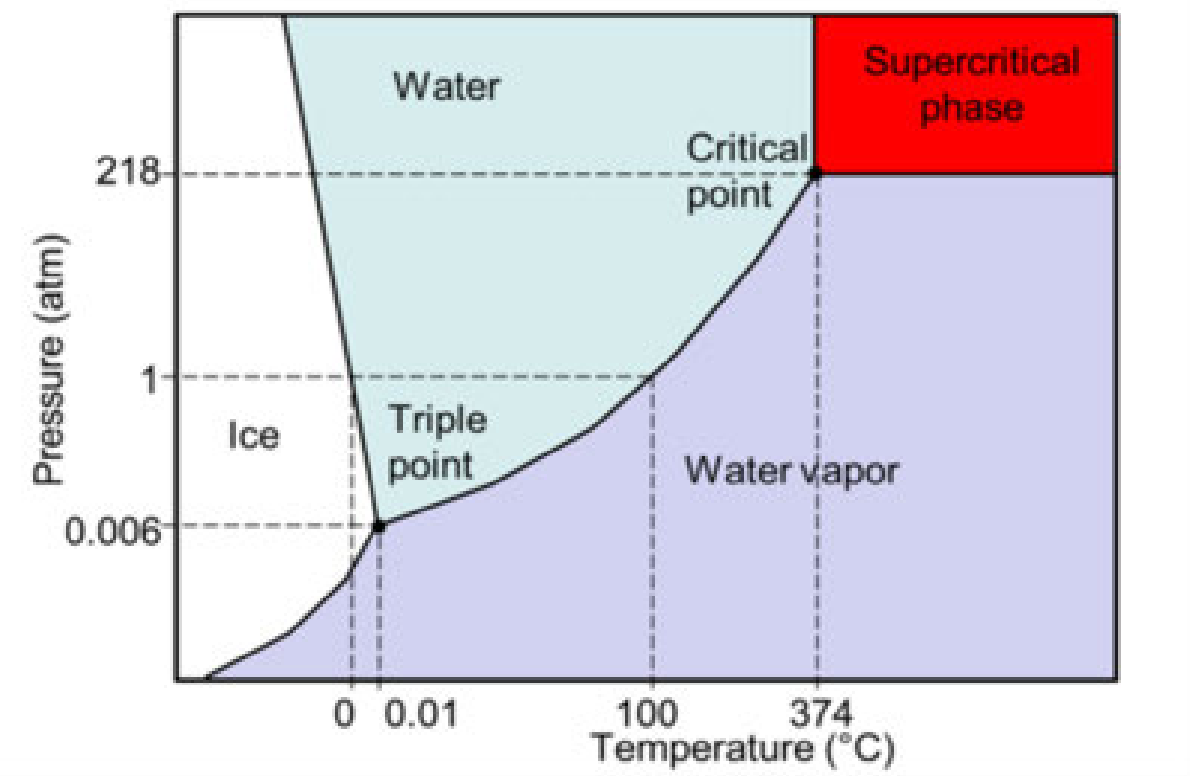

Figure 11 Phase diagram for water (Bridgman, 2013)

At supercritical temperatures and pressures, water is used to remediate by exploiting capacities in dissolving oxygen and non-polar organic compounds allowing the oxidising of organics into water and carbon dioxide (Veriansyah et al., 2007). Compounds like fillers and salts precipitate out and recovered and reused (Lancaster & Xu, 2009). SCWO is also known as hydrothermal oxidation (Veriansyah et al., 2007). SCWO is a reaction medium of low diffusivity, viscosity and high density, allowing rapid oxidation reactions (Crain et al., 2000). SCWO has lower temperatures compared to conventional methods like incineration, significantly reducing formations of NOx and SOx, posing significant advantages. PPMS undergoing SCWO does not require dewatering as water present is utilised in the process, and sludge of 10% dry solids can be processed (Lancaster & Xu, 2009).

Within SCWO, oxygen together with pressurised sludge are fed into the preheater reactor at temperatures of 25 degrees Celsius and pressure of 25.5 MPa (Antal et al., 2000). In the preheater, temperatures increase to between 300-400 degrees Celsius allowing water achieving a supercritical state, which dissolves organics and hydrolyse polymers preventing formation of chars (Antal et al., 2000). The mixture is then fed into the main reactor where organics remaining are oxidised with residence times between 5-10 minutes and maximum temperatures of 600 degrees Celsius (Antal et al., 2000). Thereafter, effluent is cooled with energy recovery occurring, with up to 45% of the heating value is recovered (Antal et al., 2000). Products are then separated into solids requiring landfilling, and liquids requiring wastewater treatment (Lancaster & Xu, 2009).

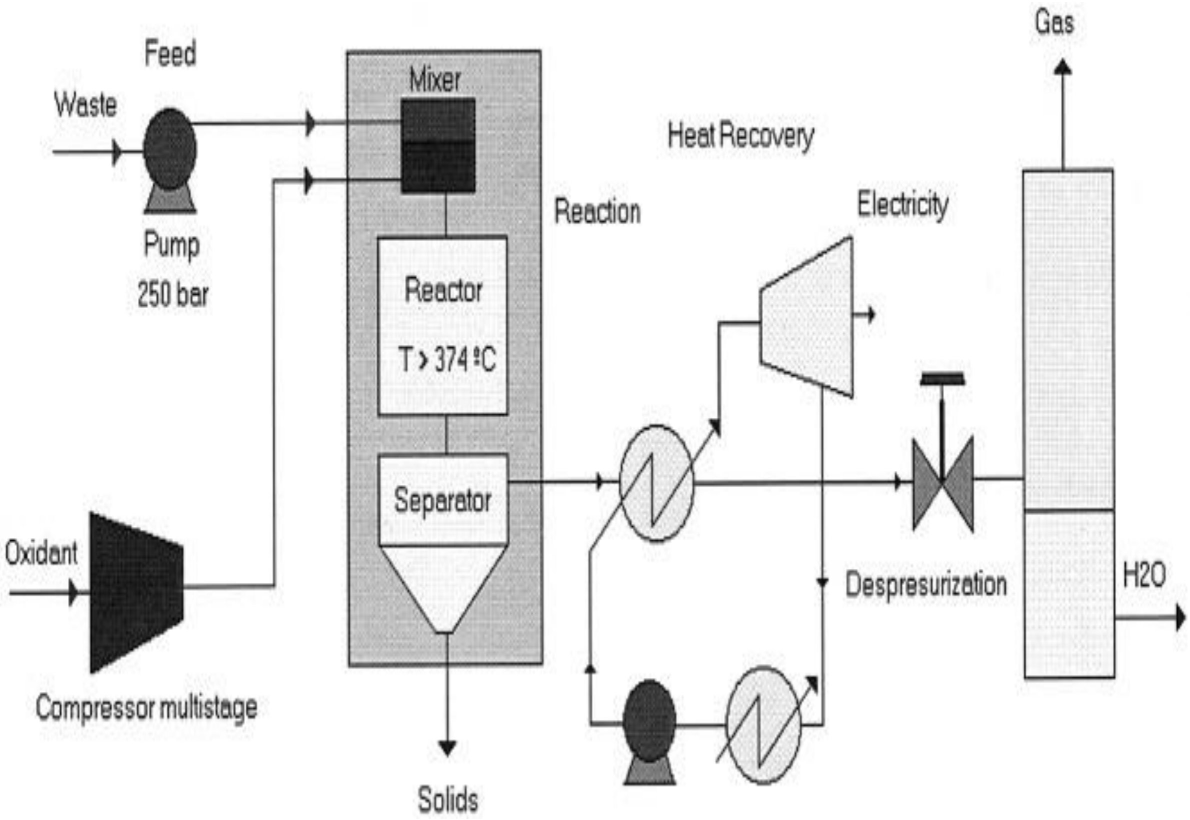

Figure 12 Schematic overview of supercritical water oxidation (SCWO) (Schmieder & Abein, 1999)

SCWO proves efficient as it can utilise a wide range of feedstock can be utilised including; abattoir waste, pig manures, agricultural wastes, slurries, sewage sludge, PPMS, organic materials and hazardous wastes undergo complete oxidation (Crain et al., 2000). Implementing SCWO in treating PPMS allows for a high degree of materials being recovered and reused, and recovered energy exceeds the energy input, illustrating significant economic benefits.

2.8 Waste Management of PPMS

Waste management of solid wastes from PPI's differ and dependent on materials processed i.e. virgin pulp and paper mills, mills processing recycled fibres, and the different manufacturing processes utilised (Latha et al., 2018). Operations processing recycled fibres are commonly located within close proximities of urban areas due to logistical advantages (Bajpai, 2015). Incinerating fibre rich sludge manifests as ramifications of harmful emissions (Bajpai et al., 1999). Many laws and regulations apply to such emissions because of the close proximity to population centres, posing severe environmental and social ramifications if inadequately regulated (Smith, 2011).

2.8.1 Recycling

A method of recycling fibres from primary sludge is utilising PPMS as a feedstock in other mills, known as fibre transfer, shown to be a viable method in valorising waste materials sustainably (Bajpai et al., 1999). Limitations faced is characterising such waste streams as some substances present require permits and specialised equipment to transport such waste (Monte et al., 2009). Waste sludge is also utilised in the manufacture of value-added products like; ceramics, construction and building materials such as concrete, cements and bricks. Sludge is utilised in combination in the manufacture of cementitious products, where its used as a filler or an aggregate in cement mixtures, and is shown that the presence of sludge increases the materials strength (Sandberg et al., 2012). Sludge is also recycled through process changes, where primary sludge returns to the internal fibre processing system resulting in economic advantages with significant savings in purchasing wood resources and electricity costs (Smith, 2011). Recycling also includes transforming sludge into energy pallets due to the high organic matter allowing for its utilisation as a sustainable source of energy and fuel (Sandberg et al., 2012). Pellets can be used as bedding and litter for animals, and can be blended and converted to animal feeds but carbohydrate and ash content limits such uses (Sandberg et al., 2012).

Fermenting fibres during secondary treatment generates sludge with high contents of cell protein and extracting this material i.e. cell protein is possible but high costs in concentrating solids limits such uses (Bajpai et al., 1999). Difficulties arising in recycling of fibres is due to the remaining sludge becoming colloidal at greater proportions as the fibre fractions reduced. In mitigating this, addition of fibres to the waste stream in reducing the resistance to dewatering (Bajpai et al., 1999). Lowering the fibre fraction causes remaining wastes becoming less stable as a solid. Reducing the fibre fraction causes a reduced internal shear strength. Reducing the stability of sludge has ramifications to landfilling and designs of the landfill, limiting the available options in PPMS waste management (Blanco et al., 2004). It could be inferred there is a balance in amounts of fibres which can be removed from waste materials i.e. PPMS and subsequent options available in waste management.

2.8.2 Land Application

PPMS is carbon rich, but low levels of nitrogen and phosphorous limits its use as a fertiliser. Sludge’s depressive effect is neutralised with time as it undergoes biotic processes ranging between 5 – 10 months (Arshiya et al., 2020). Carbon-nitrogen and carbon-phosphorous ratios of ppms is due to the depressive effect of sludge (Arshiya et al., 2020). The pollution potential is low with many studies showing an effect in the exchangeable sodium content, with no heavy metal pollution expected and found with the land application of ppms (Monte et al., 2009). Biological sludge has higher contents of nitrogen and phosphorous compared to primary sludge, making them suitable for application to soils (Smith, 2011). The nutrient contents vary as they are site and process specific.

Another method utilised in land applications is through composting of mixed sludge, and economic viability limiting the use of this method, as economic success is directly dependent on current markets (Sandberg et al., 2012). Land application of ashes from incinerating ppms has a high potential because it is rich in calcium, aluminium and silica, shown having no value as a fertiliser, but the ash acted as a limiting agent to increases in soils pH (Arshiya et al., 2020). Major concerns on the suitability of land application of ppms is extensive research required on the environmental impacts from leeching of pollutants, and contamination of groundwater (Kuokkanen et al., 2008; Monte et al., 2009; Smith, 2011).

2.8.3 Landfilling

Landfilling of solid wastes from PPI's is the most common method of waste management (Bajpai, 2015; Latha et al., 2018). This method is limited by the presence of trace chemicals like PCB's having a leeching potential and contaminating groundwater (Kuokkanen et al., 2008). Modern landfills i.e. sanitary landfills are designed in a way able to reduce leeching of waste and emissions into the atmosphere. Problems associated with landfilling PPMS is leachates and production of gasses (Kuokkanen et al., 2008). Improved techniques when constructing these landfills include linings of synthetic materials and clays allowing for reduced leaching.

PPI's find it economically viable paying fees with collection and landfilling at municipal and large industrial installations, compared to operating and maintaining their own landfill (Arshiya et al., 2020). PPMS is a solid waste that is bulky causing increased strain on landfills of common usage (Smith, 2011). Landfilling is not sustainable and landfill air space is a non-renewable resource. Decreasing landfill availability simultaneously with the realisation of environmental impacts from burying solid waste (Smith, 2011). Costs of landfilling is predicted to increase drastically, and new landfills becoming ever increasingly difficult to site (Dlamini et al., 2018).

Combinations of primary and biological sludge can be utilised as a cover material for daily activities in municipal landfills, and a landfill capping material during closure of the landfill. This allows resources being conserved whilst utilising PPMS as a value added product in capping landfills. A measure of the wicking potential, known as hydraulic conductivity of PPMS, is low and can be further reduced with additions of fly ash. Limitations on the use of PPMS in landfill capping is the high moisture content and low shear strength.

2.9 Water Use in South Africa

Limited availability of water resources makes South Africa the 30th driest country globally (Jansen, 2012) causing the water crisis becoming the second biggest risk in conducting business in South Africa. South African rainfall distribution varies from eastern to western regions because of the warm Indian Ocean along the east with higher rainfalls compared to the western side with the cold Atlantic Ocean. Different climatic regions with evaporation rates higher than precipitation is a factor resulting in South Africa being regarded as water scarce (Greenberg et al., 2013; Macdonald, 2004).

Water usage is dominated by agricultural activities and municipalities utilising 62% and 27% include different residential, commercial and industrial activities (Jansen, 2012). Water use varies between provinces and municipalities which is directly dependent on human settlement patterns and localised economies (Jansen, 2012). Although a water scarce nation, water consumption per capita per day is around 237 litres, significantly higher than the global average of 173 litres per capita per day (Matikinca et al., 2020). A high demand on water resources which is predicted to increase with greater demands from agricultural, industrial and municipal sectors (Matikinca et al., 2020). Increased demands from municipalities is predicted being the greatest resultant of rapid urbanisation and growth in the industrial sector with greater production capacities (Matikinca et al., 2020).

Estimates show 40% of South Africa’s wastewater is untreated. This problem is further compounded by 825 water treatment works being in a critical state, if not rectified immediately will have ramifications felt in present and future generations (Otto et al., 2018). Social and environmental consequences include a large portion of the population having no access to running water, depending on river systems and water bodies as a water source (Greenberg et al., 2013; Macdonald, 2004).

Extreme climatic events further affecting South Africa’s water resources is predicted and a result of climate change, an example being the El Nino system affecting the region, with effects been devastating droughts with ramifications on agriculture and economy. Currently, South Africa faces the La Nina system which is associated with higher than average climatic events such as weather systems and rainfall events, with high flooding probabilities and associated ramifications on social, economic and environmental spheres. It is forecasted that by 2050, most of South Africa will become highly vulnerable to risks in water supply (Matikinca et al., 2020) illustrating an imminent need in significantly reducing dependence on rainfall as a water source and explore sustainable alternatives such as utilising groundwater reserves, coastal cities adopting desalination technologies and increased wastewater recycling.

2.9.1 Water Scarcity

Water scarcity is the rarity in the supply of water and expressed as a ratio between an areas water supply and water consumption by humans (Bischoff-Matson et al., 2020). Two primary factors affecting water scarcity i.e. physical and economic scarcity. Economic or social water scarcity is the absence of investments towards infrastructural or human capacity in order to satisfy demands placed on water in regions of water abundance (Stavenhagen et al., 2018). This scarcity is resultant from factors such as political policies resulting in inadequate infrastructural development in water and sanitation (Stavenhagen et al., 2018). Many rural areas of South Africa cannot access a basic water supply due to geospatial planning of the apartheid regime and many areas still facing its ramifications, and most of the effected population of poor demographics located in areas of the Eastern Cape, Limpopo and KwaZulu-Natal.

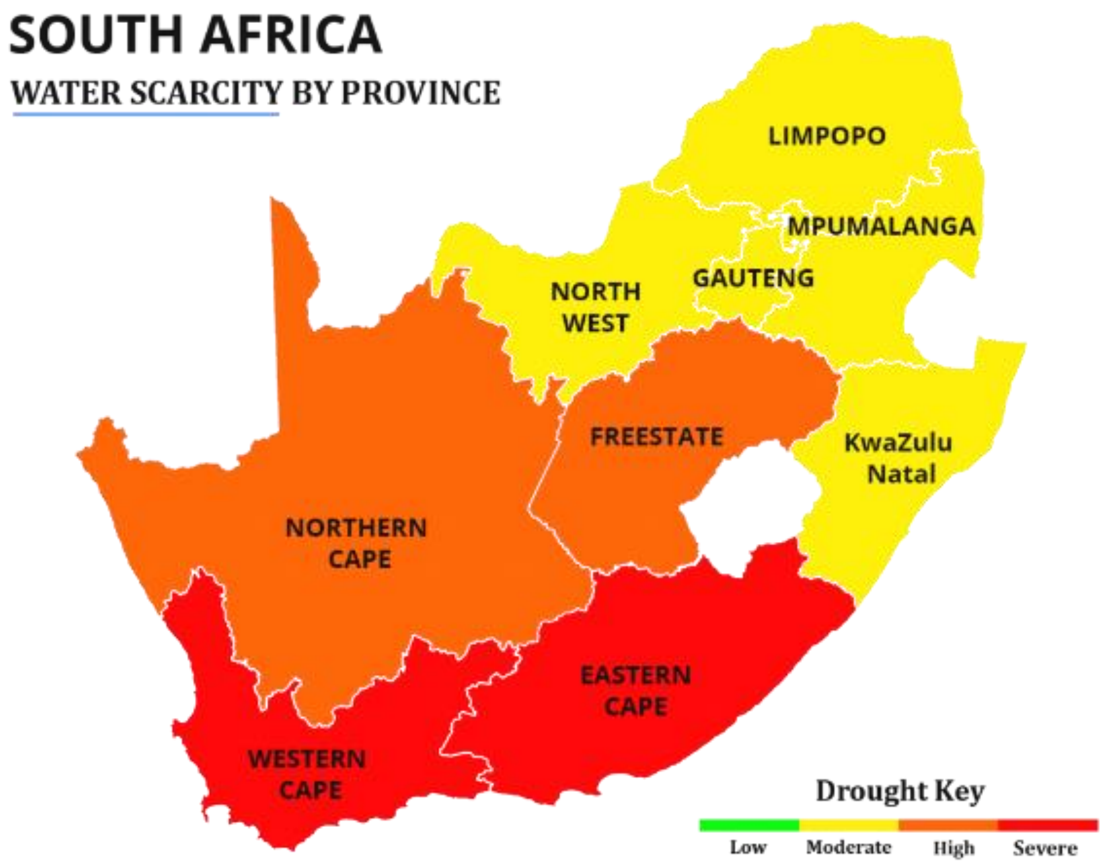

Figure 13 South African map illustrating water scarcity at a provincial level for 2019 (Postel, 2000)

Water scarcity could also be resultant of physical factors such as enhanced climatic conditions due to global warming combined with greater demands on water resources (Bischoff-Matson et al., 2020). Physical water scarcity is the inability in meeting demands because there is not enough water or inadequacies faced by water resources. Four factors driving physical water scarcity i.e. demand-driven water scarcity, population-driven water scarcity, climate-driven water scarcity and pollution driven water scarcity (Bischoff-Matson et al., 2020).

The population of KwaZulu-Natal and Gauteng is predicted to increase by the immigration of 1 million people between 2016 and 2021, and Cape Town had a population growth of 7% between 1995 and 2018. Population growth causes increased demands on water resources from residential levels (McDonald et al., 2011). Imbalances between demand and supply of water resources because of population growth at local levels combined with the negligent use of water resources, causes greater strain on water resources that are further compounded with influx of pollutants into river systems leading to overall decreases in available water resources.

Table 13 The causes and results of economic and physical water scarcity

	Causes	Results
Economic Water Scarcity	• Political policies • Poverty • Inequality	• Inadequate infrastructural developments in water and sanitation to certain groups of people. • Lack of investments and infrastructure to utilise water from rivers, aquifers and other water sources
Physical Water Scarcity:		
Demand-Driven Water Scarcity	• Water demands surpass capacity of available water resources • Higher degree of water scarcity can be due to urbanisation and the rapid growth of urban areas putting additional strain on water resources	• Populations with high densities in areas with low freshwater availability are at greater risk of water scarcity
Climate-Driven Water Scarcity	• Insufficient rainfalls with high evaporation rates resulting significantly less water available as runoff and limited water availability • High degree of variability in climates	• The mean annual rainfall received in South Africa 450mm compared to the global average of 860mm • North-western regions receive an annual rainfall of 200mm compared to eastern regions receiving between 500-900 mm annually
Pollution-Driven Water Scarcity	• Degradation in the quality of water beyond a point where the water is considered unusable • Resultant of urbanization, deforestation, wetland destruction, mining, agricultural and energy use	• Water scarcity is not only a volumetric problem, but also a problem regarding the quality

Adapted from (Bischoff-Matson, 2020; Hadden, 2014; Matikinca, 2020)

Water, one of the cheapest resources with minimal concern on costs associated with dispensing, recycling and disposing. A paradigm shift is urgently needed to view water as a scarce valuable resource, with water scarcity compounded by changing climates resultant of global warming (Otto et al., 2018). This is substantiated with devastating droughts ravishing South Africa in recent years with Cape Town having recorded its worst water crisis to date.

2.9.2 Water Use in South African Pulp and Paper Industries

A countries water demands directly relates to the level of development and economic activities of that country (Jansen, 2012). Water usage in developed nations is less than developing nations per capita, with differences attributed to different diets and lifestyles of the country's population.

PPI's are water intensive industries dependent on water to successfully produce pulp and paper products, and PPI's being the 6th largest polluter industry globally (Donkor, 2019). During production, all major processes involved have high water demands vary with utilisation of between 70 to 230 cubic metres of water per a ton of product (McDonald et al., 2011). Another problem with the high-water demands is the discharge of effluents, which if not adequately treated will lead to ramifications on environmental and human health.

The South African government established regulations and policies towards encouraging responsible freshwater extraction and use, and included; the Water Services Act (1997) and National Water Act (1998) aimed at regulating water supply management and conservation, The National Water Act (1998) and Environmental Conservation Act, making it compulsory for industries obtaining permits from governmental authorities for water supplies (Mokebe, 2008). Below is an outline of South African regulations governing activities of different industrial sectors. Establishing such legislative framework aiming at protecting the health and well-being of the South African population and environment for present and future generations, enhancing pollution prevention, lower ecological degradation, and the sustainable development use of resources.

Table 14 South African legislative framework governing the operation of processes

Act	Legislative framework
Environmental Conservation Act, 1989	• Providing effective environmental protection with controlled utilization of resources • Section 22: Prohibition on undertaking identified activities; • No person to undertake an activity unless with written authorization after considering an EIA report. • Unauthorized commencement is an offence
National Environmental Management Act, 1998	• Control on activities that can have ramifications on the environment • To encourage cooperate governance • Transforming and shift of the constitutional environmental right to a reality • Section 24: ensuring adequate consideration of activities effecting the environment
National Water Act, 1998	• Regulations on managing the water supply • Conserving water • Effluent minimization
National Environmental Management: **Air Quality Act** **(Act No. 39 of 2004)**	• Protect, restore and enhance air quality in South Africa • Encourage pollution prevention and cleaner production • Promoting reduction of pollutants to harmless levels • Encourage pollution reduction at source
National Energy Bill, **September 2004.**	• Providing provisions towards sustainably developing and use of energy resources • Provide provisions for renewable resources

Stringent regulations placed by the South African government, illustrates the need for industries utilising water in maximising amounts of recycled process water that is reused in the production system, allowing for decreases in water demands and effluents, with higher amounts of water conserved.

2.10 South African Pulp and Paper Industries

South Africa is a relatively young industrial nation compared to other nations globally. Industrial development began towards the end of the nineteenth century and majority of growth at the time focussed on the mining industry (Donkor, 2019). Paper was initially imported as demands were low. Only 5 paper mills operated in South Africa prior to the 1950’s and products included; wrapping papers, ticket boards, toilet paper, writing papers and boards (Macdonald, 2004).

The PPI of South Africa saw rapid growth between 1950 to 1984 with the development of 13 new mills (Greenberg et al., 2013; Macdonald, 2004). New mills caused existing mills focussing on increasing capacities. Post 1985, most developments in the PPI were of small scale relating to sanitary products (Greenberg et al., 2013; Macdonald, 2004).

2.10.1 Raw Material for Pulp Production

Commercial forestry in South Africa utilise exotic tree species as a favourable climate has shown faster growth rates compared to indigenous tree species, which are unsuitable for manufacturing of paper or grow at very slow rates (Pogue, 2009).

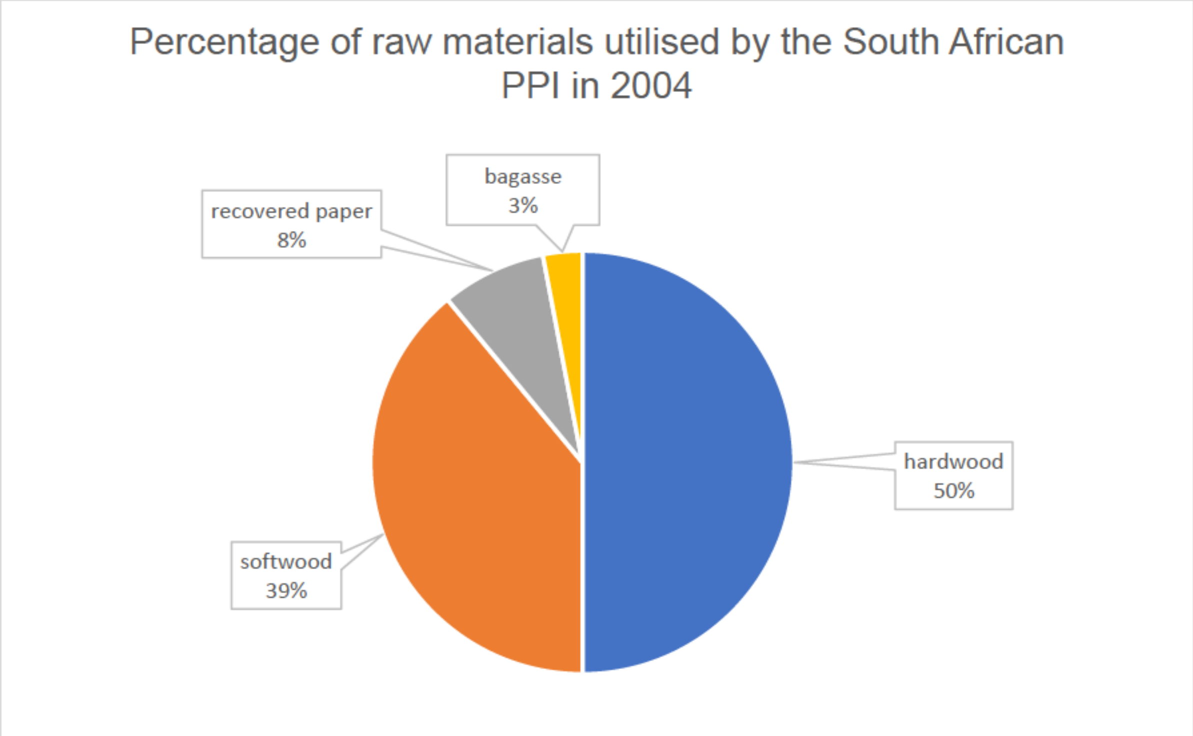

Figure 14 Pie graph showing percentages of raw materials used in South African PPI's. Adapted from (Macdonald, 2004)

Softwoods are grown in KwaZulu-Natal, Mpumalanga, Limpopo, Eastern and Western Cape. Softwoods are utilised in paper production and construction (Pogue, 2009). Principal softwood species are *Pinus patula, Pinus taeda* and *Pinus elliotii* (Pogue, 2009). Hardwoods are grown in KwaZulu-Natal, Eastern Cape and Mpumalanga, and utilised in construction, mining and paper manufacturing (Pogue, 2009). Principal hardwood species are *Eucalyptus grandis, Eucalyptus nitens* and *Eucalyptus saligna* (Pogue, 2009). Production in the South African PPI totalled between 2.2 to 2.7 million tonnes annually between 2001 to 2011 (Donkor, 2019).

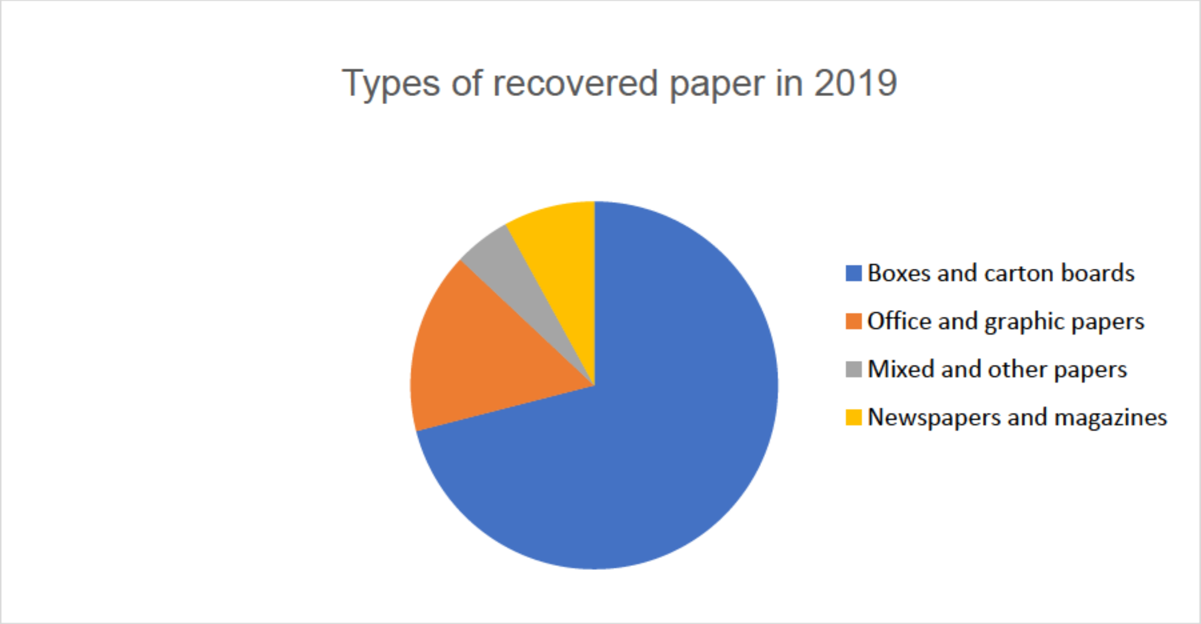

Figure 15 Pie graph showing percentages of recovered paper types in South Africa in 2019 (Paper Manufacturers Association of South Africa, 2019)

Another source of fibre is recycled fibres in manufacturing of paper (Mokebe, 2008). Rapid growth in the recycled fibre industry led to establishing of different mechanisms to collect and recycle fibres (Donkor, 2019). South Africa achieved a paper recovery rate of 73% in 2020, increasing from 68.5% in 2019. A recovery rate of 73%, translates to 1.1 million tonnes of paper and packaging products successfully recycled and reused avoiding landfilling. Over the past 15 years, South Africa diverted 19 million tonnes of paper from landfills. South African PPI production capacities grew significantly over the last 4 decades and considered the 15th and 24th largest producer of pulp and paper in relation to paper production capacities (Donkor, 2019)

2.10.2 South African Forestry Value Chain

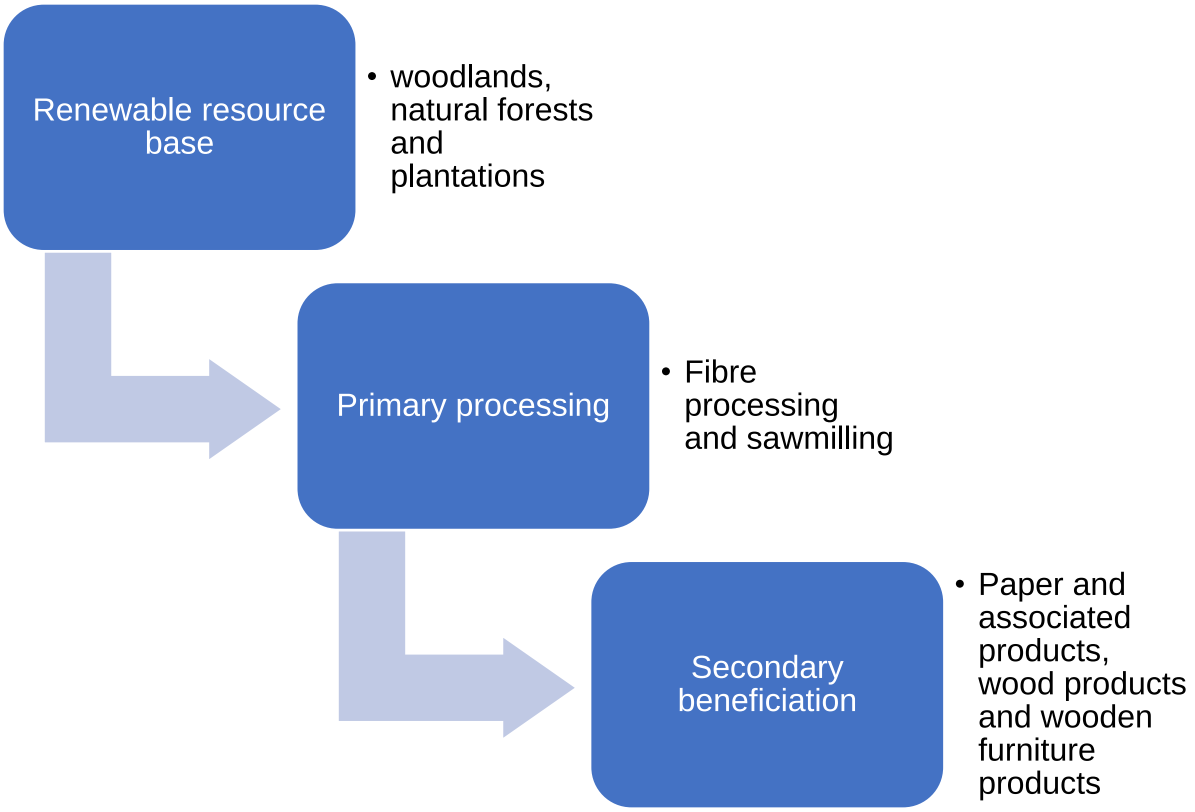

Figure 16 15 Schematic overview of the South African forestry value chain (FVC). Adapted from (Ackerman et al., 2017; Pogue, 2009)

South African PPI's is a component within the South African forestry value chain (FVC), and broadly classified into three production stages (Ackerman et al., 2017; Department of Agriculture, 2016). The FVC is founded on renewable South African resources base which includes woodlands, natural forests and plantations. Apart from the production of timber resources, the resource base also includes livestock, agricultural crop and non-timber forestry products (Pogue, 2009).

Primary processing of raw materials is the second stage of the FVC, where processing the resource to adding value to it. Numerous sectors constitute primary processing including processing wood fibres, sawmilling and charcoal production (Ackerman et al., 2017). Following is the secondary beneficiation stage, which allows further additions to the values of products. Constituents of secondary beneficiation include, the manufacture of pulp and paper products, furniture, and other wood-based products (Ackerman et al., 2017). A common factor of the FVC is the utilisation of wood resources, with each stage and components differing in processes undergone and finished product

2.10.2.1 Renewable Resource Base

The South African forestry resources area, majority of which is occupied by woodlands accounts for 93% of the total forest area (Department of Agriculture, 2016; Greenberg et al., 2013). Woodlands are of economic importance because of associated activities like agriculture and tourism adding revenue to the economy. Woodlands are important to informal sectors, where it is a source of energy from wood. The total forest area of South Africa consists of 2% natural forests, although much smaller than woodlands, supports complex ecosystems enhancing ecological diversity (Greenberg et al., 2013). Natural forests are sources of wood products and non-timber products. The remaining 5% of the total forest area comprises of plantations providing majority timber products to the FVC (Greenberg et al., 2013). Plantations can be of three types i.e. emerging farmers, private farmers and corporates.

Primary tree species in plantations are eucalyptus, pine and wattle (Pogue, 2009), with 50% of the total forest area occupied by pine producing softwoods, 40% by eucalyptus species in producing hardwoods, and 9% by wattle species producing hardwoods (Ackerman et al., 2017; Greenberg et al., 2013). Growth cycles differ with consequences to different management approaches, and environmental factors influencing growth cycles (Ackerman et al., 2017). Implications of different growth cycles is tree reaching maturity and processed for fibres in half the time than a tree processed for saw logs (Ackerman et al., 2017). Challenges facing the renewable resources base are consequences of the established production system. Many challenges can be alleviated through utilising alternative production techniques which requires a paradigm shift in breaking away from large plantations (Pogue, 2009). Alternative production techniques of wood resources include the use of natural regeneration opposing plantations of specific species, resulting in increased amounts of viable land available to community-based growers as a source income, in a country ravaged with poverty and unemployment (Ackerman et al., 2017).

2.10.2.2 Primary Processing

Primary processing of timber is divided into the following i.e. fibre processing and sawmilling (Ackerman et al., 2017). Fibre processing comprises of pulp milling, wood chipping and production of fibre board. Pulp milling, an important component in processing fibres which is integrated with downstream processes like, paper manufacturing, with wood chippings a component of paper production. Chipping plants were established in the 70's and focussed on exports, only integrated in international markets post-apartheid causing a huge demand for wood chips (Pogue, 2009). Chip milling became a source of pulping timber and exceeded domestic processing capacities. Primary markets for South African wood chips is Japan, which imported 98% of all wood chips produced between 2003 and 2006 (Department of Agriculture, 2016)

Sawmills are of three types i.e. formal sawmills, low-cost mills and micro mills (Ackerman et al., 2017; Pogue, 2009). Two thirds of local sawn timber are processed in formal sawmills. Between 1980's to early 2000's, had a rapid decline in the amount operational mills from 188 to 45, the mills remaining having increased production capacities (Ackerman et al., 2017). Low cost mills process 27% of total sewn timber, which operate continuously and generally kiln dry timber. Micro-mills are commonly mobile processing units that generally process timber utilised by local communities (Department of Agriculture, 2016). Limitations of the sawmilling industry is availability of sawlogs, which are of ever-increasing shortages (Ackerman et al., 2017). Shortages experienced will only increase with time unless alternative production techniques are implemented in mitigation.

2.10.2.3 Secondary Beneficiation

Secondary beneficiation is divided into three categories i.e. paper, wood and wooden furniture products (Ackerman et al., 2017). Increased building activities since the 2000's resulted in increased demands for wooden products (Pogue, 2009). Increased imports of wooden products and competition caused local manufacturers focussing towards specialised niche products for domestic use and export (Pogue, 2009). This sector is dependent on sawn timber from primary processing with inputs from plastic, metal and textile industries (Ackerman et al., 2017; Pogue, 2009). Majority of South African PPI's are located in KwaZulu-Natal, Mpumalanga, Limpopo and Gauteng because of close proximity to wood resources, allowing logistical advantages (Ackerman et al., 2017; Department of Agriculture, 2016). PPI's located close to cities and population centres process higher amounts of recycled fibres.

Globalisation allowed internationalisation of different operations and products. South African PPI production capacities is dominated by two companies, although other companies operate with significant capacities (Ackerman et al., 2017). SAPPI, a South African company, and Mondi based in the United Kingdom, operate globally and regarded as key players in the global PPI. Resultant of globalisation, the South African FVC is regarded as internationally competitive with high international standards (Macdonald, 2004). Increased revenues from PPI's allowed for increased growth of the South African GDP. Shortages in technological capabilities, skills and high costs of establishing new productive capacities are challenges facing the South African PPI's, with ramifications being the formation of a barrier within local PPI's ability in meeting the ever-growing demands

2.11 Linear and Circular Economies

Circular economies in which the "loops are closed" and its products stimulated by life cycle analysis in efforts to achieve a greater degree of sustainability in meeting economic and environmental goals of waste reduction and energy conservation (Dlamini et al., 2018). A circular economy are systems of interactions between economies and environment where relationships are created by utilising resources and waste residuals, in efforts of mitigating existing environmental issues and resource scarcity (Dlamini et al., 2018; Godfrey & Oelofse, 2017).

South Africa's industrialisation is relatively young and characterised by linear consumption (Rasmeni et al., 2019). Current economies operate in a way resulting in resource scarcity. In a linear design product are created, utilised and disposed of with minimal concern of environmental ramifications with waste disposal (Godfrey & Oelofse, 2017; Rasmeni et al., 2019). Linear economies are driven by fossil fuels and heavily dependent on economic growth.

A suitable alternative in achieving higher degrees of sustainability is a circular economy, where industrial systems benefit society and nature, where reusing of products and materials in maximising their value (Dlamini et al., 2018; Kubanza & Simatele, 2019). A circular economy is deliberately regenerative in design allowing the end of life and disposal of products being replaced by restoration, reducing the use of toxic chemicals obstructing the reuse of products and eliminate wastes through careful design of its systems and products (Godfrey & Oelofse, 2017).

2.12 Waste Management in South Africa

Generally, waste management approaches are poorly funded and uncoordinated (Rasmeni et al., 2019). Key exacerbating factors included inadequate services provided for waste collection for large percentages of the population, illegal dumping, unauthorised waste management services, limited availability of landfill airspace, insufficient activities towards waste reduction and recycling efforts and lack of waste legislation combined with enforcement of legislative frameworks (Kubanza & Simatele, 2019; Mokebe, 2008; Rasmeni et al., 2019). Municipalities operating waste management services and facilities face increased pressure in coping with the collection and diversion of waste from landfills. Approximately 76% of South African waste is landfilled with negative effects on environmental and human health (Rasmeni et al., 2019).

By adopting a circular economic model plays an important role especially due to an increased population size producing waste streams of higher volumes and greater complexity, resultant of industrial developments and urbanisation (Godfrey & Oelofse, 2017). Municipalities have greater responsibilities in achieving effective and efficient waste management.

The department of environmental affairs in efforts to transition to a circular economy introduced legislative measures to industries managing their products once deemed waste, setting goals for reduction, recycling and reuse of waste (Dlamini et al., 2018). These measures affecting industries are referred to as 'industry waste management plan.' The strategy and effectiveness are based on the following interventions i.e. Extended producer responsibility (EPR), Priority waste and Waste act of 2008 (Dlamini et al., 2018).

Table 15 Interventions of extended producer responsibility, priority waste and waste act of 2008

Extended producer responsibility (EPR)	• Identifying products with potential challenges to waste management or toxic constituents, and • Holding the industry responsible for such products beyond its sale
Priority Waste	• Identify categories of waste requiring special measures not to negatively affect environmental and human health
Waste Act 2008 **(59 of 2008)**	• Provide lists of specified wastes activities which warrant licensing and setting conditions • And a list of waste activities not requiring licenses as long as they follow procedures put in place

Insufficient funding hindered effective waste management efforts and led to the national waste management strategy raising the Polluter Pays Principle, indicating waste generators from household to industrial levels are liable for costs incurred by the different wastes including collection, treatment and disposal as well as external costs such as damage to health and environment which arise from its waste (Donkor, 2019; Rasmeni et al., 2019).

There is a need for an integrated waste management approach as implications include and allows for coordination of different functions found within the waste hierarchy and most importantly landfill diversion resulting through waste minimisation and recycling efforts. By recognising significance of adequate waste management in progressing up the waste hierarchy focussing on avoidance and minimisation will consequently reduce the impacts of waste downstream. Integrated waste management requires preplanning as the composition, quantities and characteristics of waste can be predicted which in turn will ensure effective and systematic processes in waste management.

Table 16 Aspects of the waste hierarchy

Waste Prevention	• Prevent or avoid the production of certain wastes. • Initiatives addresses the industrial sector, promoting the use of cleaner technology as well as schools and private households in broader awareness campaigns. • The highest priority in waste management principles, South Africans should aim at reducing the quantity of waste generated
Waste Minimisation	• Economically reducing volumes of waste generated during production, through different processes or implementing clean technologies • Minimize the generation of wastes • Waste minimization is implementation of reducing waste at its source
Resource Recovery	• Utilizing wastes from a process as the raw materials in another • Energy recovery through incineration or biodegradation. • Recovery utilizes resources found in waste, allowing in savings of raw materials
Waste Treatment	• Contributes in reducing the volumes or hazardous nature of waste • Alleviates environmental impacts and human health risks
Waste Disposal	• The most utilized option • Landfilling results in the underutilization of resources found in wastes and is the lowest on the waste hierarchy • The most common waste management method prevalent in South Africa

Adapted from (Kubanza, 2019)

2.13 Hazardous Status of PPMS

Waste management of hazardous wastes is a vital element in protecting South Africa's environment. Inappropriate and inadequate handling of hazardous wastes could potentially lead to pollution of the ground, groundwater, and watercourses. In order to 73 manage the wastes responsibly in a legal manner, it must be classified in establishing characteristics and associated hazards in determining an acceptable location to dispose of such wastes, and also prevent any negative impacts arising.

South African legislation prescribed a revised system for the classification of hazardous wastes in relation to the Globally Harmonized System of Classification and Labelling of Chemicals known as the SANS 10234-GHS, with a separate assessment procedure for waste disposal to landfill, which was implemented in August 2016 and replaced the Minimum Requirements of 1998 that used SANS 10228.

A Hazard Class is no longer in effect with the SANS 10234, as it provides a Hazard Rating which determines the class of landfill required by assessing the specific requirements for a containment barrier. There are 4 classes of landfills where hazardous wastes can be disposed, and classified into between 0 and 5 of Waste Risk levels, where a level 0 means waste cannot be disposed and requires treatment.

A waste stream comprising of organic or inorganic elements or compounds, by which the physical, chemical or toxicological properties of the waste stream, may potentially have detrimental impacts on human health or the environment is known as hazardous wastes. PPMS is a highly organic waste with inorganics present, and with inadequate waste management could lead to negative impacts to human health and environment. PPMS is regarded as hazardous waste due to the following hazards present in it.

PPMS is regarded a hazardous waste as it contains/may contain the following constituent's; gaseous wastes, inorganic wastes, organic halogenated and/or sulphur containing wastes, other organic wastes without halogen and sulphur, and slag with potential negative impacts

Level 1	Level 2		Level 3	
	Major Waste Type		Specific Waste Type	
	Number	Name	Number	Name
Hazardous Waste	HW 01	Gasseous Waste	1	Gases (excluding Greenhouse gases)
			2	Obsolete ozone depleting gases
	HW 05	Inorganic Waste	1	Liquid & sludge inorganic waste
			2	Solid inorganic waste
	HW 09	Organic halogenated and/or sulphur containing was	1	Liquid & sludge containing halogens and/or sulphur
			2	Solids containing halogens and/or sulphur
	HW 11	Other organic waste without halogen or sulphur	1	Liquid & sludge organic waste
			2	Solid organic waste
	HW 16	Slag	2	Non-ferrous metal slag
			3	Other

3. Methodology

3.1 Introduction

Many natural and limited resources are utilised directly and indirectly during the running of many PPI worldwide and within South Africa. These PPI's also generate large amounts of waste products that require further processing in efforts of achieving mineral and energy recovery. Majority of these waste products are then landfilled as part of their waste management practice which is highly unsustainable.

In efforts to increase sustainability within the PPI, it is required to transition from a linear to circular economic model through the principles of reduce, reuse and recycle. This research aimed to maximise landfill diversion of waste generated in the PPI through exploring alternate-end-of-life-pathways.

3.2 Methodological Approach

Desktop research is not about collecting data, but the role of the researcher is to review previous research findings to gain a broad understanding of the field being researched (Greehoot, Follmer & Dawsett, 2012). Desktop research is the analysis of data or information that was either gathered by someone else or for some other purpose than the one currently being considered, or often a combination of the two (Hoffmann, 2017). The data that has been gathered was analysed in the same way as if it were obtained from other sources, the only difference is that data has been obtained from secondary sources such as books and articles rather than primary sources, such as human beings (Struwig & Stead, 2013).

By mixing both quantitative and qualitative research and data, the researcher gains in breadth and depth of understanding and support, while offsetting the weaknesses inherent to using each approach by itself (Maree, 2016). Mixed methods research is a method for conducting research involving collecting, analysing, and integrating quantitative and qualitative research in a single study or a longitudinal programme of inquiry (Creswell, 2016). A desktop study will be used as a method of data collection for this research, and a mixed methods approach will be implemented. This research was divided into four phases towards meeting the aims and objectives set out.

3.3 Limitations of The Study

The following limitations have been identified during this research, although these will not fully explain patterns and trends which may occur in replicating this study or those not identified during this research. PPI wastes, may have characteristics and compositions that are similar due to the same materials processed and manufacturing processes employed, making PPI wastes site specific that vary in composition. Characterisation of PPI wastes are vital to determine applicable waste management options. This research was conducted in the wake of the COVID-19 pandemic, resulting in changes in the purchasing patterns of consumers. Rapid digitisation globally may have reduced demands on paper products, but increased demands on sanitary products like toilet paper. These factors could have a significant impact on amounts and types of waste generated in PPI's.

PHASE 2: ALTERNATE PATHWAYS ENABLING CIRCULARITY WITHIN THE PULP AND PAPER INDUSTRY

4.1 Utilising PPMS as a Soil Amendment

PPMS is an active organic material allowing it to pose potential benefits in waste management practices where it is regarded as a source of nutrients for soil and plants especially in degraded lands extending potential uses to the agricultural sector (Larney & Angers, 2011). The potential negative effects of active organic materials application to land can have adverse effects resulting in reduced soil fertility and crop yields, and loss of topsoil with nutrients leaching out the soils profile causing soil loss, consequently becoming vulnerable to natural elements and prone to erosion (Canadian Ministry of Agriculture Food and Rural Affairs, 2021). A crucial requirement in soil protection is ensuring soil fertility is not negatively impacted due to contamination by heavy metals

4.2 Methodology

A desktop study used as the method of data collection for this research. A desktop study is the process of “gathering and analysing information already available in print or published on the internet” (Stuurwig, 2013). This is a desktop study using a mixed methods approach.

4.3.1 Research Aims Include:

1. Determine whether PPMS can be applied safely to land without adverse effects on the;
   A. *soils pH,*
   B. *salinity,*
   C. *organic matter content,*
   D. *cation exchange capacity and exchange acidity,*
   E. *heavy metals concentration and*
   F. *nitrogen immobilisation and mineralisation.*

4.3.2 Objectives of This Study Include:

1. Maximising landfill diversion of PPMS
2. Suitability and viability in the direct application to land
3. Effects on the fertility of soils
4. Optimizing PPMS
5. Outcome of toxic and harmful elements present when applied to soils

This research objectively analysed previous studies completed on the land application of PPMS. These studies varied from determining the immediate effect PPMS had on soil properties to the effects PPMS had on such properties after 1 year, 2 years and 3 years, in efforts to determine the long-term effects of PPMS on soils.

4.4 Results

4.4.1 The Effect of PPMS on Soil Properties

The tables below contain data from three farms i.e. Farm A, Farm B and Farm C, in which sugar cane was cultivated. PPMS was applied to the soils in these farms to determine the changes and effects it had on the soil's quality.

Table 17 Soil property changes for samples obtained from farm A, farm B and farm C cultivating Saccharum officinarum (sugar cane)

	Sample	Years since application	Exchange acidity (cmol/L)	Cation exchange capacity (cmol/L)	Acid saturation (%)	pH
Farm A	Control	-	0.05	2.67	1.87	4.81
	2010	1	0.82	3.01	27.24	3.89
Farm B	2010	1	0.06	5.16	1.16	6.4
	2009	2	0.03	6.21	0.48	6.57
Farm C	Control	-	0.02	3.86	0.52	5.94
	2010	1	0.09	11.82	0.76	7.09
	2008	3	0.08	11.6	0.69	5.24

Adapted from (Singh, 2014)

Table 18 Results and analysis of soils nutrients, organic carbon and carbon:nitrogen ratios (C:N) from farms A, B, and C cultivating Saccharum officinarum (sugar cane)

	Sample	Years_since application	Soil_ organic carbon (%)	**C/N (%)**
Farm A	Control	-	1	20
	2010	1	1.5	18.75
Farm B	2010	1	0.5	10
	2009	2	0.7	14
Farm C	Control	-	0.5	10
	2010	1	2.4	48
	2008	3	4.3	14.33

Adapted from (Singh, 2014)

4.4.1.1 Cation Exchange Capacity

The cation exchange capacity (CEC) is an indication of soils capacity in holding cations, a high CEC is desirable (Abu Bakar et al., 2015). Untreated soils of farm A and C have a low CEC (2.67 and 3.86 (cmol/L)), an indication of decreased soil fertility and a low resistance to changes in soil chemistry resultant of land use (Abu Bakar et al., 2015).

Conversely, soils treated with PPMS had increased CEC capacities with farm C increasing three times that of untreated soil (11.82 (cmol/L)) (Singh, 2014). An increased CEC allows for greater buffering capabilities against adverse effects relating to changes in the pH, availability of nutrients, levels of calcium and structural changes (Durigan et al., 2017). Many investigations have shown CEC increasing following application of PPMS to soil (Gavrilescu et al., 2012; Reddy & Pillay, 2005; Singh, 2014).

4.4.1.2 pH

Addition of PPMS to soils increased organic matter and pH (Singh, 2014). Increased pH resultant the alkaline nature of PPMS (Singh, 2014). PH, an important chemical characteristic in plants growth affecting nutrient availability, nutrient toxicity and microbial activity (Lal, 2015). Many studies have shown the calcium carbonate content in PPMS, when added to land increased the soils pH with significant positive responses and impacts on a diverse range of crops found on acidic soils (Abdullah et al., 2015; Lal, 2015; Singh, 2014).

PH increased following additions of PPMS (Singh, 2014). An increased pH was not sustained and decreased over time, shown in farm C (pH 7.09 at year 1 to pH 5.24 at year 3). This is due to decomposition of PPMS, until its completely decomposed with pH levels becoming similar to untreated soils (Singh, 2014).

4.4.1.3 Nutrient Availability

Soils pH directly affects the nutrient availability by changing the form of the nutrient found in the soil (Lal, 2015). Generally, nutrients found in soils become less available at pH less than 4.5 and 5 respectively (Lal, 2015; Singh, 2014). Farm A (treated soil) had a pH of 3.89 that is highly acidic. Nutrients from soil analysis at farm A were lower than farm B and C (Singh, 2014). Low pH levels facilitate some nutrients to bind with soil and other nutrients like phosphorous, and undergo chemical structural changes, becoming unavailable to plants (Simpson, 2010).

4.4.1.4 Soil Organic Carbon (SOC)

SOC has effects on the chemical, physical and biological properties of nutrient availability and organic matter in soils (Abdullah et al., 2015). An increased SOC content was observed with addition of PPMS in all samples (Singh, 2014), showing positive accumulations of SOC with additions of PPMS. Studies have shown applications of PPMS increased the SOC and soil organic matter (Abdullah et al., 2015; Singh, 2014)

Increased SOC causes; improved water holding capacities, whilst reducing water loss and erosion, increases supply of micro- and macronutrients and organic matter content, creating a better root environment for the plant (Abdullah et al., 2015; Lal, 2015; Singh, 2014).

4.4.1.5 C:N Ratio

Land application of PPMS with a high C:N ratio results in net immobilisation of N, that is an indication that PPMS undergoing microbial decomposition initially would compete with plants in securing the available N present prior to releasing a portion of its own N content due to a limited N contents (Jackson & Line, 1997). C:N greater than 30 results in immobilisation and less than 20:1 results in mineralisation (Gavrilescu et al., 2012). PPMS increased the C:N ratio when added to the soils. Farm C, during 2010 had C:N ratio 10:1 and increased after one application of PPMS to C:N ratio of 48:1 resultant of N immobilisation (Singh, 2014). Following immobilisation is mineralisation where the organisms decompose releasing nitrogen (Singh, 2014).

Fertilisers are added to soils as a way of mitigating effects of immobilisation and nitrogen losses of nitrogen (Singh, 2014). The rate that immobilised N is released is a function of soil turnover and biomass that constitutes a greater fraction of immobilised N. An important factor is decomposition of plant organic residues and mineralisation of the substrate will not be uniform, resultant of gradients in biodegradability of organic materials varying in composition and characteristics (Johns, 2015)

4.4.1.6 Heavy Metals

Investigations have shown application of PPMS to agricultural lands did not lead to heavy metal bioaccumulation in plants and soils (Abdullah et al., 2015; Abu Bakar et al., 2015; Jackson & Line, 1997; Reddy & Pillay, 2005; Singh, 2014). Increased levels of copper and zinc on all farms following the application of PPMS (Singh, 2014) and could be due to using deinking PPMS containing dyes and pigments from recycling processes.

Elevated levels of copper due to deinking PPMS was investigated (Turgut & Kose, 2015) and found no sign of increased levels of copper in plant leaves, stems and roots, and concluded that copper was immobilised resultant of complexing with organic matter present or through ion-exchange

Table 19 The average heavy metal contents found in soils, sewage sludge and PPMS, as well as the minimum amount of wastes applications required towards reaching the limits for soil metal contents in the United Kingdom at a pH range of between (pH 6.0 – 7.0)

	Zn	Cu	Ni	Cd	Pb	Hg	Cr
PPMS – Cumulative metal concentrations (mg/kg)	93	103	10.7	<0.25	21.4	0.07	23.8
Sewage sludge – Average concentration of metals (mg/kg)	922	574	65	5	201	3.5	208
Soils - Normal total concentration (mg/kg)	80	18	24	0.5	37	0.09	54
Soil limits (mg/kg) in soils amended with sludge in the United Kingdom	200	135	75	3	300	1	400
Amount of application required to reach the limit if applications are done at 250kg N/ha							
PPMS	62	55	227	>508	589	592	698
Sewage sludge	51	80	307	198	511	99	650

Adapted from (Aitken et al., 1998)

The table above shows the minimum number of PPMS applications raising soils to the limits put in place for heavy metals by the United Kingdom (Aitken et al., 1998). During the long-term application of PPMS, the most limiting metal found was copper and would require 55 applications at 250kg N/ha to reach the limit

5.1 Potential in Composting PPMS

PPMS contains organic and inorganic materials, with potential nutritional value to soils (Singh, 2014). Application to soils may potentially rectify the organic and nutrient status of poor soils, improve fertility and reduce disposal costs (Abdullah et al., 2015). Composting is advantageous as it successfully diverts waste from landfills, reducing environmental impacts of wastes in landfills like reduced methane production. Through composting proves being a viable alternative to minimise and recycle wastes.

5.2 Methodology

Desktop research is the analysis of data or information that was either gathered by someone else or for some other purpose than the one currently being considered, or often a combination of the two (Hoffmann, 2017). Mixed methods research is a method for conducting research that involves collecting, analysing, and integrating quantitative and qualitative research in a single study or a longitudinal programme of inquiry (Creswell, 2016). This is a desktop research following a mixed methods approach

5.3 Research Aims:

1. Maximising landfill diversion of waste PPMS,
2. Determining the effects of composting PPMS has on;
    A. *micro and macronutrients*
    B. *heavy metals*
    C. *soluble slats*
    D. *C:N ratio*
    E. *oxygen*
    F. *moisture content*
    G. *temperature*

This research objectively looked at previous studies on composting of PPMS which were conducted on three scales i.e. lab experiments, 50 kg and 1 tonne.

5.4 Objectives Include:

1. Optimising PPMS
2. Assessing the potential of PPMS to composting
3. Determining if composting could safely reduce PPMS
4. Determining if the composted PPMS can be applied safely to land
5. Viability in composting PPMS as a waste management strategy in PPI's

5.5 Results

5.5.1 Process Monitoring Parameters

5.5.1.1 Temperature

Temperatures around the centre of the heap generated most heat resultant of microbial activity, and decreased with increasing distances from the centre (Jackson & Line, 1997). The main process indicator of composting is temperature, where the process is gauged by monitoring temperature changes (Jackson & Line, 1997). Temperatures are predicted to rapidly raise once the thermophilic range is reached.

Small scale composting of PPMS, temperature peaked at 4 weeks, longer than predicted (Singh, 2004). Resultant of the moisture content being high, disrupting the flow of oxygen and limiting activity of organisms. Rapid heat loss following the peak is not an indication of completed composting. If the process had completed following the peak, it would be due to moisture content being close to the upper limits of the available range, inhibiting oxygen flow resulting in limited or ceased microbial activity, ending the process early.

During large-scale composting, max temperature reached 38 degrees Celsius, below the predicted temperature range of 60-70 degrees Celsius (Singh, 2014). The low maximum temperature was resultant of disrupted microbial activity by unnecessary turning heaps in efforts to ensure adequate aeration and avoid anaerobic conditions.

The addition of nutrients in day 1 caused the mean windrow temperature (temperature at centre of heap) increasing from 15 to 52 degrees Celsius due to nutrients stimulating microbial activity (Jackson & Line, 1997).

5.5.1.2 pH

During the thermophilic stage, proteolytic bacteria and temperature directly affects acetic acid formation and ammonium content changing the pH, and expected dropping to anoxic conditions before stabilising (Singh, 2014). Prior to completion, pH is expected to decline and representative of the degradation of recalcitrant compounds such as cellulose, hemicellulose and lignin. An increase in pH thereafter indicates maturity of the final product (Jackson & Line, 1997). pH varies over time and an optimum pH range is (6.5 to 7.5).

This can be seen on small scale compostability by (Singh, 2014) initially pH dropped to anoxic conditions resultant of acetic acid formation by microbial activity. Maturity of the compost is indicated by the pH reaching neutral levels. Large scale composting showed similar results, initially dropping to anoxic conditions followed by stabilisation to neutral levels. The initial decline is resultant of organic acid formation by degrading easily degradable carbon sources. The pH thereafter stabilises through liberation of ammonia and the depletion of carbon sources.

It was determined that without adequately managing the pH, between 54-62% of the nitrogen pool could be lost resulting from ammonia volatisation (Jackson & Line, 1997). Absence of ammonia volatisation was evident and confirmed with a C:N ratio 23:1 and pH 5.4 at 21 weeks (Jackson & Line, 1997).

5.5.1.3 Moisture Content

Moisture content at high levels occupy most porous spaces, limiting oxygen circulation, and mitigated with additions of bulking agents (Lal, 2015). At low levels, microbial activity limits as they require wet environments for survival. Below 10%, microbial activity ceases.

Aeration was a limiting factor on the small scale compostability due to a high moisture content. A vital parameter, as porous spaces are required for air circulation. A high moisture content hinders the circulation of air (Singh, 2014).

Large scale composting showed deviations in moisture content during the first 6 weeks, as PPMS is clumpy and retains water in pockets, deviations decreased after 7 weeks resulting in moisture content becoming uniform (Singh, 2014). A desirable moisture content is between 40 and 60% (Jackson & Line, 1997)

5.5.1.4 Heavy Metals

Decreasing trends of heavy metals is resultant of oxidation and formation of organo-mineral complexes during the thermophilic stage, reducing soluble contents of metals (Jackson & Line, 1997; Singh, 2014). Humic substances are found to bind with metals exchangeable and carbonate fractions (Lal, 2015).

All heavy metals in small scale and large-scale composting are shown to be within an acceptable limit (Environmental limits on compost quality) (Singh, 2014). Trends in both small- and large-scale experiments showed decreasing levels of copper and zinc (Singh, 2014) Another cause of disparity between PPMS and compost analysis is because of the bulk mass reducing during composting resultant of a concentrating effect. Reducing the volume increases the bulk density of compost.

5.5.1.5 Soluble Salts

Determining the soluble salt content provides an indication of deficiencies and excess regarding nutrient status of soil. The soluble salt contents of a growth medium receive contributions from all ionic compounds present (Johns, 2015). Nutrients do not damage plants, but effects water by reducing its potential, resulting in less water being available (Johns, 2015). Higher amounts of salts cause more energy being required to take up water (Singh, 2014).

Soluble salts normal range is between (0.35 to 0.64 dSm-1) (Jackson & Line, 1997), if below the normal range indicates the need for fertilization, and if above the range for extended periods result in root injury, leaf chlorosis, marginal burn and physiological drought (Jackson & Line, 1997). (Jackson & Line, 1997) obtained an electrical conductivity of 2.78dSm-1, and due to it falling significantly higher than the normal range, it would require reduction prior to soil application. Reductions can be achieved by leaching the composts with water in reducing the salt concentration.

Mineral nutrients are utilised as sources of nitrogen, phosphorous and potassium combined with volume reduction causes increases in the bulk density and ash content (Jackson & Line, 1997). Increased bulk density results in increased elemental concentrations, consequently increasing electrical conductivity

5.5.1.6 C:N Ratio

Carbon, an energy source, nitrogen necessary for plant growth and function, and microorganisms for protein and cellular synthesis, therefore achieving an optimal C:N ratio is a critical parameter in composting (Lal, 2015). By carefully reviewing literature available on this topic, an initial C:N ratio 30:1 is recommended and an optimal C:N ratio is between 20:1 & 25:1 (Reddy & Pillay, 2005), depends on bioavailability of carbon and nitrogen.

PPMS undergone small scale composting had an initial C:N (54.14:1) (Singh, 2014). Such a high ratio will cause composting process not to heat up due to insufficient nitrogen for organism's growth. In mitigating this nitrogen deficiency, urea pellets were added to achieve C:N 30:1 (Singh, 2014).

Large scale composting by (Singh, 2014) had shown C:N ratios drop to 13:1, an indication of increased carbon removal through decomposition.

Studies done on PPMS composting by (Jackson & Line, 1997) showed the C:N ratio decrease from 218:1 to 23:1 after 147 days with the supplementation of nutrient, indicating that the composted material will not immobilise nitrogen if applied to soils

5.6 Discussion: The Potential in Composting PPMS and Thereafter Utilising the Material as A Soil Amendment Towards Mitigating the Effects of Climate Change

Severe effects and consequent impacts of climate change can be seen in South Africa. These devastating impacts of weather-related hazards cause parts of the country increasingly experience drought regimes whereas other parts contrastingly experience severe storms with changes in rainfall patterns. These effects, if not mitigated through urgent adaptation measures has the potential in causing environmental, social and economic losses in cities and towns in South Africa, affecting millions. People will now become vulnerable and exposed to ramifications of climate change.

Increased frequency of such events allows effects of climate to grow with time. This is evident in South Africa, where the events recorded between 1996 to 2016 increased by 57% compared to the period of 1976 to 1996. Currently, in the 8th month of 2021 and all 9 provinces have experienced flooding events.

Compounding the effects of climate change is the ENSO (El Nino Southern Oscillation), a recurring weather pattern involving changes in ocean temperature in the Indian and Pacific Ocean with effects felt throughout South Africa. Within ENSO, there are three distinct stages i.e. El Nino (drought phase), neutral phase and La Nina (wet phase). ENSO is characterised in alternating of different phases every 3 to 7 years.

El Nino phase is characterised by below average climatic events being observed, such as reduced rainfall resultant of decreased ocean surface temperatures causing less water becoming available for cloud formation. The major drought facing South Africa from early 2016 up until late 2020's is attributed as an effect of the EL Nino phase of ENSO. Neutral phase can be described with normal climatic conditions. La Nina, contrastingly to EL Nino results through increased ocean surface temperatures allowing larger amounts of water becoming available for cloud formation. Effects of La Nina are characterised by an increased frequency in rainfall and storm events with subsequent higher rainfall intensities.

Climate change coupled with ENSO results in detrimental and in many cases catastrophic effects in the Southern African region. A simple example on such an effect having one of the largest contributing industries to the South African GDP, being agriculture. EL Nino phase resulted in the largest recorded drought crippling the agricultural sector with thousands of animals dying due to malnutrition and minimal 87 water available with millions of hectares of crops, flora and fauna destroyed due to this drought. La Nina phase followed between the end of 2020 into 2021 subsequently bringing excessive amounts of rain to the region, such rainfall described as destructive and not beneficial.

Effects were severe and ramifications still being felt and others yet to manifest themselves. A significant proportion of these effects could have been avoided by early mitigation and adaptation strategies. Employing such strategies are of a proactive approach prior to such effects, then following a reactive approach in the wake and aftermath of such events. This would allow factors with risks such as soils having an increased resilience in the face of uncertainty (Hao-an et al., 2020).

With much of the climatic conditions attributed to ENSO with literature supporting it, it does not rule out the possibility of such events or a proportion of these events caused by climate change as it causes the severity of climatic events to increase. Examples of such events are increased rates of melting of polar ice caps, changes in ocean currents, rising sea levels, changes in climate and vegetation, desertification and increased global temperatures.

Climate change is not a new climatic occurrence effecting earth, previously, many historic global cooling and warming events occurred. A huge differentiating factor between past and current events and subsequent conditions are due to anthropogenic activities accelerating changes at unprecedented rates combined with an increased magnitude of effects (Simpson, 2010). Effects of these changes at such rapid rates are at the forefront of research still being investigated.

In determining mitigation strategies in the aim of increasing our adaptability to uncertainty, it would be logical in focussing on renewable resources produced as a result of climatic conditions especially in the face of uncertain climatic conditions, examples of such is soil and freshwater.

Formation of soil found on the earth's surface takes millions of years (Durigan et al., 2017; Hao-an et al., 2020; Rasa et al., 2020). Numerous literatures agree that formation of approximately 1 cm of soil takes between 80 and 400 years, and between 3000 and 12000 years in building soil reserves adequate in formation of productive land (Simpson, 2010). Soil, a fragile foundation anchoring all life on earth either directly or indirectly (Hao-an et al., 2020). It is one of the most valuable resources available to humans comprising of countless species in creating a dynamic and complex ecosystem (Reddy & Pillay, 2005). Therefore, although soil technically is a renewable resource, the renewability is not on a human time scale implicating the need to regard and treat it as a vital non-renewable resource.

Soil erosion occurs when erosion is greater than the rate of soil formation (Canadian Ministry of Agriculture Food and Rural Affairs, 2021). Anthropogenic accelerated effects in climate change lead to in massive quantities of soil becoming lost through erosion. Erosion is a natural process, but anthropogenic activity caused rapid acceleration of this process. Globally, half of all topsoil was lost over the past 150 years (Canadian Ministry of Agriculture Food and Rural Affairs, 2021). Soil erosion is a major problem confronting South African land and water resources (Singh, 2014).

Prolonged erosion results in soil loss becoming irreversible (Hao-an et al., 2020). Major effects are reductions in ecological functions such as biomass production, and hydrological functions such as infiltration and water holding capacities (Hao-an et al., 2020). Other pertinent issues facing soil erosion in South Africa is loss in productivity of soils and increased mobilisation of soil sediments causing mobilisation resulting in clogging of waterways and siltation of dams putting massive strains on water resources especially as this country can be classified in having water scarcity (Makgae, 2011).

Soil erosion is naturally occurring affecting all landforms. Often referred to as wearing a way of topsoil due to natural forces acting on it such as water, wind and anthropogenic activity (Lawaal, 2009). Three distinct actions occur resulting in soil erosion. These are soil detachment, movement and deposition (Lawaal, 2009). Generally, via the means of natural forces, soil erosion is a slow process yet, contrastingly, it can occur swiftly and rapidly at alarming rates. Soil degradation accelerates erosion process with factors increasing rates of soil degradation are soils with low organic matter content, soil structure, poor drainage, soil pH and compaction (Hao-an et al., 2020; Johns, 2015; Lal, 2015; Rasa et al., 2020). There are many factors controlling the rate and magnitude of soil is erosion via natural forces of water and wind. The following factors are pertinent to keeping in line of this research. These factors are rainfall and runoff, soil erodability, vegetative cover and climatic conditions.

Rainfall is directly related to soil erosion, increased intensity and duration of a rainstorm results in higher erosion potential. Rain drops hit the soil surface, causing breaking and dispersing of soil aggregates (Lawaal, 2009). Lighter aggregates in the case of fine sands, silt, clay and organic material easily break down and removed through the splash caused by rain drops and runoff (Lawaal, 2009). Increased rainfall intensity and runoff allow for removal of larger particles of sand and gravel. Soil movement is greatest in short high intensity rainfall and thunderstorms, but erosion occurring over time with reduced intensity rainfalls may not be as noticeable compared with high intensity rainfalls, although effects off soil erosion compounded through time results in substantial losses of soil (Lawaal, 2009). When excess water is present and cannot infiltrate or absorb in to the soil, this results in surface runoff (Hao-an et al., 2020). Factors reducing amounts of waters ability to infiltrate soils are compaction, crusting and freezing of soils, causing increasing runoff.

Estimation of soils resistance to erosion is referred to as 'erodability' of soil, based on its physical characteristics (Kemner & Adams, 2021). Primary factors affecting erodability are soil texture, organic matter content, structure and permeability. Greater infiltration, organic matter and structure improve soils resistance to erosion (Kemner & Adams, 2021; Lal, 2015; Lawaal, 2009).

During wind erosion, small particles are lifted into the air and transported over large distances, medium particles are lifted for short distances but fall back to the surface, and upon impact damage vegetation, breaking down and dispersing soil aggregates, Large particles unable to lift are dragged along the surface (Lawaal, 2009). A major effect from wind erosion is abrasion caused by wind-blown particles breaking down surface aggregates increasing erodability of soils (Lawaal, 2009). 89

Vegetative cover directly relates to soil erosion. Vegetative cover that's minimal or absent have increased potential to erosion (Kemner & Adams, 2021; Lawaal, 2009). Vegetative cover allow for a degree of protection from rain drops and splashes, reduces speed of consequent runoff generated simultaneously allowing for greater infiltration (Lawaal, 2009). This is effective in controlling potential of wind erosion as vegetation cover acts as a wind break. Vegetation completely covering soils has the highest efficiencies controlling erosion through intercepting all rain drops. Whereas vegetation partially covering soil is effective, but at reduced efficiencies since they provide channels for infiltration of surface water and runoff (Lawaal, 2009).

Eroded soils cause exposing of the subsurface layer that has a poorer structure and reduced organic matter content than surface layers, allowing for an increased erodability potential compared to surface layer of soils (Durigan et al., 2017).

Soil structural properties are of the same importance as chemical and biological properties in defining soils fertility (Durigan et al., 2017). Primary soil particles combine and arrange themselves with other solid components in soils influencing their abilities in retaining and transmitting air, water, organic and inorganic substances, resulting in the formation of lumps known as aggregates.

Resistance of soil to degradation is known as aggregate stability (Turgut & Kose, 2015), which directly influences the physical behaviour of soils including infiltration, permeability and erosion at a macro scale. Organic matter present in soil is a major factor affecting aggregate stability, due to soil organic carbon acting as a binding agent, allows for aggregate formation where acts as a nucleus, and increasing the resistance offered by aggregates against dispersive and dissolution actions of water through formations of strong intra-aggregate bonds (Turgut & Kose, 2015).

Aggregates can be differentiated into two groupings i.e. micro- and macro-aggregates. Micro-aggregates are particles of silt and clay bound together, collections of microaggregates together with organic matter and other particles are known as macroaggregates (Turgut & Kose, 2015). Secretions from microbial activity, plant roots and mycorrhizae are major factors in the formation of macro-aggregates (Kemner & Adams, 2021).

Declining soil structure is form of land degradation (Makgae, 2011). Soil structure is majorly influenced by changes in biological activity and climate. Improving of soil structure through management where increasing amounts of carbon and decreasing the rate of carbon loss through soil management through decomposition and erosion (Lawaal, 2009). Management of soil structure and aggregates improve productiveness, porosity and decreases erosion potential (Rasa et al., 2020; Turgut & Kose, 2015).

Such management practices include tillage, addition of manures, composts, fertilisers and nutrients to the soil. Addition of fertilisers and nutrients have variable effects on aggregation, but when applied correctly, allow for increased soil productivity, soil organic carbon and microbial activity, resulting in an increased amount of aggregation (Turgut & Kose, 2015). Application of composts improves the structure whilst lowering density of soil. Composting materials have high potential in increasing aggregation 90 and aggregate stability (Turgut & Kose, 2015). Use of composting practices face limitations such as environmental conditions like drought and effects of composts generally are short lived.

South Africa, a country with primary GDP contributing industries involving the agricultural sector, but only 9.9% of its total land area is arable land. Soil erosion has potential in causing detrimental effects to the environment, social and economic wellbeing of the nation. In the face of climatic extremities been felt, with more effects yet to manifest themselves directly, as a result of climate change coupled with ENSO, existing situations of erosion could only be predicted with increased frequencies and magnification in future effects. Special attention, adaptation and proactive mitigation strategies need to be implemented in areas where soils face a higher risk and vulnerability to erosion.

5.7 Concluding Summary on the Use of PPMS as A Soil Amendment

From literature reviewed, the addition of PPMS to soil as an amendment does not negatively affect fertility of soil. Addition of PPMS as a soil amendment increases soil organic carbon directly improving water holding capacity, supply of macro and micronutrients, root environment and cation exchange capacity. Changes due to PPMS on pH affected nutrient availability but stabilised allowing for increased plant nutrient uptake and C:N ratio increased indicating beneficial use with more applications.

Composting PPMS show it becoming stable upon curing. Heavy metals present were reduced to acceptable levels during the thermophilic phase. Oxidation and organomineral complexes reduced the soluble contents of metals, therefore facilitating its transformation to an environmentally friendly product.

This has implications for waste management practices of pulp and paper industries. Potential of PPMS as a soil amendment or compost in improving factors allowing for increased soil fertility that in turn improves probability of aggregation overall resulting in a better structure. Such effects from either using PPMS as an amendment or compost will directly increase resistance of soils to degradation ultimately allowing for reduced erosion potential of soils.

Costs associated with purchasing of manures, composts and fertilisers can become exponentially high when determining amounts needed to remediate large tracks of lands requiring a proactive adaptability and mitigating approach prove unfeasible. Through utilisation of PPMS as an amendment or compost allow for substantial amounts of landfill diversion and the transformation of PPMS into a non-hazardous environmentally friendly product. Resource recovery is facilitated through such a practice. An important factor in such practices allow for carbon sequestering, substantially lowering the carbon footprint of PPI's. This is possible as PPMS will no 91 longer be incinerated and landfilled saving the environment from emissions of harmful gasses released from combustion and landfill gasses such as methane.

6.1 Pelletizing PPMS into an Energy Pellet

The ever-increasing focus to produce energy from wastes generated poses challenges in developing technologies and processes towards producing biofuels (Wibowo et al., 2020). PPI waste sludges exemplify a cheaper alternate energy source due to its high contents of organic material (Gore, 1986).

Waste management of PPI's are constantly seeking new sustainable alternatives to incineration and landfilling for the wastes generated. Utilising sludge to produce a solid fuel pellets as a method of energy recovery has shown promising benefits including it been a source of alternate energy and enabling landfill diversion of PPMS (Ahmad et al., 2021; Matus et al., 2018; Nosek & Holubcik, 2017).

The grade of a fuel pellet for energy demands depends on its chemical composition (Nosek & Holubcik, 2017). The primary chemical components in solid fuel pellets are carbon, hydrogen, nitrogen and oxygen. The quality of fuel pellets is determined by key parameters which include the ash content, heating value, amount of fines, mechanical durability and bulk density (Nosek & Holubcik, 2017).

The use of PPMS in an energy pellet for energy demands is not a straightforward process, due to limitations facing PPMS as a fuel, additives will be required in ensuring efficiency of transforming PPMS into a fuel pellet (Wibowo et al., 2020).

Different additives were investigated such as molasses, proteins, coal, cooking oils and fossil fuels (Ahmad et al., 2021; Matus et al., 2018). It has been found that generally with additions of cooking oils, bio-oils and fossil fuels, positive effects can be seen on key factors including ignition and combustion durations, increased heating values and reduced environmental impacts (Ahmad et al., 2021). The major limitations hindering the use of PPMS in a fuel pellet is due to the high ash contents, low heating value, and an increased ignition and lowered combustion duration (Ahmad et al., 2021).

6.2 Methodology

The data that has been gathered was analysed in the same way as if it were obtained from other sources, the only difference is that data has been obtained from secondary sources such as books and articles rather than primary sources (Struwig & Stead, 2013). This is a desktop research following a mixed methods approach.

6.3 Aims Include:

1. Determine suitable additives to the co-palletising of PPMS into an energy pellet
2. Produce an energy pellet which could be used as a source of energy

This research objectively looked at previous studies where PPMS was used in coproducing of an energy pellet. Proximate and ultimate analysis of PPMS had been determined to see how certain additives could affect the potential in the co-production of an energy pellet utilising PPMS.

The following combinations of PPMS and additives were critically analysed;

- PPMS co-pelletized with sawdust (mixed at 70:30 ; 60:40 ; 50:50)

- PPMS co-pelletized with ion-refined oil (IRO) (Mixed at PPMS: IRO 5%, 10%, 15%, 20%, 25%, 30%)

- PPMS co-pelletized with sawdust and ion refined oil (PPMS 50: sawdust 50: IRO 5%, 10%, 15%, 20%, 25%)

These optimum blend ratios from each of the studies mentioned above were chosen for comparison in the results, and done in order to investigate effects of a particular additive or in combinations, on PPMS in the production of an energy pellet

6.4 Objectives Include:

1. Optimising of PPMS whilst maximising landfill diversion
2. Transforming PPMS into a fuel pellet
3. Determining additives in co-pelletizing of PPMS into an energy pellet
4. Determining the effects palletisation of PPMS has on the following parameters:
    A. *bulk density*
    B. *particle density*
    C. *moisture content*
    D. *mechanical durability*
    E. *gross calorific value*
    F. *ash content*
    G. *contents of chemical elements*
5. Determining emissions from an energy pellet made from PPMS and associated potential environmental impacts.

6.5 Results

Table 20 Proximate analysis of a PPMS pellet

Moisture content	6.17 + - 0.29
Ash content	51.52 + -0.90
Volatile matter	41.62+ -0.10
Fixed carbon	0.70 + -0.06

Adapted from (Nosek & Holubcik, 2017)

Proximate analysis of PPMS showed a high ash content in the sample (51%), and assumed the remaining 48% being cellulosic fibres (Nosek & Holubcik, 2017). Ash content indicates proportions of non-combustibles in PPMS, directly effecting the calorific value. A low fixed carbon content and high ash content in PPMS limits its use a fuel, as such factors may potentially clog the burner or suffocate the flame during combustion (Nosek & Holubcik, 2017).

Proximate analysis also indicated a high content of volatile matter (41%) in the sample. This high content of volatiles matter is advantageous during ignition of the pellet.

6.5.1 PPMS as an Additive in Wood Pellets (50:50)

Fuel characteristics of a PPMS pellet were improved when PPMS was utilised as an additive in an energy pellet. A combination of PPMS and wood significantly increased the fixed carbon and volatiles content of the pellet. The increased volatiles content will be advantageous in achieving a quicker ignition of the pellet (Matus et al., 2018).

The combination of PPMS and wood also had a significant effect on reducing the ash content of the pellet. PPMS alone had a high ash content which could limit its use as a fuel (Matyus et al., 2018), but when used as an additive together with wood caused the ash content to drop significantly with decreasing portions of PPMS

Table 21 Results for produced pellets measured by TGA (Thermogravimetric analysis)

Pellet composition	Moisture %	Volatiles %	Ash %	Fixed carbon %
Wood pellet	8.21	74.99	0.49	16.31
50:50 (wood:PPMS)	5.40	67.20	22.23	5.17
60:40 (wood:PPMS)	5.22	65.13	26.83	2.82
70:30 (wood:PPMS)	4.69	63.69	30.89	0.73
PPMS pellet	12.04	43.42	44.33	0.21

Adapted from (Matus et al., 2018)

Primary components vital for combustion is carbon, hydrogen and oxygen (Matus et al., 2018; Nosek & Holubcik, 2017). From the table below, proportions of carbon and hydrogen significantly increase with decreasing proportions of PPMS. Higher amounts of nitrogen in the pellets are resultant of wastewater treatment processes where its added to precipitate sludge and control microbial activity (Matus et al., 2018)

Table 22 Contents in the produced pellets (wet basis) of carbon (C), hydrogen (H), nitrogen (N) and sulphur (S)

Pellet composition	Carbon %	Hydrogen %	Nitrogen %	Sulphur %
Wood pellet	48.780	6.310	0.017	0.066
50:50 (wood: PPMS)	36.021	4.702	0.044	0.046
60:40 (wood: PPMS)	34.996	4.533	0.016	0.047
70:30 (wood : PPMS)	32.899	4.188	0.034	0.040
PPMS pellet	24.752	2.587	0.189	0.045

Adapted from (Matus et al., 2018)

The table above indicates utilising PPMS as an additive in energy pellets enhanced its fuel characteristics. Fixed carbon content increased. Increased fixed carbon results in increases to combustion durations (Matus et al., 2018). Volatiles content has a strong relation to ignition and combustion characteristics and duration of the fuel, and increasing the volatiles content increases ignition and decreases combustion durations (Andreae, 2019).

6.5.2 PPMS Augmented with Sawdust and Pyrolysis Oil (50:50:20)

From the table below, the additions of ion-refined oil (pyrolysis oil or bio-oil) increased the oxygen and carbon contents. Volatiles content increased with increasing proportion of IRO, resulting in higher reactivity of the produced fuel (Ahmad et al., 2021).

The fixed carbon content is considered a key factor in the production of energy during combustion (Nosek & Holubcik, 2017). PPMS had a low content of fixed carbon, when mixed with IRO, fixed carbon content increased. Increasing the fixed carbon contents allows for an increased combustion duration (Ahmad et al., 2021).

PPMS ash content was 10 times greater than sawdust, limiting its use as a fuel. Addition of IRO reduced the ash content whilst increasing the volatiles and fixed carbon content, improving the quality of fuel (Ahmad et al., 2021).

Table 23 Properties of energy pellets made from PPMS and sawdust (50:50) and mixed with ion-refined oil

	Sawdust	PPMS	IRO-5	IRO-10	IRO-15	IRO-20
Moisture content%	2.51	6.63	6.26	6.68	6.81	6.74
Volatiles content%	73.84	40.70	49.85	62.06	66.30	67.62
Ash content%	4.48	52.30	29.05	15.70	8.49	6.82
Fixed carbon%	19.17	0.33	14.84	15.56	18.41	18.83
Carbon%	45.07	23.41	36.12	38.38	40.65	42.19
Hydrogen%	6.57	2.90	5.31	5.32	6.11	6.25
Oxygen%	42.34	18.03	24.96	38.09	42.92	42.92
Nitrogen%	0.42	2.40	1.28	1.26	1.08	1.07
Sulphur%	0.50	0.96	0.83	0.82	0.76	0.75
Chlorine %	1.49	0.91	0.81	0.74	0.61	0.53
Bulk density (kg/m3)	630.04	837.98	830.26	805.04	803.69	769.15
Fines content%	0.08	0.07	0.07	0.13	0.18	0.19

Adapted from (Ahmad et al., 2021)

Primary components of combustion are carbon, hydrogen, and oxygen (Nosek & Holubcik, 2017). Addition of IRO increased these components. Fuel characteristics of PPMS are inefficient and require improvements using supplements such as sawdust and IRO.

PPMS nitrogen and sulphur contents is greater than sawdust, and added during wastewater treatment processes to precipitate sludge and control microbial activity. Nitrogen, sulphur and chlorine emissions are harmful to the environment and need to be minimised (Ahmad et al., 2021). The addition of IRO decreased contents of nitrogen, sulphur and chlorine.

PPMS has a bulk density greater than sawdust, due to higher proportions of inorganic particles allowing for an increased bulk density. Increased bulk density increases energy density, improving the quality of fuel (Ahmad et al., 2021; Wibowo et al., 2020). The addition of IRO negatively affected bulk density, and decreased with increasing amounts of IRO.

Mechanical disabilities of solid fuels is a vital factor pertaining to storage capacities, logistics and transportation (Wibowo et al., 2020). Sawdust had a small effect on mechanical durability of the pellet. Contrastingly, IRO had a negative relationship on the mechanical durability of pellets, and was limited to 20%. IRO had a high viscosity causing bonding capacities of fine particles weakening, allowing generation of fine particles (Ahmad et al., 2021).

Table 24 The effects on ignition and combustion of energy pellets (comprised of PPMS and sawdust (50:50)) augmented with ion-refined oil (pyrolysis oil or bio-oil)

	Sawdust	PPMS	Ion refined oil -5	Ion refined oil -10	Ion refined oil -15	Ion refined oil -20
Ignition durations (seconds)	10	24	10	9	7	4
Combustion duration (seconds)	108	5	81	104	118	130

Adapted from (Ahmad et al., 2021)

PPMS had longer ignition and shorter combustion times than sawdust pellets. These characteristics are undesirable in fuels and require improvements towards shortening ignition and lengthening combustion durations, such modifications would make production of such energy pellets viable. The addition of IRO shortened ignition and lengthened combustion durations. However, combustion durations were still shorter compared to sawdust pellets, due to PPMS high ash content. IRO had a greater proportion of volatile organic materials including light hydrocarbons, ketones and aldehydes, and could explain why the addition of IRO shortened ignition durations (Ahmad et al., 2021).

Sawdust pellets comprises of lignin, cellulose, hemicellulose, carbon compounds, phenolic compounds, volatile compounds and mineral contents, facilitating and allowing for decreased ignition and increased combustion times (Nosek & Holubcik, 2017)

Ignition time with addition of 5% IRO was the same as sawdust pellets, and combustion duration increased by 600%. The addition of 20% IRO caused the ignition time decreasing by 50%, compared to sawdust pellets. Combustion duration was greater than sawdust pellets.

Generally, the bulk density of pellets decreased with increased contents of PPMS. (Matus et al., 2018) showed bulk densities of wood pellets combined with IRO and PPMS to decrease with increased proportions of PPMS.

Conversely, particle density increased with increased proportions of PPMS. This is due to greater proportion of PPMS resulting in increased particle cohesion, making pellets longer with greater porosities in the bulk material allowing for reductions in bulk density (Ahmad et al., 2021). Particle density influences the behaviour experienced during combustion as fuels with particle densities that are high will experience longer combustion durations (Ahmad et al., 2021; Nosek & Holubcik, 2017)

The use of ion-refined oil in augmenting PPMS pellets have shown positive results. PPMS has a low carbon, oxygen and volatile matter content. Supplementing the energy pellet with ion-refined oil caused the carbon and oxygen levels to increase. Carbon content of the fuel pellet also increased due to a higher carbon content found in ion-refined oil causing the volatile matter and reactivity to increase facilitating for fast burning as a fuel. Volatile matter directly influences ignition and combustion characteristics and duration of fuel, and high contents of volatile matter is disadvantageous resulting in lengthened ignition and shortened duration of combustion (Nosek & Holubcik, 2017)

6.6 Discussion: The Potential in Pelletizing PPMS into Energy Pellets in Efforts Towards Achieving Carbon Neutrality

South Africa is facing an unprecedented energy crisis where its failing to meet energy demands of the nation. Most electricity produced originates from coal fired power stations, with many ramifications of these emissions still unknown or waiting to manifest itself (Lundqvist, 2020).

Gauteng has the highest population when compared to other provinces. Resultant of urbanisation, there is a high percentage of unemployed people without access to basic infrastructure such as water and electricity, a directly resultant of poverty and poor governance. In alleviating energy needs, many utilise combustion of coal due to cost and availability in the region with numerous coal mines found in surrounding areas.

PPMS co-pelletized with sawdust showed promising results in a reduced ignition and longer combustion time, allows for PPMS transformed into an energy source, contrastingly, PPMS alone is limited as an energy source due to its high ash content (Ahmad et al., 2021; Matus et al., 2018; Nosek & Holubcik, 2017).

Optimising PPMS through co-palletisation in the generation of energy is an attractive source of bioenergy. Bioenergy is a renewable resource. Their short life cycle can potentially displace fossil fuels. Carbon is absorbed from the atmosphere as biomass grow and released to the environment when incinerated (Andreae, 2019).

Landfill diversion of PPMS through co-pelletizing will result in landfill space saving, reduced methane emissions and resource recovery, can be achieved in PPI's, but at what cost to the environment as incinerating biomass leads to increased CO2 emissions (Andreae, 2019).

With both advantages and disadvantages present in combustion of PPMS (a woody biomass), environmental offsets need to be established in combustion of fossil fuels vs biomass, with both sources having significant ramifications on the environment. Effects need to be quantified in determining 'lesser of the evils' before application of such waste management alternatives of PPMS towards increasing sustainability of PPI's in South Africa.

In diverting PPMS from landfills in the production of energy pellet, environmental effects from emissions need to be understood carefully with mitigation strategies in place prior to its use. Landfill diversion allow for reductions in methane, nitrous oxide and landfill air space, but will emissions of carbon dioxide, methane and nitrous oxide from combustion of PPMS pose a net benefit or detriment on the environment.

In determining such outcomes, comparisons between emissions per mass or volume unit of fossil fuels such as coal (anthracite and lignite) are compared to those of a woody biomass

Table 25 Analysis of emissions per volumes or mass units in the combustion of biomass and fossil fuels

Fuel Type		Heat Content (HHV)	Emission Factors		
		(mmBtu/ton)	(kg CO2/ton)	(g CH4/ton)	(g N2O/ton)
Fossil Fuel: (Coal)	Anthracite	25,09	2,602	276	40
	Lignite	14,21	1,389	156	23
Biomass:	Woody Biomass	17,48	1,64	126	63

Adapted from (Ecofys, 2009; Environmental Paper Network, 2018; Howard et al., 2016)

When comparing emissions from the volume or mass during combustion of coal and woody biomass, coal (anthracite) generates almost 1.58 times more CO2 than woody biomass. Reductions in methane emissions is also achieved from combusting woody biomass compared to coal (anthracite and lignite)

Emissions of nitrous oxide from woody biomass is significantly greater than coal, nitrous oxide is an extremely powerful greenhouse gas that traps heat more efficiently in the atmosphere than carbon dioxide, almost 256 times more powerful than CO2 in trapping heat (Andreae, 2019).

Increased potential of woody biomass in displacing fossil fuels resulting in decreased CO2 and methane emissions. N2O emissions are significantly higher from woody biomass and could be mitigated through the co-combustion of woody biomass and other fuel sources.

Factors limiting conclusions from this comparison is due to efficiencies of burning fossil fuels are higher than compared to woody biomass (Lundqvist, 2020), therefore to better understand effects of combusting these fuel sources, comparing emissions per an energy unit are compared between these sources result in greater understanding of such emissions.

Table 26 Analysis of emissions per an energy unit in the combustion of biomass and fossil fuels

Fuel Type		Emission Factors		
		(kg CO2/mmBtu)	(g CH4/mmBtu)	(g N2O/mmBtu)
Fossil Fuel: (Coal)	Anthracite	103.69	11	1.6
	Lignite	97.72	11	1.6
Biomass:	Woody Biomass	93.8	7.2	3.6
Landfill Gas:	Methane	52.07	3.2	0.63

Adapted from (Ecofys, 2009; Environmental Paper Network, 2018; Howard et al., 2016)

From the table above, carbon dioxide, methane and nitrous oxide emissions increased significantly when diverted from landfills, and emissions of nitrous oxide almost 5.7 times higher when combusted instead of landfilled. In comparing woody biomass to landfill gas and other fossil fuels such as anthracite. Reductions in carbon dioxide, methane and nitrous oxide are achieved from combusting landfill gas

The amounts of carbon dioxide and methane produced from combusting anthracite and lignite is higher than woody biomass highlighting its potential in displacing coal, but increased amounts of nitrous oxide emissions from woody biomass can lead to detrimental effects on the environment (Pradhan & Mbohwa, 2014).

This leads to the point of environmental offsets, would the continuation of business as normal approach in utilising fossil fuels and associated emissions have a greater effect on climate change and increased global warming. Or alternatively, utilising what was once a waste product as a source of energy have a reducing effect on climate change and global warming, although most emissions are reduced compared to fossil fuels, nitrous oxide from woody biomass is almost double that of fossil fuels

In determining such conclusions, such emissions require to be viewed in a holistic way in which of the different sources are closest to the natural cycles present on earth such as the natural carbon cycle (Makgae, 2011). Although air pollution is present and rife in all options compared, it needs to be determined which types of emissions will result in net overall increases to greenhouse gasses in the atmosphere and which type will allow for maintaining a net equilibrium of greenhouse gasses. The origin and source of these fuels play a pivotal factor in determining such conclusions (Sandberg et al., 2017).

Although carbon dioxide released from biomass may be slightly less or equal to that of coal, this is resultant of the chemical composition of woody biomass and coal (Sandberg et al., 2017). A paradigm shift is needed by analysing differences between energy supply of woody biomass and fossil fuels and not through analysis of emissions.

Woody biomass may be regarded as carbon neutral (Pradhan & Mbohwa, 2014), this is because combustion of woody biomass emits carbon which had been part of the carbon cycle, conversely fossil fuels release carbon which had been stored in the ground for millennia.

Therefore, fossil fuels cause a net increase in amounts of carbon found in the atmosphere. Whereas woody biomass operates within the system where combustion causes carbon being released to the atmosphere (Pradhan & Mbohwa, 2014), this carbon will be absorbed and utilised by the growth of plants

Outcome of net greenhouse gas emissions from the use of woody biomass cannot be determined through comparisons of emissions with fossil fuels at the point of combustion as their many factors which affect the net greenhouse gas emissions such as in the case of palletising PPMS, biogenic carbon flows from harvesting, processing and transport need to be accounted and thereafter compared with the energy system displaced (i.e. coal) as well as the biogenic carbon flow in the absence of woody biomass (Gore, 1986; Lundqvist, 2020; Pradhan & Mbohwa, 2014)

PPMS palletisation is as a form of bioenergy regarded as carbon neutral. Carbon neutrality, in the biosphere with the use of woody biomass as a source of bioenergy can be achieved. This is because carbon emitted through combustion was previously sequestered from the atmosphere and possibility of sequestration again through plant growth is highly likely (Sandberg et al., 2017).

The above premise on carbon neutrality from combustion of biomass is dependent on a number of factors, some of which can be controlled such as carbon stocks in forest soils through different land uses and agricultural practices and uncontrolled and unpredictable factors such as carbon losses due to natural disturbances like fires and insect attacks such as locust plagues (Pradhan & Mbohwa, 2014; Sandberg et al., 103 2017). These factors can affect carbon neutrality causing a net increase or decrease in amounts of carbon in the atmosphere

6.7 Summary Chapter: Viability in Utilising PPMS in The Coproduction of an Energy Pellet

Use of PPMS as an additive in fuel pellets leads to improving fuel characteristics while allowing for reductions in amounts of PPMS requiring landfilling. Energy pellets produced could be used as a source of energy to many households located around PPI's, allowing for displacement of fossil fuels in alleviating energy needs.

Energy pellets produced from biomass (PPMS and sawdust) pose both benefits and harms to the environment. Primary benefits include displacing of fossil fuels, landfill diversion and optimisation of PPMS. Negative effects include increased carbon dioxide and nitrous oxide levels when combusting woody biomass compared to fossil fuels.

Long residence times of carbon dioxide in the atmosphere allows for the source of carbon to be negligible in the effects on the atmosphere, whether carbon was released shortly after harvesting and processing of living biomass or whether it originated from dead decomposing biomass. The most important factor would be in increasing the use of biomass in alleviating energy demands will consequently allow for changes in the carbon stocks whilst reducing the use of fossil fuels

7.1 Anaerobic Digestion

Utilising anaerobic digestion for the treatment of the ever-increasing rate in generation of solid wastes, this technology can be utilised in the treatment of an assortment of organic and industrial wastes like agricultural wastes and to treat sludge's produced in wastewater treatment plants (Anderson & Halan, 1995).

There is not much literature available on the anaerobic digestion of PPMS originating from recycling and deinking processes. The anaerobic digestion of deinking sludge may prove not to be a viable owing to the presence inorganic materials at high contents, and deinking sludge may contain high levels of toxic compounds originating from inks as well as a variety of other additives used in PPI's (Meyer & Edwards, 2014).

A major problem limiting the use of anaerobic digestion to treat wastewater treatment sludge's produced in PPI's can be attributed to the long residence time required in the digestion of sludge which could vary between 18-30 days (Elliot & Mahmood, 2007). This limiting factor can be mitigated through pre-treating the sludge. Different technologies utilised in the pre-treating of sludge prior to anaerobic digestion include physical, chemical, and biological treatments. Pre-treating the sludge results in the destruction of the cell walls consequently making them less resistant and more prone to degradation (S. Bayr et al., 2013)

Anaerobically treating of combined primary and biological sludges facilitates the production of value-added products through the valorisation of waste materials, anaerobic digestion can also be used as a method in pre-treating wastewaters through the removal of organics entering aerobic treatment systems. Such technologies allow for a transition towards a circular economic model in which waste products can be recycled and reused ensuring sustainability as we progress towards the future

7.2 Methodology

The role of the researcher is to review previous research findings to gain a broad understanding of the field being researched (Greehoot, Follmer & Dawsett, 2012). Mixed methods research is a methodology for conducting research that involves collecting, analysing and integrating quantitative and qualitative research (Johnson, 2013).

By mixing both quantitative and qualitative research and data, the researcher gains in breadth and depth of understanding and support, while offsetting the weaknesses inherent to using each approach by itself (Maree, 2016). Desktop research following a mixed methods approach was implemented in this study

Research aims included; determining an alternate process in which pulp and paper mill sludge can be utilised allowing for landfill diversion of PPMS, waste reduction, energy recovery with the possibility in producing value added products

7.3 Research Objectives Include:

1. Optimising PPMS
2. Maximizing landfill diversion of PPMS
3. Determining if PPMS be anaerobically digested successfully Limitations facing anaerobic digestion of PPMS
4. Mitigation measures to successfully treat PPMS through anaerobic digestion
5. Resource and energy recovery from PPMS

7.4 Anaerobic Digestion of Wastewater and Sludge

Large variations in the chemical composition of PPI effluents is evident between individual mills, and daily within a specific mill. All pulp processed is unique in their wastewater, resultant of differences from handling raw materials, pulping processes, chemical recovery, bleaching and the mills age (Elliot & Mahmood, 2005; Habets, 2007; Hall, 1985). Large variability in PPI effluents results in anaerobic digestibility of PPI wastewaters and sludge varying significantly.

Commonly, effluent streams are found having nutrient deficiencies that are necessary for successful anaerobic treatment, resulting in additions of macro-nutrients and trace elements during the pre-acidification stage (Meyer & Edwards, 2014). Effluent streams also display unbalanced substrate compositions resulting in process disturbances and reduced methane production. Imbalances are mitigated through the co-digestion of inmill effluents containing substrates from a wide range of sources (Koster & Cramer, 1987).

Lignocellulosic biomass in PPI wastes may potentially slow the hydrolysis step during anaerobic digestion (M. Kamali et al., 2016). Other factors which may potentially slow the process include the reactors configuration, operational and environmental conditions, presence of inhibitory compounds, and compounds with a high resistance to biodegradation, could potentially slow the anaerobic digestion process, reducing methane yields and increasing process instability (Elliot & Mahmood, 2007).

7.4.1 Operating Conditions

7.4.1.1 Hydraulic Retention Time (HRT)

Hydraulic retention time is a key factor directly influencing and affecting performance of an anaerobic reactor. A higher HRT allows for increased contact time, enhancing removal of COD. Performance under various HRT's affects operating temperatures. (M. Kamali et al., 2016) illustrated increasing the HRT (11.7 – 26.2h) increased thermophilic digestion performances, with no significant effect on mesophilic digestion.

7.4.1.2 Temperature

The operational temperatures utilised is a variable affecting efficiencies of COD removal and biogas production, such as the rate of microbial activity depending on operating temperatures. Anaerobic digestion is usually conducted under mesophilic conditions between 35-37 degrees Celsius (Anderson & Halan, 1995; Hall, 1985; Meyer & Edwards, 2014).

Studies show that maintaining thermophilic conditions allow for increased rates in COD removal and biogas production. Other benefits include, maximising the specific growth rates of microorganisms which allows greater degradation of organic matter in reduced times, colour removal capabilities and improved anaerobic digestion stability (Habets, 2007). Although mesophilic and thermophilic digestion pose advantageous, recent emergence of low temperature anaerobic digestion is an economically viable way of cooling and diluting effluents considered inapplicable substrates in anaerobic digestion (Meyer & Edwards, 2014).

Performance of anaerobically treating wastewaters at low temperatures was reviewed by (Naicker et al., 2020) and concluded adopting of adequate and efficient posttreatments for low temperature anaerobic digestion is a method in meeting strict environmental regulations. With low temperature anaerobic digestion, application of physical, chemical and biological supplements is required at high rates, to enhance the efficiencies of anaerobically digesting wastes whilst increase biogas production (Meyer & Edwards, 2014).

7.4.1.3 pH

Anaerobic digestion is highly sensitive to pH changes. Changes usually occur from restrictions of methanogens below pH 6.6 (M. Kamali et al., 2016). Methanogens have a smaller pH range and sensitive to changes compared to fermentative microorganisms with a pH range of 4.0 to 8.5. PH variation affects microorganisms' metabolism directly affecting degradation rates, as bacterial community's morphology is affected with pH variations (Li et al., 2012).

Methanogen inhibition facilitates in the production of volatile fatty acids subsequently converting into acetic acid, hydrogen and carbon dioxide. PH decreases with the further inhibition of microbial activities (Li et al., 2012). In correcting pH, a viable method is allowing methanogens reproduction by stopping substrate feeding into the system. Co-digestion is anaerobically digesting the primary substrate with a suitable ratio of another substrate, is a method of providing the system with a conducive pH allowing increased buffering capacities (Bayr & Rintaka, 2012; S. Bayr et al., 2013).

7.5 Limitations Hindering Anaerobically Treating PPMS and Mitigation Strategies

PPI's effluents contain an array of compounds including inhibitors and toxicants. These compounds may have an individual or synergistic effect on anaerobic processes and difficult to predict, resulting in efficiencies of anaerobic systems becoming limited by the presence of these compounds and elements (Meyer & Edwards, 2014). Variations exist amongst microbial community's responses to different stressors

7.5.1 Acclimation, Adaptation and Community Shifts of the Microbial Population

Microbial communities can increase acclimation to specific stressors either physical or chemical, or even adapt metabolising new substrates. Modification of organisms such as alteration of their lipid content in their membranes or metabolic rate, in response to stressors is referred to as acclimation relating to phenotypic plasticity (Callejas et al., 2013). Such changes are not permanent and could be rapidly induced by the organism.

Individuals within a population can acquire genetic mutations, allowing them becoming advantaged under unfavourable conditions, with selection of these individuals over others for generations to follow (Callejas et al., 2013). Acclimation and adaptation occur simultaneously.

Combined with microorganism's physiology and genetics, are shifts to community structures. These effects allow for an improved tolerance under adverse conditions (Callejas et al., 2013). This was illustrated by (De Vrieze et al., 2013) where bleaching effluents proven toxic to un-adapted microorganisms, caused no disturbance to the process by microorganisms adapted over time. Recent technological advancements like next generation sequencing and molecular biological tools, allowed identification and distinguishing of mechanisms in acclimation, adaptation and community shifts (Callejas et al., 2013). Generally, the effects of changes were reported without understanding underlying causes.

7.5.2 Wood Extractives

Wood extractives such as resin acids, long chain fatty acids, volatile terpenes and tannins, result in inhibition of anaerobic digestion, although dependent on their concentrations in wastewater (Jokela et al., 1997). From the anaerobic inhibitors in PPI wastewaters, resins acids are most common. Volatile terpenes have higher toxicities compared to other wood extractives, with 50% IC values ranging from 42 to 330mg/L (Callejas et al., 2013), and tannins share similar toxic characteristics and found in wastewaters from debarking effluent.

There are numerous reported thresholds in which anaerobic inhibition from resin acid occurs, with large variations exists and range between 20 and 600 mg/L (Bayr & Rintaka, 2012; Meyer & Edwards, 2014). It is crucial to monitor compounds that sorbed into anaerobic granular sludge such as resin acids, as sludge concentrations from the bed were found to exceed influents by up to 2 orders of magnitude (Anderson & Halan, 1995) Resin acid anaerobic inhibition depends on the degradability during treatment (Bayr & Rintaka, 2012). Mitigating measures include upfront settling of solids prior to anaerobic treatment (De Vrieze et al., 2013) and dilution with non-toxic aerobic effluents prior to anaerobic treatments towards reducing resin acid concentrations.

Long chain fatty acids, common in PPI effluents at lower concentrations compared to resin acids. IC values (values at which inhibitions of 50% of methanogenic microorganisms occur) ranges between 73 to 1670mg/L (Callejas et al., 2013). Majority of long chain fatty acids are sorbed into solids due to their hydrophobic nature. Major impacts from the effects of long chain fatty acids inhibition is sludge accumulation on the bed whilst encapsulating biomass, creating physical barriers against transport of substrate and products (Meyer & Edwards, 2014). This can be mitigated through non-feeding periods, allowing long chain fatty acids becoming substrate for microorganisms (Bayr & Rintaka, 2012).

7.5.3 Sulphur Compounds

PPI effluents specifically chemical pulping have significant concentrations of sulphur derived compounds like sulphate, sulphite, thiosuphate, sulphur dioxide, hydrogen sulphide including many organic sulphur derived compounds like lignisulphates. Sulphur removal mechanisms exists and include hydrogen sulphide volatisation, ion sulphide precipitation, formation of elemental sulphur incorporating sulphur into biomass (Eis et al., 1983). Sulphur compounds are considered significant anaerobic inhibitors.

Hydrogen sulphide is corrosive, toxic and increases effluent COD. High concentrations of oxidised sulphur compounds either partially or completely in wastewater causes a decreased methane yield, since these compounds accept electrons from sulphate and sulphite reducing bacteria. These bacteria have significantly greater success compared to acetogenic bacteria's and methanogenic archaea in utilising volatile fatty 109 acids (Eis et al., 1983). Thermodynamic advantages of sulphate reducing bacteria over its competitors is huge factor explaining its success.

Concentrations of sulphide at greater than 100mg/L may potentially result in anaerobic inhibition (Dufresne et al., 2001). Wastewaters of low COD concentrations and COD/SO4 ratios less than 7.5, may likely face sulphide inhibition (Dufresne et al., 2001) and quantities of biogas produced is inadequate in stripping sulphide from liquid during production. Mitigating strategies include recirculating biogas through the digester (Dufresne et al., 2001). Conversely, compared to sulphide, less literature is available on toxicity of sulphite specifically during anaerobic treatment of PPI wastewaters, as both compounds may pose problems (Habets, 2007). Due to the reactivity, it's used as an inhibitor in foods and food processing. Much research is required and imminent to understanding diversity and microbial metabolism of sulphur compounds

7.5.4 Chlorinated Compounds AOX

Bleaching processes effluent streams often contain elevated concentrations of chlorinated organic compounds, and resulting wastewaters having various chlorinated organic compounds, and quantified by the parameter ‘adsorbable organic halides’ (AOX) (M. Kamali et al., 2016). High AOX concentrations are considered toxic and inhibitory to anaerobic digestion processes. Conversely, many studies of varying scales, have indicated these waste streams can be partly included in anaerobic treatment after been diluted through upfront mixing or sufficient adaptation of the microbial community occurred (Kullavanijaya, 2013; M. Kamali et al., 2016; Meyer & Edwards, 2014)

7.5.5 Peroxide

Peroxide alkaline bleaching leads to the presence of hydrogen peroxide in wastewater effluent in high concentrations. Concentrations greater than 50mg/L deteriorates anaerobic processes (Fiorenza & Ward, 1997). Elevated concentrations over 1g/L can be digested by utilising of a pre-acidification tank before treating wastes, in which peroxide and oxygen levels decrease (Fiorenza & Ward, 1997). Numerous microorganisms contain enzymes like catalase, which efficiently decomposes hydrogen peroxide into water and oxygen. Facultative bacteria utilise oxygen as electron acceptors when converting volatile fatty acids in wastewaters (Ferguson et al., 1990; Fiorenza & Ward, 1997)

Peroxide alkaline bleaching leads to the presence of hydrogen peroxide in wastewater effluent in high concentrations. Concentrations greater than 50mg/L deteriorates anaerobic processes (Fiorenza & Ward, 1997). Elevated concentrations over 1g/L can be digested by utilising of a pre-acidification tank before treating wastes, in which peroxide and oxygen levels decrease (Fiorenza & Ward, 1997). Numerous 110 microorganisms contain enzymes like catalase, which efficiently decomposes hydrogen peroxide into water and oxygen. Facultative bacteria utilise oxygen as electron acceptors when converting volatile fatty acids in wastewaters (Ferguson et al., 1990; Fiorenza & Ward, 1997)

7.6 Anaerobically Digesting PPMS

There is much literature on the anaerobic digestion of sludge of non-mill sources, and limited investigations conducted on anaerobically digesting PPMS (Elliot & Mahmood, 2007; M. Kamali et al., 2016; Meyer & Edwards, 2014). In reviewing literature, characterisation of paper mill biological sludge differs from municipal biological sludge, with a key difference being the large amounts of lignocellulosic derived materials in PPMS biological sludge (M. Kamali et al., 2016). Although established full scale anaerobic treatment facilities for PPI effluents exist, anaerobic treatment of PPMS is in its early stages (Elliot & Mahmood, 2005, 2007). The presence of lignocellulosic derived materials, complex organics like extracellular polymeric substances in PPMS, and microbial cells results in hydrolysing of these constituents becoming difficult requiring extended durations compared to other waste streams undergoing hydrolysis (Meyer & Edwards, 2014).

High sludge retention times resultant of slow and incomplete hydrolysis, large reactors and high investment costs are major limitations to anaerobically digesting PPMS. In minimising limitations faced by anaerobically digesting PPMS, there are two methods which significantly increases viabilities are; pre-treatment and co-digestion with other substrates (Elliot & Mahmood, 2007).

Pre-treating PPMS breaks down compounds difficult to biodegrade such as cellulose, hemicellulose and lignin, which have a high resistance to hydrolytic enzymes. This enhances biodegradability of the substrate and improve yields from biological treatments. Recalcitrant nature of lignocellulosic contents hinders biodegradation of PPMS, forming a barrier in the conversion of PPMS to biogas. Therefore, hydrolysis of PPMS during anaerobic digestion is a rate limiting step (Jokela et al., 1997).

Pre-treatments rupture the cell walls, releasing extracellular polymeric substances. This allows for the release of intracellular organic material becoming available for acidogenic and methanogenic microorganisms. Effectiveness of pre-treatments are determined in their ability to enhance digestibility of lignocellulosic derived materials, utilising a wide range of mechanisms including lignin deconstruction, increased the surface area that is accessible, reducing cellulose crystallinity and decreasing the rates of polymerisation (Habets, 2007; Kullavanijaya, 2013)

Effects vary depending on the treatment type and includes; hemicellulose and lignin solubilisation, increasing cellulose accessibility, causing lignocellulose becoming swollen increasing accessibility whilst decreasing cellulose crystallinity and polymerization. A microbial population which is dynamic has a greater resilience to operational stress, such characteristics can be achieved through substrate 111 diversification utilising co-substrates (M. Kamali et al., 2016). Even with different mechanisms involved, a shared aim involves increasing access of available lignocellulose to methanogenic and acidogenic microorganisms, and integration of these methods prior to anaerobic digestion enhances digestibility of lignocellulosic materials (M. Kamali et al., 2016).

7.6.1 Pre-Treatment Methods

Pre-treatment is a crucial tool utilised in the conversion of cellulose {Bajpai, 2014; 2017). Pre-treatment is essential to change structures of cellulosic biomass towards increasing availability of cellulose to enzymes, which convert carbohydrate polymers to fermentable sugars (Meyer & Edwards, 2014). Different pre-treatment methods exist allowing for subsequent processes occurring at faster and more efficiently, and associated with reduced costs. Different pre-treatment includes physical, chemical and biological methods (Meyer & Edwards, 2014).

7.6.1.1 Chemical Pre-Treatments

Of the many pre-treatment methods available, chemical pre-treatment is the most cited. PPI’s use chemical pre-treatments in delignification of cellulosic materials in manufacturing of products (Li et al., 2012). Acid’s or base’s are added to solubilise it, and these additions remove requirements of high temperatures allowing these methods being conducted in open environments or at moderate temperatures (S. Bayr et al., 2013; Li et al., 2012).

7.6.1.2 Physical Pre-treatments

Thermally pre-treating PPMS involves the rapid heating through differing modes like hot air, liquid hot air and steam, at specified durations encouraging the hydrolysis of holocellulose with rapid decompression (S. Bayr et al., 2013). Such methods present opportunities to PPI’s by allowing for greater viability in anaerobically digesting PPMS.

Hydrodynamic, often referred to as mechanical pre-treatments, are conducted with the objective of rupturing cell walls and increase soluble COD content (S. Bayr et al., 2013). This can be achieved with numerous methods including forcing PPMS under increased pressures on to a collision plate. Another form of physical pre-treatments is microwave and ultrasounds (S. Bayr et al., 2013). Cavitation originating from frequency waves results in disintegration of PPMS, enhancing anaerobic digestibility. Ultrasound treatment uses acoustic waves and microwave uses electromagnetic waves (S. Bayr et al., 2013).

7.6.1.3 Biological Pre-Treatments

Biological pre-treatments utilise microorganisms, bacteria and enzymes, by modifying chemical compositions or destruction of PPMS materials (S. Bayr et al., 2013). Biological pre-treatment has many benefits including no chemical requirements, milder environment conditions, lower energy usage and environmentally friendly. Disadvantages are also apparent including metabolic activities occurring at slow rates, large space requirements, and a meticulous control on environment growth conditions (S. Bayr et al., 2013).

7.7 Co-Digestion with PPMS

Feedstock such as PPMS, highly rich in protein or could have harmful and toxic compounds resulting in slowed digestion with reduced gas yields (Elliot & Mahmood, 2007). Such limitations may be mitigated through co-digestion with other substrates of adequate C:N mixing ratios, inhibitors, biodegradability of the feedstock and total solids content (Bayr & Rintaka, 2012). Lignin and sulphur containing compounds with nutrient deficiencies are considered key limitations resulting in incomplete anaerobic treatment of PPMS (S. Bayr et al., 2013; Meyer & Edwards, 2014).

Another strategy is developing and modifying a microbial community of a greater resilience to operational stress, through diversifying in utilising co-substrates (Hagelqvist, 2013). PPI's generate an array of effluents, and greater digester stability is achieved by treating different waste streams simultaneously through anaerobic codigestion treatments.

Many studies show differences in biogas yields from anaerobic digestion, and influencing factors being the substrate used, source and composition of inoculum (Elliot & Mahmood, 2007). An appropriate inoculum can upsurge degradation rates, increase biogas yields, shorten starting time with greater stability in the digestion process (Meyer & Edwards, 2014)

7.8 Discussion: Anaerobic Digestion of PPMS Facilitates Circularity Within the PPI with Potential to Alleviate South Africa's Energy Crisis

Increasing demands faced by Eskom coupled with great debt burden resulted in ramifications in the availability of electricity to South Africans. Rolling blackouts or "loadshedding" has become a common reality affecting most South Africans as Eskom does not have the capacity to accommodate energy demands. This led to South African regulations changing in respect to licenses in generation of power, with the threshold in generating power without licenses lifted from 1MW to 100MW. This will independent power utilities establishing new generation capacities which in turn should stimulate the economy.

This unveils huge potential displacing a centralised single vertically integrated utility in the establishing of decentralised, decarbonised, renewable power systems, allowing energy production closer to where its used rather than at a large plant away supplying energy to a national grid.

These changes in regulations highlight the potential in anaerobically treating wastes such as in the case of PPMS becoming viable alternatives, as huge investment costs can become feasible in the long run with revenue through gas to electricity generation from anaerobic digestion, whilst providing alternate sustainable waste management practices for organic wastes generated.

Although full scale anaerobic treatment facilities of wastes generated in PPI is practically non-existent, there are certain waste streams undergoing anaerobic treatment with biogas produced burnt in alleviating energy demands of the mill. Most effluent streams from PPI's are suitable for anaerobic treatment. Even in the case of elevated concentrations of AOX commonly thought of being toxic to biomass, can be treated if diluted or co-digested with other waste streams. Microbial adaptation can occur even if initially at a slow rate, eventually will lead to increased digestibility of such waste streams

Lignocellulosic materials in PPMS has increased resistance to digestibility and degradation with organisms illustrates another limitation of anaerobically treating PPMS due to high costs associated with pre-treatment of PPMS prior to anaerobic treatment. Many studies show the viability of co-digesting PPMS with other substrates such as manure lead to mitigation of limitations faced in anaerobically treating PPMS alone such as slowed reaction rates and reduced gas production.

PPI's within close proximities to primary cattle farming areas of South Africa, where it can be feasible in respect to the transport of different substrates such as manure in co-digestion of PPMS in energy generation and nutrient recovery from residuals remaining that can be used as a fertiliser.

Such alternatives will allow for waste management of PPMS in PPI's increasing sustainability where energy and nutrient recovery of PPMS can occur, while energy produced from burning biogas can be sold to the national grid. This will allow for a shift from PPMS being thought as a waste to become a resource and 'feedstock' that can successfully be anaerobically treated resulting in nutrient and energy recovery.

Costs associated with transport and landfilling become nullified where costs associated with waste management of PPMS will now become potential revenues from waste management of PPMS. Such alternatives facilitate transition away from a linear economy and the implementation of a circular economic model through the valorisation of PPMS waste generated in PPI's. A circular economic model, when applied will ensure sustainability in such industries as we head towards the future.

8. Other Potential Waste Pathways Facilitating Landfill Diversion Applicable to PPMS

8.1 Introduction

Economically viable and environmentally acceptable methods in recycling of organic wastes are needed by the PPI's. Viability of current waste management methods in PPI's are reducing such as incineration due to the high mineral content of PPMS and landfilling due to environmental ramifications posed. Determining alternative uses of PPMS is a key area of focus in PPI waste management strategies. Application of industrial wastes as fertilisers or soil amendments, has been seen as an environmentally friendly alternate use of PPMS, regarded as an ecologically sound option when compared to incineration and landfilling.

8.2 Methodology

The next set of alternative waste management options reviewed follow a qualitative approach. Potential alternate pathways were determined by their applicability to PPMS

8.3 Aims and Objectives:

1. Determine alternate pathways applicable in the waste management of PPMS
2. Optimising PPMS
3. Maximise value and benefits posed by the composition of PPMS
4. Explore and determine potential alternate pathways for PPMS with respect to;
   A. viability in the process
   B. chemical composition and properties of PPMS
   C. physical characteristics of PPMS

5 Maximising landfill diversion of PPMS

8.4 Results

8.4.1 Reuse Within the Paper and Board Industry

Soil waste generated in PPI's are utilised in the production of various industrial products (Ahmad et al., 2013; Dorica & Simandl, 1995; Johnston et al., 2000; Kujala, 2012). Differentiation into two distinct categories in utilising ppms in producing potential products i.e., ones requiring a high inorganic and low organic contents, and others requiring a high organic and low inorganic content (Rothwell & Éclair-Heath, 2007). Successful methods to recover fibres from waste streams were patented, allowing for the utilisation of specific components opposed to utilisation of PPMS as a whole. The methods of separating different components of PPMS can be achieved easily with available equipment or involves complex systems (Andreola et al., 2005). Common waste management alternatives focused on utilising PPMS as a feedstock in manufacturing of fibreboards, building materials and a landfill cover material (Ahmad et al., 2013; Blawaik & Raut, 2011; Karam & Gibson, 1994; Moo-Young, 1998). Such alternatives allow for upgrading of the high fibre and filler contents such as in the production of fibreboards, building materials, and a landfill cover material

8.4.1.1 Fibreboard Products

Fibreboards are engineered wood wallboard comprising of wood chips, plant fibres, softwood flakes and other recycled materials like paper and cardboard (Davis et al., 2003; Geng et al., 2007). These materials are bonded together at high temperatures and pressures with synthetic resins prior to compaction into sheets (Davis et al., 2003). Gypsum fibreboard is a reinforced material composed of gypsum and cellulose fibres (Dorica & Simandl, 1995).

Fibreboard panels, a popular material used in building and furniture, with great variation in compositions of fibreboards (Davis et al., 2003). Fibreboards are utilised in dry walls, panelling and lining in walls, ceilings and floor. Several types of fibreboard exist i.e. particle boards, medium-density fibreboards and hardboards (Davis et al., 2003). Many studies show the use of PPMS in producing gypsum fibreboards or as an additive in fibreboard (Jesis & Alda, 2008; Johnston et al., 2000). PPMS is characterised with having large amounts of fibres, but the amounts of intact fibres are low. Internal bonding and structure depend on the particles size, affecting properties of panels produced (Xing et al., 2012).

Biological sludge from three separate mills employing thermomechanical, thermoschemical and Kraft pulp to produce particleboards were investigated by (Xing et al., 2012) and concluded using secondary PPMS to manufacture particle boards is viable, and also stated an optimal percentage for each sludge in relation to technologies and processes utilised in its generation (Xing et al., 2012). In producing medium density fibreboards, different sludge types i.e. primary, biological and deinking sludge were compared to applicability in the manufacture of such products (Geng et al., 2007). The least applicable sludge type was deinking sludge resultant of a lower ash content, increased holocellulose content, greater presence of longer fibres and low pH. These characteristics showed PPMS of virgin mills being a better fibre source over recycling mills. Mechanical and physical properties of medium density fibreboards, where deinking sludge was investigated (Davis et al., 2003) showed the clay content having the greatest effect on mechanical properties, negatively affecting factors such as modulus of rupture and elasticity, and the internal bond strengths. Clay content also affected the moisture content, weight and volume of the fibreboard (Davis et al., 2003).

An increased clay content proved advantageous in decreasing flammability of the fibreboard, whereas increasing fibre contents lead to increased flammability (Jesis & Alda, 2008). Inorganic contents of deinking sludge specifically clays, reduced mechanical properties of fibreboard (Jesis & Alda, 2008). Other than the inorganic contents, there were no physical and operational limitations in utilising deinking sludge to augment fibreboard production (Jesis & Alda, 2008). It was concluded a small proportion of inorganic contents or 35% fines did not affect properties of the produced board (Jesis & Alda, 2008). An implication is partial removal of fillers from deinking sludge may lead to an economically viable waste management alternative to landfilling.

In reviewing PPMS from 20 different mills in their fiber content, fibre quality, physical and chemical properties such as humidity, ash content, abrasiveness, drainbility, oxygen uptake, and effect when used as an additive in medium density fibreboard (Jesis & Alda, 2008). PPMS, had several shared features compared to recycled paper, with implications on waste management practices, sludge could be combined with recycled paper to produce fibreboards (Jesis & Alda, 2008).

8.4.1.2 Moulded Pulp

Moulded pulp or moulded fibre, referred to as a packaging material usually used as a protective packaging food service trays and beverage carriers, with egg trays being the first product of moulded pulp manufactured (Kujala, 2012). Since its initial production in the 1940's, amounts of products were produced increased over time (Kujala, 2012). Recycled fibres were used predominantly in manufacturing of moulded pulp (Glenn, 1997). Pulp is forms over a desired mould a where partial removal of water occurs through the use of a vacuum forming the shape of the product (Glenn, 1997). Suitability of PPMS in producing of mouloded pulp is applicable, with a major limitation being requirements of an ash content lower than 10% (Rothwell & Éclair-Heath, 2007).

8.4.1.3 Millboard

Recycled paper products include millboards and is manufactured completely from recycled fibres (Kujala, 2012). Millboard differentiates from fibreboard due to its increased density, and thickness of the final product (Eroglu & Saatci, 1993). Millboard is generally utilised in the automobile, shoe, furniture and packaging industries (Eroglu & Saatci, 1993) and regarded as a hard board with a high density

PPMS is suitable for use as an additive in millboards, since requirements include high fibre and low ash content to ensure 'caliper' in the final product (Kujala, 2012). Limitations facing its use is the ash contents included in the fibre fraction of the waste stream leading to unfavourable outcomes in caliper of produced millboard (Kujala, 2012). PPMS may potentially be reused in millboard production due to a high fibre contents, depending on capabilities to separate fibre from ash fractions (Rothwell & Éclair-Heath, 2007). Utilising PPMS in millboard production will facilitate landfill diversion, and the production of value-added products.

8.4.1.4 Softboard

Primary uses of softboard is in pin boards, and an insulating and fireproofing material in construction (Kujala, 2012). Raw materials used to produce softboard consists of short fibres and ash contents less than 10%, allowing for optimal caliper thickness, and commonly produced from recycled newspapers (Rothwell & Éclair-Heath, 2007)

PPI solid wastes containing approximately 80% sludge and 10% other fibres and could be utilised to produce softboard (Goroyias et al., 2004), origins of other fibres can be of virgin wood or recycled fibreboards (Goroyias et al., 2004). Deinking and primary sludge utilised in such applications due to high contents of organic fibres, so utilising PPMS to produce softboards can potentially displace virgin wood fibres, increasing sustainability

8.4.2 Valorisation into Mineral-Based Products

Deinking sludge presents a range of potential recycling possibilities and depends on compositions of inorganic compounds. Generally, calcium carbonate and clay are inorganics in deinking sludge. Primary components in the combustion of deinking sludge are calcium oxides and sintered clays. Historically, PPMS was used in the building industry, and methods of utilisation included utilising it as feedstock in a cement kiln, in cementitious composites as organic fibres increasing durability and reducing cracking resulting from shrinkage.

8.4.2.1 Cements and Cementitious Products

Cements, universally used as a binder working and setting independently whilst binding other materials (Ahmad et al., 2013; Andreola et al., 2005; Karam & Gibson, 1994). Different cements exist and referred to as hydraulic, due to hardening resultant of hydration as inorganic chemical reactions providing strength to cement and nonhydraulic cements only develop strength in dry circumstances (Ahmad et al., 2013).

Limestone, clay, sand and iron ores are primary raw materials required in producing cement (Ahmad et al., 2013). Limestone and clay proportions in kiln feed is between 80-90% and 10-15% (Ahmad et al., 2013). Silica and aluminium are beneficial to the process, as raw materials exposed to high temperatures results in formation of calcium, silicon, aluminium and iron oxides (Ahmad et al., 2013). Clinker, a hard substance in the kiln usually mixed with gypsum to produce Portland cement (Chun & Naik, 2004). Utilising gypsum results in cements prevented from flash setting, and proportions of clinker to gypsum is around 95:5 (Chun & Naik, 2004).

Deinking sludge usually high in inorganics containing these substances, and could provide components like calcium carbonate, clays, silicon dioxide and aluminium, proving beneficial to cement making processes (Blawaik & Raut, 2011). Fly ash resulting from incinerating PPMS could contain reactive lime, silica and aluminium which could chemically contribute to cement ingredients. Therefore, PPMS fly-ash is a suitable ingredient contributing calcium, silica, alumina into the cement kiln or in the manufacturing of blended cements (Ahmad et al., 2013; Blawaik & Raut, 2011).

Utilising PPMS in partially replacing cement in concretes was investigated. It was concluded that PPMS up to 5% of weight with particles sizes lower than 90mm can utilised successfully as a cement to prevent reductions in workability (Ahmad et al., 2013). The high calorific value of PPMS has potential in the use as a fuel and thereafter use the ash as a cement replacement (Ahmad et al., 2013; Andreola et al., 2005).

A universal formula for cement does not exist with varying compositions of ingredients globally therefore, using deinking sludge depends on how suitable specific materials present sludge relate to proportions of raw material for the desired application (Yan & Sagoe-Crentsil, 2011). Chemical composition of deinking sludge shows inorganics 120 providing the most compounds found in cements. Regarding heavy metals, no guidelines exist on trace elements and threshold limits for cements (Ahmad et al., 2013). This could be due to trace metals present bound to cement during hydration, consequent leachate would be minimal posing no hazard to human life and environment (Ahmad et al., 2013).

The addition of PPMS in cement production facilitates energy and materials recovery. Energy recovery occurs as PPMS is calcined within the kiln and ash remaining added to the clinker (Ahmad et al., 2013; Karam & Gibson, 1994). Deinking sludge is the most suitable and applicable in these processes when compared to primary and secondary sludge because its contents of different organic and inorganic components. Limitations faced is the high moisture content with costs involved in dewatering, with a low heating value compared to other fuels used in cement production (Ahmad et al., 2013).

Utilising PPMS in cementitious products have received much focus, using organic fibres like in the use of wood pulp in augmenting cementitious composites, pose advantages including increased durability, ability to pumping and reduced cracking resulting from shrinkage (Ahmad et al., 2013; Chun & Naik, 2004; Yan & SagoeCrentsil, 2011)

8.4.2.2 Concretes

Globally, concretes are one of the most used construction materials, which is a composite, of sand and gravel aggregates combined with water, and cement working as a binder (Ahmad et al., 2013; Srinivasan et al., 2010). The production of cement causes significant amounts of carbon dioxide, a major greenhouse gas being released (Srinivasan et al., 2010). A ton of cement clinker generates approximately a ton of greenhouse gasses (Srinivasan et al., 2010). This led to numerous environmental issues facing cement and concrete industries, with sustainable development being the centre of focus in this industry (Srinivasan et al., 2010).

Sustainable concrete structures are designed in which total environmental impacts from its life cycle is minimised (Srinivasan et al., 2010). Utilising green materials exemplifies low energy costs, also having a high durability with low maintenance requirement allow for it been regarded as a sustainable building material (Srinivasan et al., 2010).

Concrete are a sustainable material due to its low energy requirements, and produced with minimal wastes (Blawaik & Raut, 2011). It is produced from renewable resources and recycled materials, making it completely recyclable (Blawaik & Raut, 2011). Concrete is dynamic and constantly evolving to satisfy ever increasing demands from its users (Srinivasan et al., 2010). Reuse of industrial by-products and consumer waste is vital to produce greener concretes (Srinivasan et al., 2010). Boiler and wood ash, natural pozzolans and pozzolanic derived materials are examples of such waste (Srinivasan et al., 2010). Utilising such materials to produce concretes alleviates demands of manufactured cement clinker whilst producing concretes of higher durability. This allowed for an improvement to air quality and minimised solid wastes.

In exploring alternatives, (Blawaik & Raut, 2011) and (Yan & Sagoe-Crentsil, 2011) investigated the use of PPMS in concretes and mortar. PPMS caused increased compressive, splitting tensile and flexural strengths by up to 10% PPMS, and further additions caused gradual reductions to strength properties (Blawaik & Raut, 2011). An increasing strength results from differences in fibre proportions, where long intact fibres allow for higher strength characteristics opposed to short and damaged fibres (Blawaik & Raut, 2011; Yan & Sagoe-Crentsil, 2011). Numerous literature is available on utilising PPMS to augment in the production of cements and cementitious products, and such alternatives are implemented to an extent (Chun, 2002; Chun & Naik, 2004). Sludge and ash recovered from incineration have uses in the cement industry.

Difference of opinions arise with the use of deinking sludge to produce cement, one group concludes that deinking sludge limits the mechanical strength of products whereas, another group agrees that utilising deinking sludge of up to 10% was proved being beneficial (Zani & Tenaglia, 1990) Both groups agree and prefer using deinking sludge in cementitious products. Many studies have shown ash from incinerating PPMS contain substantial amounts of aluminous-siliceous material with great potential in utilisation as a unique cement replacement material (Ahmad et al., 2013; Blawaik & Raut, 2011; Srinivasan et al., 2010; Yan & Sagoe-Crentsil, 2011).

8.4.2.3 Insulating Material

There is potential to utilise deinking sludge to produce insulating materials (Cavaleri & Contu, 2011). Numerous investigations were conducted to determine thermal and acoustic properties when utilising PPMS as an insulating material (Cavaleri & Contu, 2011; Morozova & Shargatov, 2001; Neckermann, 1982). Advancements in utilising deinking sludge as a material providing thermal insulation primarily owing to its thermal conductivity factor lower the 0.055 Wm2K (Morozova & Shargatov, 2001; Toolbox, 2013) compared to current insulating materials like fibreglass 0.045 W/m2K and expanded polystyrene 0.033-0.046 W/m2K(Toolbox, 2013).

There are many possible ways to utilise PPMS as an insulating material. Investigating such alternatives, (Cavaleri & Contu, 2011) used deinking sludge with moisture contents ranging between 25-60%, deinking sludge was added together with liquid additives such as fungicide and flame retardants. After drying the mixture and subsequently pulverising to flakes. It was shown the presence of long fibres is favourable, with the inorganic content having an inverse relationship with the products insulating properties (Cavaleri & Contu, 2011).

Another method of materials recovery, in which insulating properties of deinking sludge can be recycled and used to produce boards was shown by (Morozova & Shargatov, 2001). Versatility of the boards exemplifies untapped potential where insulating properties of the material were conserved in the manufacture of wall panels providing thermal insulation, with residential and industrial uses (Morozova & Shargatov, 2001; Zvyagina, 1996).

8.4.3 Transforming PPMS into Animal Feed Facilitating Resource Recovery

In exploring alternate uses of PPMS, many researchers regarded it as a promising substrate in the production of single cell proteins (Harkin, 1982; Millet et al., 1973; Norgren et al., 2020; Bajpai, 2010; Pamment et al., 1979). Assessing the potential economic value of PPMS contents, the greatest value is from proteins, and was significantly higher than lignin, phosphorous, nitrogen, potassium and when utilised in biofuels (Norgren et al., 2020).

Carbohydrates found in PPMS primarily as cellulose and other nutrients, can be utilised by incorporating PPMS directly in animal feed mixtures (Millet et al., 1973), with many studies conducted on the digestibility and palatability of PPMS in animal feeds. Results showed great potential as cellulosic components are directly available to ruminant animals (Millet et al., 1973). The presence of lignin and mineral matter impaired digestibility (Rogers, 1982). Limiting such use is the high ash content which is undesirable as inorganic matter has no food value but only adds bulk (Rogers, 1982).

Another method to recycle PPMS into proteins for animal feed was rearing black soldier fly larvae (Norgren et al., 2020) which was shown to survive and grow on municipal sewage sludge. The black soldier fly larvae could then be used as a source of protein utilised in animal feeds. It was shown nutrients were not readily accessible to larvae, but simple modifications like the addition of nutrients did not affect the weight gain, but increased survival rates (Norgen et al., 2020). This may be due to lignocellulosic food media known being difficult for larvae to access due to the crude fibre content, in which larvae are forced to penetrate the outer cuticle layers of materials derived from plants (Norgren et al., 2020).

Although PPMS proved being an unviable substrate to rear black soldier fly larvae, it illustrates potential in co-digesting with other substrates, and if inhibiting factors on black soldier fly larvae is minimised through finding a viable pre-treatment strategy (Norgren et al., 2020).

8.4.4 Potential in Utilising PPMS as A Landfill Barrier Cover Material

Many countries including South Africa investigated utilising PPMS as a hydraulic barrier material in landfill cover systems, resultant of advancements in the use of PPMS as a landfill cover material towards displacing clays and geo-composites (Ahmad et al., 2013; Rokainen et al., 2009; Van Ham & Mullen, 2009). In investigating geotechnical properties of PPMS, a high-water content and compressibility showed similarities to organic soils (Moo-Young, 1996). Effectiveness as an impermeable barrier indicated PPMS provides an acceptable hydraulic barrier, with such characteristics showing potential uses in light duty road bed construction and tennis courts (Moo-Young, 1996; Van Ham & Mullen, 2009).

Geotechnical, hydrodynamic, and chemical properties of PPMS behave like highly organic soils, with such characteristics showing potential in utilising PPMS as a hydrodynamic barrier in landfill cover (Moo-Young, 1996). Such alternatives have been implemented in North America between 1990 to 2003, 29 landfills were closed and used PPMS as a hydraulic barrier layer which ranged in sizes between 1.6 acres to a municipal landfill of 30 acres. (Moo-Young, 1998; Moo-Young, 1996)

Suitability of PPMS in covering and sealing material was investigated and results showed decreased strength properties, a reduced coefficient of permeability and increased compressibility (Rokainen et al., 2009). Further investigations showed strength properties could be improved with fly ash and cement supplements, with the results fulfilling the conditions prescribed of a mineral hydraulic protection layer to cover a waste body and seal the bottom of a landfill Rokainen et al. (2009).

Utilising PPMS within the liner in landfill expansion allows for reduced needs and cost associated with transporting clays from other locations, providing PPI's with a sustainable low-cost waste management option. Landfill diversion of PPMS and ash can occur, with materials that were going to be landfilled, now utilised in the structure of the landfill (Van Ham & Mullen, 2009). Results from differing investigations show PPMS performing just as well as clay barriers (Moo-Young, 1996; Rokainen et al., 2009). The use of PPMS in landfill covers facilitates the transformation from a waste to resources (Van Ham & Mullen, 2009).

9.1 The Transition of Pulp and Paper Industries Towards a Circular Economic Model

Most PPI's globally are characterised by having a linear economic model where waste generated are incinerated prior to landfilling. Incineration usually is done towards energy and resource recovery, but energy balances from incinerating PPMS due to its characteristics and composition leading to overall net energy deficits in the system. Although globally, there is an increased degree of recycling efforts of paper products which led to established systems successfully processing recycled fibres in manufacturing of paper products.

Recycling systems within the PPI’s are enabling a transition towards a circular economy, in which waste paper products are successfully processed and remanufactured into useful products. This is the basis of a circular economy that advocates for the reuse and recycling of products are resources, where wastes generated in PPI is regarded as a resource due to its chemical composition

Through exploring of alternate end-of-life pathways for solid wastes generated in PPI will maximise resources like timber and water utilised within this industry, as these solid wastes can be reused and recycled into a variety of value-added products opposed to disposal and landfilling. Such efforts and alternate pathways in this research will facilitate landfill diversion and conserve landfill air space, mitigate increased demands on limited natural resources, economic benefits through creating value added products, proactively mitigate anticipated effects of climate change, social upliftment through job creation, and ultimately lead to increased levels of sustainability within environmental, social and economic spheres of PPI’s.

The figure below, illustrates processes of a circular economy and is very similar to a linear economy, with waste management practices being a major distinguishing factor facilitating landfill diversion through reuse, refurbishing, remanufacturing, and recycling of wastes, enabling the transition towards a circular economy.

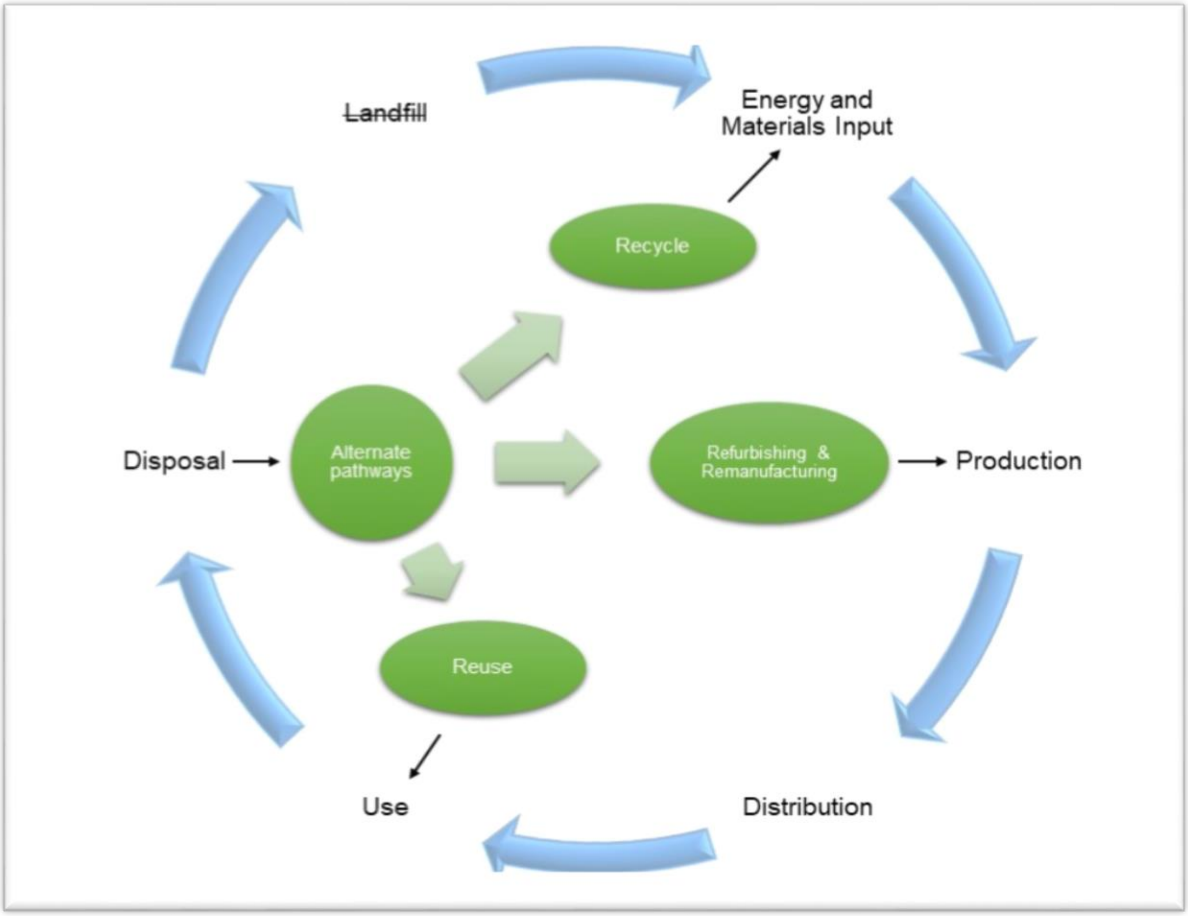

Figure 17 The circularity in the steps taken which is characterised by a circular economic model

The WROSE Model pictured above, is a waste management tool developed to provide information on the environmental, economic and technical implications and impacts to the user under different waste management scenarios (scenarios 1 to 5). (Kisoon, 2018)

The WROSE Model was employed for this research in constructing and providing scenarios towards increased sustainability in the waste management of PPI solid wastes. Within the WROSE Model, there are 5 scenarios with pathways differing in outcomes in which wastes can follow as indicated above.

Towards optimising PPMS, alternate pathways were analysed under different scenario models to determine the best possible pathways in increasing sustainability of PPI's. Currently, the only waste management method of energy and materials recovery from PPI solid wastes include incineration allowing for energy recovery prior to landfilling.

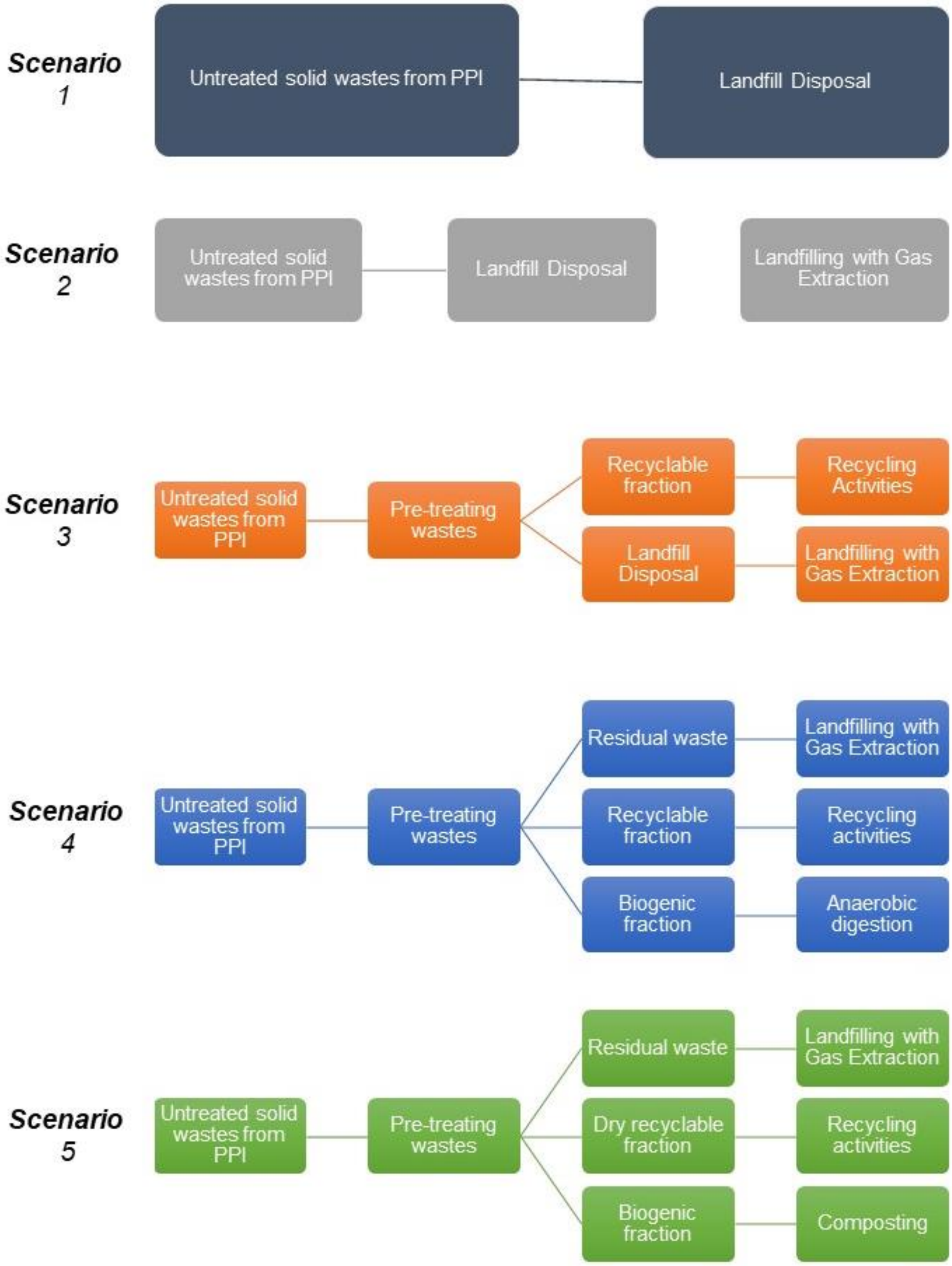

Figure 18 WROSE Model scenarios 1 to 5 of PPI solid wastes

By characterising PPI solid wastes allows for differentiation of different waste types present, and determining the most suitable alternate end of life pathway dependent on the waste's characteristics. These different alternate pathways can be analysed and compared with another in determining the most appropriate technology and sustainable waste management approach for PPI solid wastes. The WROSE^{TM} Model is a very useful tool towards determining the most efficient waste pathway. Scenario 1 and 2 will not be applicable to PPI solid wastes as they require pre-treatments in the removal of their high moisture contents.

The most sustainable waste management approach in PPI's would include following scenarios 4&5 of the WROSE model which ensures maximising of value derived from resources utilised and processed and simultaneously enabling a greater degree of circularity within PPI's.

The main difference between scenarios 4&5 is the pathway taken by the biogenic fraction where it undergoes anaerobic digestion in scenario 4 and is composted when following scenario 5. The WORSE^{TM} Model could be better suited to the PPI' solid wastes through merging of these appropriate scenarios will facilitate greater amounts of reuse and recycling of PPI solid wastes and simultaneously allow for increased diversion of wastes destined for landfills. Integrating scenarios 4 and 5 will allow for the WROSE^{TM} Model determining the best pathway.

PPI current waste management is best described by scenario 3 of the model whereas waste is sorted into the recyclable fraction and the remaining fraction is landfilled. By enabling a transition to scenarios 4 and 5 will facilitate a greater amount of PPI wastes utilised in the recyclable fractions through alternate end of life pathways, and a decreased amount of waste requiring landfilling.

This research has determined that PPI solid wastes can be successfully processed and recycled into a variety of uses such as composting, producing an energy pellet, anaerobic digestion, a landfill cover material, reused within the paper and board industry including its use in cements, concretes and hybrid building materials. With an array of different potential uses, determining the best pathway could prove challenging in the absence of a decision making tool such as the WROSE^{TM} Model. This model allows for the quantification of possible effects such as emissions (Kisoon, 2018), and such knowledge allows those in charge of waste management activities in making more informed decisions.

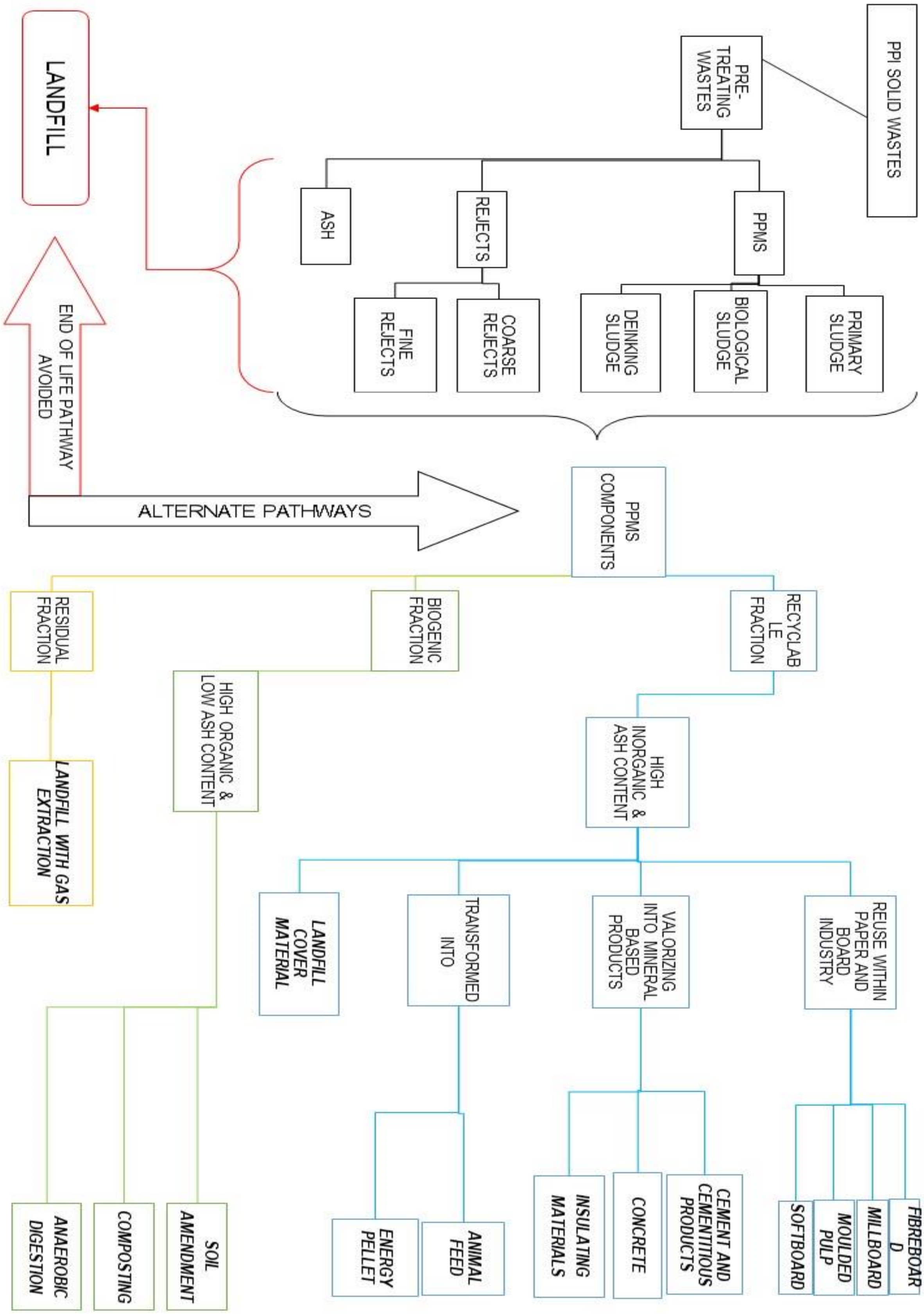

Figure 19 Illustration of possible pathways of PPMS using the WROSE Model scenarios 4&5

9.2 The Successful Implementation of Alternate Pathways PPI's Solid Wastes

The following are examples of alternate pathways successfully taken for wastes generated in PPI's:

1. The table below displays examples of incinerating PPI's solid wastes as a waste management strategy facilitating energy recovery

Plant	Year	Fuel	Capacity
Cartiere Burgo Verzuolo, **Italy**	2001	• PPMS • wood waste	27 MWth 29 tonne/h steam 86 bar @ 490ºC
Jamsankosken Voima Oy, **Finland**	2002	• PPMS • wood waste • bark • oil	185 MWth 252 tonne/h steam 107 bar @ 535ºC
Katrinefors, Kraftvarme, **Sweden**	2002	• PPMS • wood waste & residues	36 MWth 47 tonne/h steam 80 bar @ 480ºC
Elektrocieplowni Ostroleka, **Poland**	1997	• PPMS • wood waste • bark	35 MWth 47 tonne/h steam 40 bar @ 450ºC

Figure 20 Showing examples of in the incineration of solid wastes in PPI's as a form of energy recovery

Adapted from (APRIL, 2006; Bird & Talberth, 2008; International, 2006)

2. Wastes generated in Boise Mills located in Idaho, utilize solid wastes to make composts, cement additives and roofing shingles. Dewatered PPMS taken from wastewater treatment was incinerated as an alternate source of energy in producing steam (Boise, 2006).

3. Catalyst Paper which is found in British Columbia and operates 5 mills, in 2006 diverted 31 000 tonnes of residual wastes from landfills by sending it to customers that utilized this as a growing medium for plants and grasses (Catalyst, 2006).

4. The Metsallito Group, a Finnish company operating many mills, utilized ash from incinerating PPMS was composted and used as a soil improvement conditioner (Metsalitto Group, 2006).

5. Neenah Papers, operating many mills in the USA and Mexico, at the Wisconsin mills has approximately 5000 tons of PPMS converted to steam, glass aggregates and electricity annually with the primary objective being landfill diversion. Neenah Papers then purchases back the steam that is used during manufacturing processes. The "green steam" reduced consumption of natural gas by 80% annually (Neenah, 2006).

6. Nippon Paper Group, a Japanese paper manufacturer found heavy metals in PPMS ash unable to meet environmental standards, the Kushiro Mill, a subsidiary of Nippon Paper Group developed hydrothermal solidification equipment that crystallises sealing in heavy metals present in the ashes. The products are lightweight, porous with good drainage properties, and is used as a soil improvement agent (Nippon Paper Group, 2006).

7. The Nippon Paper Group successfully used PPMS ash during its roadbed construction

8. The Norske Skog (Norweigan Forest Industries) recently built modernised mills utilising wastes generated such as PPMS and other organic wastes as biofuels in thermal energy production (Norkse, 2006).

9. Stora Enso, at the newly built Hylte mill found in Helsinki, combusts PPMS at its recently developed biofuel boiler (Stora Enso, 2006).

9.3 Discussion: Achieving Circularity Via Alternate Pathways Within PPI's, the True Potential May be Limited to the Global North

Even though PPI solid wastes were successfully utilised in alternate end of life pathways, a common factor being the locations are all found within the global north, and all countries where such pathways were taken are of developed first world nations.

Third world developing countries facing the brunt of ramifications arising from inadequate and reckless waste management practices, are becoming more vulnerable to effects such as polluted water bodies and harmful toxic emissions. Much of the populations living in these countries many of which face extreme poverty, are dependent on water bodies as a source of water and food, as fish caught provide their protein intake.

If such waste management practices and techniques are passed over at an institutional level from developed nations to developing nations, it will facilitate the transition towards a circular economic model in these developing nations to a much larger extent allowing for greater degrees of sustainability within PPI's as well as in daily waste management of municipal solid wastes.

Mitigation strategies would include the characterisation of waste streams in order to correctly determine the best possible alternate pathways facilitating adding value to these waste streams while aiming for greater levels of sustainability within the PPI's. Characterisation of waste streams allow for the relative value of various waste stream illustrating the most efficient pathway. Some waste streams allow for easy materials recovery, and others prove difficult with high costs associated. The materials characteristics determines the best alternate pathway it could follow

PHASE 3: CONCLUSION AND RECOMMENDATIONS

10. Conclusion

The potential in sustainable waste management can be regarded as a solution to the many social, economic and environmental issues facing South Africa. Processes within PPI's should align themselves with an industrial-ecological approach which is part of modern sustainable management. PPI's generate large quantities of wastes presenting burdens on the environment. Efficiently managing these wastes is crucial in PPI's in ensuring sustainability within this industry. Although in recent times, many innovative alternate pathways have been successfully explored, the market demands were too small to successfully divert PPMS from landfilling.

Such alternate pathways are relevant to South Africa. In the face of climate change with increased frequencies of flood and drought regimes, the effects on soils can be mitigated by improving their structure making it less vulnerable to losses resulting from wind and water, and conserving soil as a resource, indirectly protecting water bodies from negative effects of siltation.

Another major problem effecting South Africa's energy demands which cannot be met by ESKOM due to insufficient power generational capacities. Recent changes to the legislation permitted independent power producers to operate and supply electricity to the national grid of up to 100MW, and was previously capped at 1MW. This results in an increased potential of alternate energy sources in producing clean energy. The decentralisation of power generation infrastructures away from ESKOM and our dependence on coal would allow for smaller power generational infrastructures of increased sustainability and efficiencies.

Such alternate pathways will socially uplift poverty-stricken communities surrounding mills via job creation, therefore, such pathways will ensure environmental, social and economic sustainability, whilst allowing a significant fraction of waste streams utilised in energy and materials recovery, simultaneously conserving the environment in the face of climate uncertainty.

In fulfilling aims and objectives set out:

1. Determine the types of solid wastes generated in PPI's through;

- Processing different resources

- Different manufacturing processes employed119

This was fulfilled in the initial parts of the literature review. Fibres utilised in PPI's can be of virgin fibres, recycled fibres and the use of non-wood fibres. The type of fibres processed directly affects solid wastes generated as virgin fibres generate greater amounts of organic wastes and recycled fibres generate greater inorganic wastes. The manufacturing process employed also directly affects solid wastes generated. Three distinct types of processes analysed were mechanical, thermos-mechanical and chemical pulping. Costs associated, yields, solid wastes generated and environmental impacts differed significantly between these processes.

2. Characterize solid waste streams

This was fulfilled during chapter 1.6 of the literature review. Solid waste streams analysed were primary, biological and deinking PPMS, fines, rejects and ash. Chemical composition between primary, biological and deinking PPMS differed significantly and resultant of the source of fibre and manufacturing processes employed.

3. Determine viable alternate pathways towards efficient and effective valorisation of solid wastes generated in efforts to mitigate;

• Increased demands on limited renewable natural resources

• Effects of greenhouse gas emissions and climate change at an accelerated rate, specifically the ENSO system prevalent in South Africa

• Divert wastes from landfilling allowing for the conservation of landfill air space

This was fulfilled during phase 2, chapters 3 to 5, utilising PPMS through; composting and use as a soil amendment, palletising into an energy pellet and anaerobic digestion. These viable alternate pathways were optimised allowing for greater efficiencies. These alternate pathways facilitate landfill diversion through valorising solid wastes into value added products. These products alleviate demands placed on limited natural resources and provide a proactive approach towards reducing and mitigating the effects of climate change.

4. Explore alternate end of life pathways for solid wastes generated in PPI's

This was fulfilled during chapter 6 and based on the characterisation of PPMS, alternate end of life pathways explored was determined by the applicability of PPMS to such pathways. These pathways are not viable currently due to limitations imposed by these alternatives to PPMS such as dewatering to required levels and separating solid waste streams.120

5. Using the WROSE Model to determine scenarios in valorising of PPI solid wastes

This was fulfilled during phase 4 of this thesis. In transitioning from a linear economic model towards a circular economic model with solid wastes now subjected to alternate pathways, the WROSE model was used to indicate potential pathways the different waste fractions could take. Scenario 4 and 5 were selected as the most sustainably applicable pathways for PPI solid wastes with the major difference between them being the biogenic fraction is anaerobically digested in scenario 4 and composted in scenario 5.

11. Recommendations for Future Work

Sustainably managing different the different types of PPI’s and the unique processes and technologies employed should adopt an industrial-ecological approach, which is a crucial component of the eco-symbiosis theory. PPI’s produce huge quantities of solid wastes presenting burdens to the environment. Appropriate waste management is crucial for the sustainability of PPI’s. In the past two decades, many innovative approaches to valorise PPMS into value added products have been investigated, but small market demands limited the viability of many of the potential products, subsequently limiting the amounts of PPMS that could successfully be diverted from landfills. An area of great potential in the effective waste management of PPI’s waste products would be in anaerobic digestion, although there is still much research required on the digestion and co-digestion of PPMS before such a practice would prove viable.

Another area with high potential to safely process wastes deemed hazardous due to their heavy metal concentrations would be in vermicomposting. Many studies have been completed with positive results on the abilities of earthworms in safely reducing heavy metals found in sludge. Apart from safely reducing heavy metals, other benefits posed by vermicomposting is that these earthworms can thereafter be processed and utilised as an alternate source of protein.

Another important factor directly affecting this research has been the covid-19 pandemic which has altered and changed the lives of the global population. It has caused a transition towards a paperless society in many instances, although the demand may have decreased for paper related products, there has been an exponential surge in the demands placed on sanitary and personal protective products such as face masks.

A limitation facing many pathways is an efficient and viable pre-treatment method in dewatering. Although there are many applicable pathways for PPMS, a common bottleneck is dewatering PPMS to required levels of moisture contents. Development of viable dewatering methods will facilitate optimising PPI solid waste streams in a broader range of alternate pathways, simultaneously reducing demands placed on natural resources. This illustrates the potential of PPI’s to produce zero-wastes as it transitions towards a circular economic model. In order to achieve the maximum value, the greatest recycling efforts must be made.

12. References

Abd el Sayed, E., El-Sakhawy, M., & Sarhaway, E. (2020). Non-wood fibers as raw material for pulp and paper industry. *Nordic Pulp and Paper Research Journal*, *35*, 215-230. https://doi.org/10.1515/npprj-2019-0064

Abdullah, R., Ishak, C., Kadir, W., & Abu Bakar, R. (2015). Characterisation and feasaility assessment of recycled paper mill sludge to arable land in relation to the environment *Int J Environ Health*, 9314-9339.

Abu Bakar, R., Abbdullah, R., & Ishak, C. (2015). Characterisation and Feasability Assesment of Recycled Paper Mill Sludges for Land Application in Relation to the Environment *Int J Environ Res. and Public Health*, *12*, 9314-9329. https://doi.org/10.3390/ijerph120809314

Ackerman, S., Reitz, D., & Titshall, L. (2017). *Mapping the South African pulpwood supply chain*. Precision Forestry Symposium https://www.sun.ac.za/afrikaans/faculty/agri/forestry/Documents/Simon%20Ackerman.pdf

Adu, C., Berglund, L., Oksman, K.., Jolly, M., & Zhu, C. (2018). Properties of cellulose nanofibre networks prepared from never-dried and dried paper

mill sludge. *Journal of Cleaner Production*, *197*, 765-771. https://doi.org/10.1016/j.jelepro.2018.06.263

Ahmad, I., Lee, M. S., Goo, H. K., & Kim, C. H. (2021). Fuel pellets from fine paper mill sludge supplemented by sawdust and by recovered lubricating oil. *Bioresources*, *16*, 1144-1160.

Ahmad, S., Malik, M., Bashir, W., & Ahmad, R. (2013). Study of concrete involving use of waste paper sludge ash as partial replacement of cement. *IOSR J Eng*, *3*, 6-15.

Aitken, M. N., Evans, B., & Lewis, J. G. (1998). Effect of applying paper mill sludge to arable land on soil fertillity and crop yields. *Soil Use and Management*, *14*, 215-222.

Anderson, R., & Halan, P. (1995). State of the art effluent treatment for a Scandinavian pulp and paper mill. *International Environmental Conference Preceedings*, 645.

Andreae, O. M. (2019). Emission of trace gases and aerosols from biomass burning – an updated assessment. *Atmos. Chem. Phys*, *19*, 8523-8546.

Andreola, F., Barbieri, L., Lancellotti, I., & Pozzi, P. (2005). Recycling industrial waste in brick manufacture. *Mater Const*, *55*, 5-16.

Antal, M., Allen, S., Schulman, D., & Xu, X. (2000). Biomass Gasification in Supercritical Water†. *Industrial & Engineering Chemistry Research - IND ENG CHEM RES*, *39*. https://doi.org/10.1021/ie0003436

Antons, A., Cirule, D., Verovkins, A., & Kuka, E. (2018). EFFECT OF THERMAL TREATMENT ON PHYSICAL AND MECHANICAL PROPERTIES OF BIRCH AND PINE WOOD. *RESEARCH FOR RURAL DEVELOPMENT*, *1*, 78-85. https://doi.org/10.22616/rrd.24.2018.012

APRIL, I. (2006). *Sustainability Report* www.corporateregister.com.

Arshiya, C., Aravind, G., Gandhi, S. S., Arokiyaraj, A., Saufishan, T., & Harimuthiah, S. (2020). An Overview on Pulp and Paper Manufacturing

Process and its Waste Treatment. *Int. Jour. Scientific and Engineering Research* *11*(10), 1060-1064.

Ávila-Pozo, P., Parrado, J., Caballero, P., Díaz-López, M., Bastida, F., & Tejada, M. (2021). Use of Slaughterhouse Sludge in the Bioremediation of an Oxyfluorfen-Polluted Soil. *International Journal of Environmental Research*, *15*(4), 723-731. https://doi.org/10.1007/s41742-021-00351-z

Bajpai, P. (2015). Basic Overview of Pulp and Paper Manufacturing Processes In *Green Chemistry and Sustainability in Pulp and Paper Industry* (pp. 34). https://doi.org/10.1007/978-3-319-18744-0_2

Bajpai, P. (2017). *Pulp and Paper Industry: Emerging Waste Water Treatment Technologies*. Elsevier Science. https://books.google.co.za/books?id=d27fDQAAQBAJ

Bajpai, P. (2018). *Biermann's Handbook of Pulp and Paper: Volume 1: Raw Material and Pulp Making*. Elsevier Science. https://books.google.co.za/books?id=oqrMtAEACAAJ

Bajpai, P., Kondo, P., & Ryuichiro, L. (1999). Management of Wastewater Treatment Sludges. In P. Bajpai, P. K. Bajpai, & R. Kondo (Eds.), *Biotechnology for Environmental Protection in the Pulp and Paper Industry* (pp. 209-238). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-60136-1_10

Bayr, J., Kaparaju, S., & Rintala, P. (2013). Screening pretreatment methods to enhance thermophilic anaerobic digestion of pulp and paper mill wastewater treatment secondary sludge. *Chemical Engineering Journal*, *223*, 479–486. https://doi.org/10.1016/j.cej.2013.02.119

Bayr, S., & Rintaka, J. (2012). Thermophillic anaerobic digestion of pulp and paper mill primary sludge and co-digestion of primary and secondary sludge *Water Res*, *46*, 4713 -4720.

Bayr, S., Rintaka, J., & Kaparaju, P. (2013). Screening pretreatment methods to enhance thermophillic anaerobic digestion of pulp and paper mill wastewater secondary treatment sludge. *Chem Eng J*, *223*, 479-489.

Becker, J., & Wittmann, C. (2019). A field of dreams: Lignin valorization into chemicals, materials, fuels, and health-care products. *Biotechnology Advances*, *37*. https://doi.org/10.1016/j.biotechadv.2019.02.016

Bhojvaid, R. (2004). Paper Raw Materials and Technology *PAPERMAKING*, 701-707.

Bird, M., & Talberth, J. (2008). *Waste Stream Reduction and Reuse in the Pulp and Paper Sector*

Bischoff-Matson, D., Maree, Z., Vogel, G., Lynch, C., Olivier, A., & Terblanche, D. (2020). Shape of a water crisis: Practitioner perspectives on urban water scarcity and 'Day Zero' in South Africa. *Water Policy*, *22*. https://doi.org/10.2166/wp.2020.233

Blanco, A., Negro, C., Monte, M. C., & Tijero, J. (2004). The Challenges of Sustainable Papermaking *Environmental Science and Technology 38*, 141-420. https://www.researchgate.net/publication/8152893_The_challenges_of_sustainable_papermaking

Blawaik, S. A., & Raut, S. P. (2011). Utilization of waste paper pulp by partial replacement of cement in concrete *Int J Eng Res Appl 1*, 300-309. http://ijera.com/pages/v1no2.html

Boise. (2006). *Delivering on our Commitments: 2005-2006 Sustainability Report* www.corporateregister.com.

Boonstra, M. J., Van Acker, J., & Tjeerdsma, B. (2007). Strength properties of thermally modified softwoods and its relation to polymeric structural wood

constituents. *Ann. For. Sci.*, *64*, 679-690. https://doi.org/10.1051/forest:2007048
Bridgman, P. (2013). The Phase Diagram of Water to 45,000 kg/cm2. In *Volume V Collected Experimental Papers, Volume V* (pp. 3200-3202). Harvard University Press. https://doi.org/doi:10.4159/harvard.9780674287785.c27
Callejas, C., Bovio, P., Fernandez, A., Passegi, M., Etchebehere, C., & Borzacconi, L. (2013). Changes in microbial community in two full scale methanogenic UASB for dairy wastewater in different feeding operation modes. World Congress on Anaerobic Digestion Santiago de Compostela, Spain
Calvo, L., García, A., & Otero, M. (2013). An Experimental Investigation of Sewage Sludge Gasification in a Fluidized Bed Reactor. *The Scientific World Journal*, *2013*, 479403. https://doi.org/10.1155/2013/479403
[Record #143 is using a reference type undefined in this output style.]
Catalyst, P. (2006). *Fresh Thinking on Paper: Sustainability Report* www.corporateregister.com.
Cavaleri, A., & Contu, J. (2011). *Process for manufacturing insulating material* EP 2389479 A2).
Chaouch, M., Petrisanns, M., Petrisanns, A., & Gerardin, P. (2010). Use of wood elemental composition to predict heat treatment intensity and decay resistance of different softwood and hardwood species *Polymer Degradation and Stability 95*, 2255-2259.
Chen, C., Duan, C., Liu, Y., Ma, X., Zheng, L., Stavik, J., & Ni, Y. (2016). Cellulose (dissolving pulp) manufacturing processes and properties: A mini-review. *BioRes*, *11*, 5553-5564. https://bioresources.cnr.ncsu.edu/resources/cellulose-dissolving-pulp-manufacturing-processes-and-properties-a-mini-review/
Chen, L., Chien, C., Chu, C. P., Lee, D., Hsieh, K., Lee, C., & Liu, J. (2002). Conditioning and dewatering of pulp and paper sludge. *Drying Technology - DRY TECHNOL*, *20*, 967-988. https://doi.org/10.1081/DRT-120003772
Chiang, K. Y., Lu, C. H., Lin, M. H., & Chien, K. L. (2013). Reducing tar yield in gasification of paper-reject sludge by using a hot-gas cleaning system. *Energy*, *50*, 47–53. https://doi.org/10.1016/j.energy.2012.12.010
Chiang, R., Kung-Yuh, L., Cheng-Han, L., & Chun-Kai, G. (2016). Characteristics of hydrogen energy yield by co-gasified of sewage sludge and paper-mill sludge in a commercial scale plant. *International Journal of Hydrogen Energy*, *41*. https://doi.org/10.1016/j.ijhydene.2016.06.199
Chun, Y. M. (2002). *Investigation on the use of pulp and paper mill residual solids in producing durable concrete* University of Wisconsin-Milwaukee]. Wisconsin-Milwaukee.
Chun, Y. M., & Naik, T. R. (2004). Repulping fibrous residuals from pulp and paper mills for recycling in concrete. *TAPPI J 3*, 7-12.
Chung, J., Lee, M., Ahn, J., Bae, W., Lee, Y., & Shim, H. (2009). Effects of operational conditions on sludge degradation and organic acids formation in low-critical wet air oxidation. *J Hazard Mater*, *162*(1), 10-16. https://doi.org/10.1016/j.jhazmat.2008.05.038
Cote, W. A. (1968). *Chemical Composition of Wood* (B. Springer, Heidelberg Ed.) https://doi.org/doi.org/10.1007/978-3-642-87928-9_2
Crain, N., Shanableh, A., & Gloyna, E. (2000). Supercritical water oxidation of sludges contaminated with toxic organic chemicals. *Water Science & Technology*, *42*, 363-368. https://doi.org/10.2166/wst.2000.0589

Czernik, S., & Bridgwater, T. (2004). Overview of Applications of Biomass Fast Pyrolysis Oil. *Energy*, *18*, 590. https://doi.org/10.1021/ef034067u

Das, T., & Houtman, C. (2004). Evaluating chemical-, mechanical-, and bio-pulping processes and their sustainability characterization using life cycle assessment. *Environmental Progress*, *23*, 345-357.

Davis, E., Shaler, S., & Goodell, B. (2003). The incorporation of paper deinking sludge into fiberboard. *Prod J 53*

(12), 46-54.

De Vrieze, J., Verstraete, W., & Boon, N. (2013). Repeated pulse feeding induces functional stability in anaerobic digestion. *Microb. Biotech*, *6*, 414-424.

Debellefontane, J. F., H. (2000). Wet air oxidation for the treatment of industrial wastes. Chemical aspects, reactor design and industrial applications in Europe. *Waste Management*, *20*(1), 15-25. https://doi.org/https://doi.org/10.1016/S0956-053X(99)00306-2

Department of Agriculture, F. a. F. (2016). *A Profile of the South African Forestry Value Chain* https://www.nda.agric.za/doaDev/sideMenu/Marketing/Annual%20Publications/Commodity%20Profiles/field%20crops/Forestry%20Market%20Value%20Chain%20Profile%202016.pdf

Desmond, P., & Asamba, M. (2019). Accelerating the Transition to a Circular Economy in Africa - case studies from Kenya

and South Africa. In P. Desmond (Ed.), (pp. 1-19). https://doi.org/10.4324/9780429434006-9

Devi, P. (2013). Effect Of Temperature On Biochar Properties During Paper Mill Sludge Pyrolysis. *International Journal of ChemTech Research*, *5*, 682-687.

Deviatkin, I. (2013). *Wastewater Treatment and Deinking Sludge Utilization Possibilities for Energy and Material Recovery in the Leningrad Region*

Dlamini, S., Simatele, M., & Kubanza, S. (2018). Municipal solid waste management in South Africa: from waste to energy recovery through waste-to-energy technologies in Johannesburg. *Local Environment*, *24*, 1-9. https://doi.org/10.1080/13549839.2018.1561656

Donkor, K. O. (2019). *Paper industry process wastewater reclamation and potential clarification from paper sludge through integrated bio-energy production* University of Stellenbosch]. Stellenbosch hdl.handle.net/10019.1/105992

Dorica, J., & Simandl, G. (1995). Separation of fiber and ash in deinking effluents — a case study. *TAPPI J*, *78*, 109-116

Douyong, J., Hasan, C., Chang, V., & Hou-Min, C. (2012). EFFECT OF LIGNIN ON ENZYMATIC SACCHARIFICATION OF HARDWOOD AFTER GREEN LIQUOR AND SULFURIC ACID PRETREATMENTS [Fermentable sugar; Hardwood; Green liquor; Pretreatment; Enzymatic hydrolysis]. *2012*, *7*(2), 12. https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_07_2_2272_Min_JCC_Lignin_Enzymatic_Sacchar_HW_Green_Liquor

Dufresne, R., & Blum, M. (2001). Anaerobic treatment of condensates: trial at a kraft pulp and paper mill. *Water Environ Res*, *73*, 103-109.

Durai-Swamy, K., Mansour, M., & Warren, D. (1991). Indirect steam gasification of paper mill sludge waste. *TAPPI*, *74*. https://www.osti.gov/biblio/7103110-indirect-steam-gasification-paper-mill-sludge-waste

Durai-Swamy, K., Warren, D., & Mansour, M. (1991). Indirect steam gasification of paper mill sludge waste. *Tappi; (United States)*, *74:10*, Medium: X; Size: Pages: 137-143 2009-2012-2017. https://www.osti.gov/biblio/7103110

Durigan, M., Cherubin, M., DeCamargo, P., Fereirra, J., Berenguer, E., Barlow, J., Signor, D., Cerri, C., & Gardner, T. A. (2017). Soil organic matter responses to anthropogenic forest disturbance and land use change in the Eastern Brazillian Amazon. *Sustainability*, *379*, 1-16. https://doi.org/10.3390/su9030379

Ecofys. (2009). *Methodology for the free allocation of emission allowances in the EU ETS post 2012: Sector report for the pulp and paper industry*

Eis, B. F., Ferguson, J., & Benjamin, M. (1983). The fate and effect of bisulphate in anaerobic treatment *J Water Pollut Control Fed*, *55*, 1355-1365.

Elliot, A., & Mahmood, T. (2005). Survey benchmarks generation, managementy of solid residues *Pulp Pap*, *79*, 49-55.

Elliot, A., & Mahmood, T. (2007). Pretreatment technologies for advancing anaerobic digestion of pulp and paper biotreatment residues. *Water Res*, *41*, 4273-4286.

Elliott, A., & Mahmood, T. (2007). Pretreatment technologies for advancing anaerobic digestion of pulp and paper biotreatment residues. *Water Res*, *41*(19), 4273-4286. https://doi.org/10.1016/j.watres.2007.06.017

Environmental Paper Network. (2018). *The state of the global paper industry*

Eroglu, V., & Saatci, A. (1993). Reuse of sludge from pulp and paper industry pilot and full-scale applications. *Water Sci Tech*, *28*, 17-26.

Ferguson, J., Luonsi, A., & Ritter, D. (1990). Sequential anaerobic/aerobic biological treatment of bleaching wastewaters *TAPPI Environmental Conference Proceedings*, 333-338.

Fiorenza, S., & Ward, C. (1997). Microbial adaptation of aromatic hydrocarbons. *J Ind. Microbiol. Biotech*, *18*, 140-151.

Fytili, D., & Zabaniotou, A. (2008). Utilization of sewage sludge in EU application of old and new methods—A review. *Renewable and Sustainable Energy Reviews*, *12*(1), 116-140. https://doi.org/https://doi.org/10.1016/j.rser.2006.05.014

Galić, J., Stajić, M., Vukojević, M., & Ćilerdžić, J. (2021). Obtaining Cellulose-Available Raw Materials by Pretreatment of Common Agro-Forestry Residues With Pleurotus spp [Original Research]. *Frontiers in Bioengineering and Biotechnology*, *9*(881). https://doi.org/10.3389/fbioe.2021.720473

Gavrilescu, D., Puitel, A., Dutuc, G., & Craciun, G. (2012). ENVIRONMENTAL IMPACT OF PULP AND PAPER MILLS. *Environmental Engineering and Management Journal*, *11*, 82-88. https://doi.org/DOI: 10.30638/eemj.2012.012

Geng, X., Deng, J., & Zhang, S. Y. (2007). Characteristics of paper mill sludge and its utilization for the manufacture of medium density fiberboard. *Wood Fiber Sci*, *39*, 345-351.

Ghinea, C., Petraru, M., Simion, I. M. S., D. , & Bresser, A. (2014). LIFE CYCLE ASSESSMENT OF WASTE MANAGEMENT AND RECYCLED PAPER SYSTEMS. *Environmental Engineering and Management Journal 13*, 1-13.

Ghribi, M., Medeb-Mouelhi, F., & Beauregard, M. (2016). Microbial diversity in various types of paper mill sludge: identification of enzyme activities with potential industrial applications. *SpringerPlus*, *5*(1). https://doi.org/10.1186/s40064-016-3147-8

Gibril, M. E., Lekha, P., Andrew, J., & Sithole, B. (2018). Beneficiation of pulp and paper mill sludge: production

and characterisation of functionalised crystalline nanocellulose
Clean Technologies and Environmental Policy, 2-13. https://doi.org/doi.org/10.1007/s10098-018-1578-3
Glenn, J. (1997). Paper mill sludge: feedstock for tomorrow. *Biocycle*, *38*, 30-35.
Godfrey, L., & Oelofse, S. (2017). Historical Review of Waste Management and Recycling in South Africa. *Resources*, *6*, 57. https://doi.org/10.3390/resources6040057
Gore, W. (1986). Energy and charcoal production from solid waste generated in the South African paper industry *South African Forestry Journal*, 1-9.
Goroyias, G., Elias, R., & Fan, M. (2004). Research into using recycled waste paper residues in construction products. *The Waste and Resources Action Programme*, 1-185.
Granström, K., & Montelius, J. (2014). Pre-treatment to Enhance Biogas Yield from Pulp and Paper Mill Sludge. *8*, 825-833.
Greenberg, S., Aliber, M., Chikazunga, D., Luow, A., Khumalo, L., Nkomo, M., Davis, N., Armour, J., Lewis, M., & Cousins, B. (2013, January 2013). *Smallholders and agro-food value chains in South Africa:*
Emerging practices, emerging challenges. Faculty of Economic and Management Sciences. ISBN: 978-0-86808-741-2
Habets, L. D., W. (2007). Anaerobic treatment of pulp and paper mill effluents - status quo and new developments. *Water Sci Tech*, *55*, 223-230.
Hagelqvist, A. (2013). batchwise mesophillic anaerobic co-digestion of secondary sludge from pulp and paper industry and municipal sewage sludge. *Waste Manag*, *33*, 820-824.
Hall, E. R. C., L.A. (1985). Anaerobic treatability of Canadian pulp and paper mill wastewaters *Pulp Pap Can*, *89*, 100-104.
Hao-an, L., Wei, G., Ruo-nan, L., & Shao-wen, H. (2020). Aggregate asspcoiated changes in nutrient propeties, microbial community and functions in a greenhouse vegetable field based om an eight year fertillisation experiment in China. *Journal of Integrative Agriculture 19*(10), 2530-2549.
Harkin, J. M. (1982). Wise use of Wisconsin's papermill sludge. In: Rock CA. Long range disposal alternatives for pulp and paper sludges, University of Maine.
Hartong, B., Abu-Daabes, M., le, T., Saidan, M., & Banerjee, S. (2007). Sludge dewatering with cyclodextrins. *Water research*, *41*, 1201-1206. https://doi.org/10.1016/j.watres.2006.12.011
Heidary, R. (2017). Effect of Temperature on Hydrothermal Gasification of Paper Mill Waste, Case Study: The Paper mill in North of Iran. *Journal of Environmental Studies*, *43*(1), 59-71. https://doi.org/10.22059/jes.2017.62061
Hii, N., Baroutian, K., Parthasarathy, S., Gapes, R., & Eshtiaghi, D. (2014). A review of wet air oxidation and Thermal Hydrolysis technologies in sludge treatment. *Bioresource technology*, *155*, 289-299. https://doi.org/https://doi.org/10.1016/j.biortech.2013.12.066
Hovey, G. R. (2016). *Drying Characteristics of Biosludge from Pulp and Paper*
Mills University of Toronto]. Toronto. https://tspace.library.utoronto.ca/bitstream/1807/72725/2/Hovey_Geanna_R_201606_MAS_thesis.pdf
Howard, J., McKeever, D., & Bilek, E. (2016). Total and per capita consumption of wood and wood products in roundwood equivelants *United States Department of Agriculture*, 28.

Hubbe, M., & Grigsby, W. (2019). From Nanocellulose to Wood Particles: A Review of Particle Size vs. the Properties of Plastic Composites Reinforced with Cellulose-based Entities [Wood-plastic composites; Cellulose-based reinforcements; Size of filler particles; Nanocomposites; Tensile strength and modulus]. *2019*, *15*(1), 52. https://ojs.cnr.ncsu.edu/index.php/BioRes/article/view/BioRes_15_1_Review_Hubbe_Grigsby_Nanocellulose_Wood_Particles

International, P. (2006). *2004-2006 Sustainability Update. An International Paper Journal* www.corporateregister.com.

Jackson, M. J., & Line, M. A. (1997). Windrow composting of pulp and paper mill sludge: Process performance and assessment of product quality. *Compost Sci*, *5*, 6-14.

Jansen, A. (2012). Aspects of the Economics of Water Management in Urban Settings in South Africa, with a focus on Cape Town.

Jesis, A. D., & Alda, O. G. (2008). Feasibility of recycling pulp and paper mill sludge in the paper and board industries. *Resour Conserv Recycl 52*, 965-972.

Johns, C. (2015). Soil structure and the physical fertillity of soil. *Soil Sci*, 1-13.

Johnston, J., Milestone, C., Northcote, P., & Wiseman, N. (2000). The alkaline digestion of reject fibre in deinking sludge as a precursor to filler recovery by wet air oxidation. *Appita J*, *53*, 54-58.

Jokela, J., RIntala, J., Oikari, A., Reinikainen, O., & Mutka, K. (1997). Aerobic composting and anerobic digestion of pulp and paper mill sludges *Wat Sci Tech*, *36*, 181-188.

Kahmark, K., & Unwin, J. (1996). Pulp and Paper Effluent Management. *Water Environment Research*, *68*(4), 551-564. http://www.jstor.org/stable/25044757

Karam, G., & Gibson, L. (1994). Evaluation of commercial wood-cement composites for sandwich-panel facing. *J Mater Civ Eng*, *6*, 100-116.

Karchiyappan, S., & Venkatachalam, T. (2015). Enzymatic catalysis treatment method of meat industry wastewater using lacasse. *Journal of Environmental Health Science and Engineering*, *13*. https://doi.org/10.1186/s40201-015-0239-2

Kaur, R., Tyagi, R. D., & Zhang, X. (2020). Review on pulp and paper activated sludge pretreatment, inhibitory effects and detoxification strategies for biovalorization. *Environ Res*, *182*, 109094. https://doi.org/10.1016/j.envres.2019.109094

Kemner, J. E., & Adams, M. B. M., L.M. Peterjohn, W.T. Kelly, C.N. (2021). Fertillisation and Tree Species Influence on Stable Aggregates in Forest Soils. *Forests*, *12*, 1-19. https://doi.org/10.3390/f12010039

Kimura, K., Miyazawa, T., Nishikawa, T., Kado, J., Okumura, S., Miyao, K., Naito, T., Kunimori, S., & Tomishige, K. (2006). Development of Ni catalysts for tar removal by steam gasification of biomass. *Applied Catalysis B: Environmental*, *68*, 160-170. https://doi.org/10.1016/j.apcatb.2006.08.007

Koster, I., & Cramer, A. (1987). Inhibition of methanogenesis from acetate sludge by long chain fatty acids. *Appl Environ Microbiol*, *53*, 403-409.

Kubanza, S., & Simatele, M. (2019). Sustainable solid waste management in developing countries: a study of institutional strengthening for solid waste management in Johannesburg, South Africa. *Journal of Environmental Planning and Management*, *63*, 1-14. https://doi.org/10.1080/09640568.2019.1576510

Kujala, A. (2012). *Papermaking sludges and possibilities of utilization as material* Lappeenrata University of Technology].
Kullavanijaya, R. W., C. . (2013). Anaerobic digestion and biomethanation of glycerol distilled residue in anerobic hybrid reactor: microbial acclimation and performance evaluation. World congress on Anaerobic digestion, Santiago de Compostela.
Kuokkanen, M., Nurmesniemi, T., Pöykiö, H., Kujala, R., Kaakinen, K., & Kuokkanen, J. (2008). Chemical and leaching properties of paper mill sludge. *Chemical Speciation and Bioavailability*, *20*, 111-122. https://doi.org/10.3184/095422908X324480
Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, *5*, 5875-5895. https://doi.org/10.3390/su7055875
Lancaster, J., & Xu, L. (2009). *Treatment of Secondary Sludge for Energy Recovery*. https://sswm.info/sites/default/files/reference_attachments/XU%20and%20LANCASTER%20ny%20Treatment%20of%20Secondary%20Sludge%20for%20Energy%20Recovery.pdf
Larney, F., & Angers, A. (2011). The role of organic amendments in soil reclamation: A review. *Canadian Journal of Soil Science 92*, 19-38. https://doi.org/10.4141/CJSS2010-064
Latha, A., Arivukarasi, M., Subashri, R., & Vishnu-Priya, V. (2018). Paper and Pulp Industry Manufacturing and Treatment Processes -A Review. *INTERNATIONAL JOURNAL OF ENGINEERING RESEARCH & TECHNOLOGY (IJERT) PECTEAM*, *6*(2), 1-13. https://doi.org/http://dx.doi.org/10.17577/IJERTCON011
Lawaal, H. M. O., J.O. Uyovbisere, E.O. (2009). Changes in soil aggregate stability and carbon sequestration mediated by land use practices in a degraded dry savana alfisol. *Tropical and Subtropical Agroecosystems*, *10*, 423-429.
Li, J., Ban, Q., Zhang, L., & Jha, A. (2012). Syntrophic propionate degradation in anaerobic digestion: a review. *Int J Agric Biol*, *14*, 843-850.
Lou, Q., Wu, R., Lyu, S., & Yang, G. (2011). Energy and Resource Utilization of Deinking Sludge Pyrolysis. *Applied Energy*, *90*, 46-50. https://doi.org/10.1016/j.apenergy.2010.12.025
Luck, F. (1999). Wet air oxidation: past, present and future. *Catalysis Today*, *53*(1), 81-91. https://doi.org/https://doi.org/10.1016/S0920-5861(99)00112-1
Lundqvist, A. (2020). *FUTURE DEVELOPMENT OF BIOENERGY IN SOUTH AFRICA* Maladaren University of Sweden]. Sweden.
M. Kamali, Gameiro, T., Costa, M., & Capela, I. (2016). Anaerobic digestion of pulp and paper mill wastes - an overview of developments and improvement oppurtunities *Chem Eng J*, *298*, 162-182.
Mabee, W. E. (2001). *Study of Woody Fibre in Papermill Sludge* University of Toronto]. Toronto.
Macdonald, C. J. (2004). *Water usage in the South African pulp and paper industry* University of KwaZulu-Natal]. Durban. http://hdl.handle.net/10413/4048
Mahmood, A., & Mahmood, T. (1984). Estimation of holocellulose, alphacellulose and lignin contents of wood of some populus species growing in pakistan. *Pak. J. Bot.*, *16*, 43-48.
Makgae, M. (2011). Key Areas in Waste Management: A South African Perspective, Integrated Waste Management In S. Kumar (Ed.), *Management - Volume II* (pp. 1-16). www.intechopen.com/books/integrated-waste-management-volume-ii/key-areas-in-waste-management-

Malkocoğlu, A., & Özdemir, T. (2006). The machining properties of some hardwoods and softwoods naturally grown in Eastern Black Sea Region of Turkey. *Journal of Materials Processing Technology*, *173*(3), 315-320. https://doi.org/https://doi.org/10.1016/j.jmatprotec.2005.09.031

Marche, T., Schnitzer, M., Dinel, H., Paré, T., Schulten, T., & Facey, H. R. (2003). Chemical changes during composting of a paper mill sludge–hardwood sawdust mixture. *Geoderma*, *116*, 345-356. https://doi.org/10.1016/S0016-7061(03)00108-3

María, E. E., David, I., Raquel, M. S., Eduardo, E., Isabel, B., & Alejandro, R. (2019). Alternative Raw Materials for Pulp and Paper Production in the Concept of a Lignocellulosic Biorefinery. In. IntechOpen. https://doi.org/10.5772/intechopen.90041

Matikinca, J. P., Ziervogel, P., Enqvist, G., & Johan, P. (2020). Drought response impacts on household water use practices in Cape Town, South Africa. *Water Policy*, *22*(3), 483-500. https://doi.org/10.2166/wp.2020.169

Matinise, S., Roos, C., Oelofse, S., & Muswema, A. (2018, 2018-10). "Implementing the waste hierarchy" -Assessing recycling potential of restaurant waste.

Matus, M., Krizan, P., Soos, L., & Beniak, J. (2018). The effect of paperkaing sludge as an additive to biomass pelletson the final quality of the fuel. *Fuel*, *219*, 1-9.

McCallum, C. S., Wang, W., Doran, J., Forsythe, D., Garrett, M., Hardacre, C., Leahy, J., Morgan, K., Dong-Soo, S., & Sheldrake, G. (2021). Life cycle thinking case study for catalytic wet air oxidation of lignin in bamboo biomass for vanillin production. *Green Chemistry*, *23*(4), 1847-1860. https://doi.org/10.1039/d0gc03685d

McDonald, R., Green, P., Balk, D., Fekete, B., Revenga, C., Todd, M., & Montgomery, M. (2011). Urban Growth, Climate Change, and Freshwater Availability. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 6312-6317. https://doi.org/10.1073/pnas.1011615108

Metsalitto Group. (2006). *Corporate Responsibility Report* www.metsalitto.com

Meyer, T., Amin, P., Allen, D., & Tran, H. (2018). Dewatering of pulp and paper mill biosludge and primary sludge. *Journal of Environmental Chemical Engineering*, *6*. https://doi.org/10.1016/j.jece.2018.09.037

Meyer, T., & Edwards, E. A. (2014). Anaerobic digestion of pulp and paper mill wastewater and sludge *Wat Res*, *65*, 321-349.

Millet, M. A., Baker, A. J., & Satter,.N. Dinius, D.A. (1973). Pulp and paper making residues as feedstuffs for ruminants. *J Animal Sci*, *37*, 599-607.

Mokebe, K. D. (2008). *Life Cycle Assessment (LCA) technique as a holistic tool for environmental impact and economic analysis of a co-pulping process* University of Pretoria]. Pretoria. hdl.handle.net/2263/28144

Molino, A., Chianese, S., & Musmarra, D. (2015). Biomass gasification technology: The state of the art overview. *Journal of Energy Chemistry*, *25*. https://doi.org/10.1016/j.jechem.2015.11.005

Monte, M. C., Fuente, E., Blanco, A., & Negro, C. (2009). Waste management from pulp and paper production in the European Union. *Waste Management*, *29*(1), 293-308. https://doi.org/10.1016/j.wasman.2008.02.002

Monteiro Nunes, S., Paterson, N., Dugwell, D. R., & Kandiyoti, R. (2007). Tar Formation and Destruction in a Simulated Downdraft, Fixed-Bed Gasifier: Reactor Design and Initial Results. *Energy & Fuels*, *21*(5), 3028-3035. https://doi.org/10.1021/ef070137b

Moo-Young, H. K. (1998, 2-5 June 1998). Overview of the use of paper clay in landfill construction in the northeastern USA. Second international workshop on the use of paper industry sludges in environmental geotechnology and construction,

Moo-Young, H.. . (1996). Geotechnical properties of paper mill sludges for use in landfill covers. *J Geotech Eng*, *9*, 74-76.

Morozova, G., & Shargatov, A. (2001). *Raw construction mixture for production of insulating materials, its production method, and production method of insulating material out of the mixture* (Russia Patent No. 2176220).

Mountouris, D., Voutsas, A., & Tassios, E. (2008). Plasma gasification of sewage sludge: Process development and energy optimization. *Energy Conversion and Management*, *49*, 2264-2271. https://doi.org/10.1016/j.enconman.2008.01.025

Mtui, G. (2012). Lignocellulolytic enzymes from tropical fungi: Types,

substrates and applications. *Scientific Research and Essays 7*, 1544-1555. https://doi.org/ 10.5897/SRE11.1812

Naicker, J., Govinden, R., Lekha, B., & Sithole, B. (2020). Transformation of pulp and paper mill sludge (PPMS) into a glucose-rich hydrolysate using green chemistry: Assessing pretreatment methods for enhanced hydrolysis. *Journal of Environmental Management 270*, 1-11.

Nations, F. a. A. O. o. t. U. (2020). *Pulp and paper capacities 2015 - 2020*.

Navaee-Ardeh, P., Bertrand, S., & Stuart, F. (2006). Emerging Biodrying Technology for the Drying of Pulp and Paper Mixed Sludges. *Drying Technology*, *24*(7), 863-878. https://doi.org/10.1080/07373930600734026

Neckermann, E. F., Wooding, J.F., (1982). *Insulating and filler material comprising cellulose fibres and clay, and method of making from papermaking waste*.

Neenah. (2006). *Sustainability Report*. www.neenah.com

Nippon Paper Group. (2006). *Sustainability Report* www.corporateregister.com.

Norgren, R., Björkqvist, O., & Jonsson, A. (2020). Bio-sludge from the Pulp and Paper Industry as Feed for Black Soldier Fly Larvae: A Study of Critical Factors for Growth and Survival. *Waste and Biomass Valorization 11*, 5679-5685. https://doi.org/doi.org/10.1007/s12649-019-00864-x

Norkse, S. (2006). *Sustainability Report* www.norkseskog.com

Nosek, R., & Holubcik, M. J., J. Radacovska, L. (2017). Analysis of paper sludge pellets for energy utilisation. *Bioresources*, *12*, 7032-7052.

Nzihou, A., & Stanmore, B. (2013). The fate of heavy metals during combustion and gasification of contaminated biomass-a brief review. *J Hazard Mater*, *256-257*, 56-66. https://doi.org/10.1016/j.jhazmat.2013.02.050

Ochoa de Alda, J. A. G. (2008). Feasibility of recycling pulp and paper mill sludge in the paper and board industries. *Resources, Conservation and Recycling*, *52*(7), 965-972. https://doi.org/https://doi.org/10.1016/j.resconrec.2008.02.005

Otto, F., Wolski, P., Lehner, F., Tebaldi, C., VanOldenborgh, G., Hogesteeger, S., Singh, R., Holden, P., Fuckar, N., Odoulami, R., & New, M. (2018). Anthropogenic influence on the drivers of the Western Cape drought 2015–2017. *Environmental Research Letters*, *13*, 124010. https://doi.org/10.1088/1748-9326/aae9f9

Ouadi, M., Brammer, J., Kay, M., & Hornung, A. (2013). Fixed bed downdraft gasification of paper industry wastes. *Applied Energy*, *103*, 692–699. https://doi.org/10.1016/j.apenergy.2012.10.038

Pamment, N., Robinson, C., & Moo-Young, J. (1979). Pulp and paper solid wastes as substrate for SCP protein. *Biotechnol Bioeng*, *21*, 561-573.

Pandey, S., Katsaros, D., Lindfors, G., Leahy, C., Tassou, J., & Savvas, A. (2019). Fast Pyrolysis of Poultry Litter in a Bubbling Fluidised Bed Reactor: Energy and Nutrient Recovery. *Sustainability*, *11*(9), 2533. https://www.mdpi.com/2071-1050/11/9/2533

Paper Manufacturers Association of South Africa. (2019). *2019 Annual report*

Pérez, J., Muñoz-Dorado, J., de la Rubia, T., & Martínez, J. (2002). Biodegradation and biological treatments of cellulose, hemicellulose and lignin: an overview. *International Microbiology*, *5*(2), 53-63. https://doi.org/10.1007/s10123-002-0062-3

Pogue, T. (2009). The South African Wood, Paper and Pulp Sector. In (pp. 132-149).

Postel, S. (2000). ENTERING AN ERA OF WATER SCARCITY: THE CHALLENGES AHEAD. *Ecological Applications*, *10*(4), 941-948. https://doi.org/https://doi.org/10.1890/1051-0761(2000)010[0941:EAEOWS]2.0.CO;2

Poykioa, R., Watkinsc, G., & Dahlc, O. (2018). Characterization of primary and secondary wastewater treatment sludge from a pulp and board mill complex to evaluate the feasibility of utilization as a soil amendment agent and a fertilizer product. *Journal of Bioresources and Bioproducts 3*, 88-96. https://doi.org/10.21967/jbb.v3i3.174

Pradhan, A., & Mbohwa, C. (2014). Development of biofuels in South Africa: Challenges and opportunities. *Renewable and Sustainable Energy Reviews 39*, 1089-1100.

Ramiah, M. V. (1970). Thermogravimetric and differential thermal analysis of cellulose, hemicellulose, and lignin. *Journal of Applied Polymer Science*, *14*(5), 1323-1337. https://doi.org/https://doi.org/10.1002/app.1970.070140518

Rasa, K., Pennanen, T., Velmala, S., Fritze, H., Joona, J., & Uusitalo, R. (2020). Pulp and paper mill sludges decrease soil erodibility *Journal of Environmental Quality 50*, 172-191.

Rashid, M., Barry, D., & Goss, M. (2006). Paper Mill Biosolids Application to Agricultural Lands: Benefits and Environmental Concerns with Special Reference to Situation in Canada. *Soil Environ*, *25*.

Rasmeni, D., Zelda, Z., & Madyira, M. (2019). A Review of the Current Municipal Solid Waste Management Practices in Johannesburg City Townships. *Procedia Manufacturing*, *35*, 1025-1031. https://doi.org/https://doi.org/10.1016/j.promfg.2019.06.052

Reckamp, J., Garrido, J., & Satrio, R. (2014). Selective pyrolysis of paper mill sludge by using pretreatment processes to enhance the quality of bio-oil and biochar products. *Biomass and Bioenergy*, *71*, 235-244. https://doi.org/10.1016/j.biombioe.2014.10.003

Reddy, P., & Pillay, V., Singh, S. . (2005). Degradation of pulp and paper-mill effluent by thermophilic micro-organisms using batch systems. *Water SA 4*, 1-6.

Rogers, D. (1982). Conversion of waste activated sludge to animal feed. Symposium on long range disposal alternatives for pulp and paper sludges proceedings, University of Maine.

Rokainen, N., Kujala, K., & Saarela, J. (2009). Use of industrial by-products in landfill cover. twelfth international waste and landfill symposium, S. Margarita di Pula, Cagliari.

Rothwell, A., & Éclair-Heath, G. (2007). A new approach to paper mill sludge. *Waste and Resources*.

Rusten, B., Johnson, C. H., Devall, S., Davoren, D., & Cashion, B. S. (1999). Biological pretreatment of a chemical plant wastewater in high-rate moving bed biofilm reactors. *Water Science and Technology*, *39*(10-11), 257-264. https://doi.org/10.2166/wst.1999.0665

Saeed, H., Lucia, A., & Chen, H. (2017). Suitable approach using agricultural residues for pulp and paper manufacturing. *Nordic Pulp and Paper Research Journal*, *32*(4), 674-682. https://doi.org/10.3183/NPPRJ-2017-32-04-p674-682

Sandberg, D., Haller, P., & Navi, P. (2012). Thermo-hydro and thermo-hydro-mechanical wood processing: An opportunity for future environmentally friendly wood products. *Wood Material Science and Engineering 8*(1), 64-88. https://doi.org/10.1080/17480272.2012.751935

Sandberg, M., Venkatesh, G., Eskandari, S., Joseph, S., Dalgaard, T., & Mohammad, A. (2017). Environmental analysis of producing biochar and energy recovery from pulp and paper mill biosludge. *Journal of Ind. Ecology* 1-17. https://doi.org/10.1111/jiec.12838

Schmieder, H., & Abein, J. (1999). Supercritical Water Oxidation: State of the Art. *Chemical Engineering & Technology*, *22*(11), 903-908. https://doi.org/https://doi.org/10.1002/(SICI)1521-4125(199911)22:11<903::AID-CEAT903>3.0.CO;2-E

Sharma, S., Ghosh, A., Pandey, A., Avtar, R., & Mudliar, N. (2015). Wet Air Oxidation Pretreatment of Mixed Lignocellulosic Biomass to Enhance Enzymatic Convertibility. *Korean Chemical Engineering Research*, *53*, 216-223. https://doi.org/10.9713/kcer.2015.53.2.216

Sikarwar, V., Singh, P., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M. Z., Nilay, S., Anthony, E. J., & Fennell, P. S. (2016). An overview of advances in biomass gasification. *Energy & Environmental Science*, *9*(10), 2939-2977. https://doi.org/10.1039/c6ee00935b

Simpson, R. (2010). *Soil organic matter and aggregate dynamics in an arctic system* Colorado State University]. Colorado.

Singh, B. (2014). *Compostability and direct land applicationof paper mill sludge* [Master of Engineerimng, University of KwaZulu-Natal]. Durban.

Smith, R. (2011). The Environmental Sustainability of Paper *Graduate Studies Journal of Organisational Dynamics*, *1*(1). repository.upenn.edu/gsjod/vol1/iss1/4

Soliman, A. S., Shehata, M. S., & Abdel-Atty, M. (2017). Evaluation of Paper Pulp and Paper Making Characteristics Produced from Different African Woody Trees Grown in Egypt. *Research Journal of Forestry 11*, 19-27. https://doi.org/10.3923/rjf.2017.19.27

Sood, S., & Sharma, C. (2019). Bacteria in Indian Food Packaging Papers and Paperboards with Various Contents of Pulp Fiber. *Food and Nutrition Sciences*, *10*, 349-357. https://doi.org/10.4236/fns.2019.104027

Soucy, J., Koubaa, A., Migneault, S., & Reidl, B. (2014). The potential of paper mill sludge for wood–plastic composites. *Industrial Crops and Products*, *54*, 248-256. https://www.academia.edu/20909838/The_potential_of_paper_mill_sludge_for_wood_plastic_composites

Srinivasan, R., Sathiya, K., & Palanisamy, M. (2010). *Experimental investigation in developing low cost concrete from paper industry waste* Polytechnic Institute of Jassy]. Romania.

Stavenhagen, C., Buurman, M., & Tortajada, J. (2018). Saving water in cities: Assessing policies for residential water demand management in four cities in Europe. *Cities*, *79*. https://doi.org/10.1016/j.cities.2018.03.008

Stora Enso. (2006). *Sustainability Report*. www.storaenso.com

Trois, C., & Jagath, R. (2011). Sustained Carbon Emissions Reductions through Zero Waste Strategies for South African Municipalities. In. InTech. https://doi.org/10.5772/17216

Turgut, B., & Kose, B. (2015). Improvements in aggregate stability of recently deposited sediments supplemented with tea waste and farmyard manure. *Solid Earth Discussion*, *7*, 2037-2053. https://doi.org/10.5194/sed-7-2037-2015

Van Ham, D.,. Morton, K. , & Mullen, S. (2009, 18-21 June 2008). Pulp and paper sludge as a barrier layer in landfill closure: a new opportunity. Paper presented at the 2008 PACWEST conference in Jasper, Alta.

Veluchamy, C., & Kalamdhad, A. S. (2017). Influence of pretreatment techniques on anaerobic digestion of pulp and paper mill sludge: A review. *Bioresour Technol*, *245*(Pt A), 1206-1219. https://doi.org/10.1016/j.biortech.2017.08.179

Veriansyah, J. D., Bambang, K., & Duck, J. (2007). RETRACTED: Supercritical water oxidation for the destruction of toxic organic wastewaters: A review. *Journal of environmental sciences (China)*, *19*, 513-522. https://doi.org/10.1016/S1001-0742(07)60086-2

Wai, R., & Lilly, P. (2002). MANUFACTURING OF EMERY CLOTH (SAND PAPER)FROM LOCAL RAW MATERIALS. *Global Journal of Engineering Research*, *1*(1). https://doi.org/10.4314/gjer.v1i1.18901

Wang, L., Shoou-Yuh, C., Hung, Y. T., Muralidhara, H., & Chauhan, S. (2007). Centrifugation Clarification and Thickening. In (pp. 101-134). https://doi.org/10.1007/978-1-59259-996-7_4

Welzbacher, C. R., Rassam, G., Talaei, A., & Brishke, C. (2011). Microstructure, strength and structural integrity of heat-treated beech and spruce wood. *Wood Material Science and Engineering*, *6*(4), 219-227. https://doi.org/10.1080/17480272.2011.622411

Wibowo, I. D., Purwanto, P., & Suherman, S. (2020). *Solid waste management in the paper industry* E3S Web of Conferences 202,

Xing, S., Ried, B., Koubaa, A., & James-Deng, A. (2012, August 27-31). Optimal percentage of pulp and paper mill secondary sludge incorporated in particleboard. Proceedings of the 55th international convention of Society of Wood Science and Technology Beijing, China.

Yan, S., & Sagoe-Crentsil, K.., (2011). Reuse of deinking sludge from wastepaper recycling in cement mortar products. *J Environ Manage*, *92*, 2085-2090.

Yongwu, H., Yu, J., & Lu, F. (2012). Application of Fischer–Tropsch Synthesis in Biomass to Liquid Conversion. *Catalysts*, *2*(2), 303-326. https://www.mdpi.com/2073-4344/2/2/303

Yu, S., Zhang, G., Li, J., Zhao, Z., & Kang, X. (2013). Effect of endogenous hydrolytic enzymes pretreatment on the anaerobic digestion of sludge. *Bioresource technology*, *146*. https://doi.org/10.1016/j.biortech.2013.07.087

Zainal, Z. A., Lean, C. H., & Seetharamu, K. N. (2001). Prediction of performance of a downdraft gasifier using equilibrium modeling for different biomass material. *Energy Conversion and Management*, *42*, 1499-1515. https://doi.org/10.1016/S0196-8904(00)00078-9

Zani, A., & Tenaglia, P., . (1990). Reuse of paper making sludge in brick production. *Ziegelindustries Int 12*, 682-690.

Zhang, L., Xu, C., & Champagne, P. (2010). Energy recovery from secondary pulp/paper-mill sludge and sewage sludge with supercritical water treatment. *Jour. Biotech*, *11*, 2713-2723. https://doi.org/10.1016/j.biortech.2009.11.106

Zvyagina, A. P. (1996). *Raw mixture for insulating material and the method of its production* (Russia Patent No. 2055055).