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End-of-life treatments for cannabis plant residues: A techno-socio-economic and environmental assessment for a New Zealand case study

A dissertation presented in partial fulfilment of the requirements
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Abstract

The cannabis plant and its products have been utilised for thousands of years in many industries but, over the last century, legislation and regulations have been introduced in many parts of the world to limit its cultivation and use. Nevertheless, the medicinal/recreational cannabis and hemp seed and fibre industries are rapidly growing around the world, and this is associated with increasing quantities of waste plant residues; up to 45% of the plant is considered waste, not including the root systems. For end-of-life (EoL) management of cannabis plant residues, current EoL treatments include landfilling, composting, anaerobic digestion, and incineration. A potential alternative treatment is pyrolysis which produces biochar or charcoal, a high-carbon content product. Biochar can decrease the soil bulk density, increase soil porosity, increase soil-specific surface area, and increase soil water retention/water-holding capacity. Another benefit of biochar is its potential for carbon sequestration when applied to soil.

In this study, a mass and energy balance of each EoL treatment was undertaken, and then a Life Cycle Assessment (LCA) of each EoL treatment. The ReCiPe 2016 v1.1 method was used to assess 15 impact categories: climate change, fine particulate matter formation, fossil depletion, freshwater consumption (inventory indicator), freshwater ecotoxicity, freshwater eutrophication, human toxicity (cancer and non-cancer), ionizing radiation, marine ecotoxicity, marine eutrophication, photochemical ozone formation (ecosystems and human health), terrestrial acidification, and terrestrial ecotoxicity. In general, the ranking across all assessed impact categories for the alternative treatments was composting (best), anaerobic digestion, pyrolysis, incineration, and landfill (worst). Although pyrolysis was in the middle of the ranking, it had the only net negative climate change impact (i.e. mitigating climate change) when accounting for the contribution of carbon storage in biochar.

Cannabis plant residues consist of leaves, stalks, and roots. Samples of both hemp and medicinal cannabis plant residues were collected at selected hemp and medicinal cannabis cultivation facilities. A pyrolysis unit fabricated by the workshop staff at Massey University was used to complete experimental trials on the residues. A pyrolysis temperature of 420-450°C was used, with a biochar yield of 37-53% and a condensate (oil and water phases) yield of 10-20% being obtained. The biochar and condensate were analysed in the Py-GCMS to find if the compounds of interest, cannabinoids, were present. This would be a concern if the cannabinoids remained in the biochar due to the risk of cannabinoids entering the human food chain (e.g. from cows grazing on pasture which has been treated with biochar). These results show that pyrolysis is a suitable EoL treatment for cannabis plant residues because it removes all the cannabinoids from the biochar; this means the biochar can be subsequently spread onto land. Cannabinoids were found to be present in the condensate which is not a problem because typically it would be flared, or the cannabis company would have stringent protocols in place to ensure no cross contamination with the biochar. The cannabinoids found were Cannabicyclol (CBL), Cannabidiol (CBD), Cannabinol (CBN), and Dronabinol (Δ^9 -THC) in all condensate samples.

As well as the environmental aspects, a preliminary assessment of the economic, social, and cultural aspects of the alternative EoL treatments were also undertaken. A basic economic analysis was completed, and it was found that the composting EoL treatment had the lowest capital costs, operating costs, and a better net present value (NPV) after 15 years across alternative EoL treatments. While many social indicators can be used, the one selected for this study was the number of hours worked by employees per year to process 30 tonnes of cannabis plant residue. The landfill and composting EoL treatments would provide 132 hours for four employees, the anaerobic digestion EoL treatment would provide 780 hours of work for four employees, and the incineration and pyrolysis would provide 420 hours of work for six employees. Through a cultural assessment, it was found that there were seven significant headings (sets of values) that represent the values of the Māori people in relation to the technologies assessed in this study. The cultural assessment found that the EoL treatment rankings were: pyrolysis (most preferred), anaerobic digestion, composting, landfill, and incineration (least preferred). When the environmental, economic, social, and cultural aspects are considered, the ranking of the alternative EoL treatments is pyrolysis (most preferred), composting, anaerobic digestion, landfill, and incineration (least preferred).

Several challenges arose during the study, including the LCA software and database specificity, site selection and sampling due to Covid lockdowns, licencing and regulation restrictions, time and funding, experimental limitations and trade-offs, and participant acquisition for cultural interviews. Multiple **LCA software** options are available with access to different databases; the one licensed by Massey University was used, and a comparison was completed on different databases. A **licence** is required for any location where cannabis plant material is stored or used in experiments. After many telephone calls and hours of discussion, the Ministry of Health decided that this project would not be granted a licence; this meant that testing had to be completed on-site at cultivation facilities; this also limited the **availability of material** for testing due to having to work around Covid lockdowns and cultivation cycles. Overall, one medicinal cannabis and one hemp plant could be tested, which meant that **selection bias** occurred due to material availability. **Time** was constrained by the degree requirements with a maximum of three years, and **funding** was constrained based on the support provided by Massey University, Callaghan Innovation, and the Dick and Mary Earle Technology Scholarship Grant. Finally, the **cultural assessment** was completed with the help of this project's original funding organisation, Zymbl Ltd, who had contacts in the local Rotorua iwi. Members were asked to join the discussion; however, only two were available. Despite these limitations, the study is still valuable for both the New Zealand and global industry as it is the first study evaluating alternative EoL treatments for cannabis plant residues.

Keywords: Cannabis, Cannabinoid, Pyrolysis, Landfill, Composting, Anaerobic Digestion, Incineration, Environmental, LCA.

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Abbreviations and Acronyms

2-AG	2-Arachidonoylglycerol
AD	Anaerobic Digestion
AEA	Anandamide
API	Active Pharmaceutical Ingredients
BAU	Business-as-Usual
BCSF	Biochar Carbon Stability Factor
BL	Biochar Lost
BP	Biochar Produced
BY	Biochar Yield
C	Carbon
CAGR	Compound Annual Growth Rate
CBC	Cannabichromene
CBD	Cannabidiol
CBDA	Cannabidiolic acid
CBG	Cannabigerol
CBL	Cannabicyclol
CBN	Cannabinol
CC	Carbon Content
CER	Certified Emissions Reduction
CF	Carbon Footprint
CFCs	Chlorofluorocarbons
CH ₄	Methane
CLCB	Cannabis Legislation and Control Bill
CO ₂	Carbon Dioxide
C _p	Specific heat capacity
CRI	Crown Research Institute
CSF	Carbon Stability Factor
db.	Dry basis
DEA	Drug Enforcement Administration
DM	Dry Mass/Matter
DS	Dissolved Solids
ECS	Endocannabinoid System
EOl	End-of-Life
EPA	Environmental Protection Authority
ERU	Emissions Reduction Unit
ETS	Emissions Trading Scheme
EU	European Union
FDA	U.S. Food and Drug Administration
FETP	Freshwater Ecotoxicity Potential
FFP	Fossil Fuel Potential
FU	Functional Unit
GHG	Greenhouse Gases

GMP	Good Manufacturing Practice
GVW	Gross Vehicle Weight
GWP100	Global Warming Potential over 100 years
HBFCs	Hydrobromofluorocarbons
HCFCs	Hydrochlorofluorocarbons
HFCs	Hydrofluorocarbons
HHV	Higher Heating Value
HTT	Highest Treatment Temperature
HV	Heating Value
Int-1-AM	Interview 1 Aaron
Int-1-WT	Interview 1 Wally
Int-2-WT	Interview 2 Wally
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LGR	Landfill Gas Recovery
LHV	Lower Heating Value
LMC	Land management change
LMTD	Log Mean Temperature Difference
LUC	Land use change
LULUC	Land use and land use change
MC	Medicinal Cannabis
MCA	Medicinal Cannabis Agency
MCB	Moisture Content of Biochar
METP	Marine Ecotoxicity Potential
MoH	Ministry of Health
MP	Members of Parliament
MPI	Ministry of Primary Industries
MUHEC	Massey University Human Ethics Committee
MW&B	Muller-Wenk and Brandao
N ₂ O	Nitrous Oxide
NaOCl	Sodium Hypochlorite
NDC	Nationally Determined Contribution
NPK	Nitrogen, Phosphorus, Potassium
NPP	Net primary productivity
NPV	Net Present Value
NZ	New Zealand
NZD	New Zealand Dollar
NZTA	New Zealand Transport Agency
NZU	New Zealand Unit
P	Phosphorus
PER	Percolation
PFCs	Perfluorocarbons

PM	Particulate Matter
PSGE	Post-Settlement Governance Entity
PYR	Pyrolysis
R&D	Research and Development
RoW	Rest-of-World
RUC	Road User Charge
SF ₆	Sulphur hexafluoride
SFE	Supercritical fluid extraction
SI	Similarity Index
SOC	Soil Organic Carbon
SOX	Soxhlet
SRT	Solids Retention Time
T	Temperature
THC	Tetrahydrocannabinol
THCA	Tetrahydrocannabinolic acid
TM	Total Mass
TMLSS	Tractor, mixing, loading, screening, and stacking
TPT	Te Pumautanga o Te Arawa
TS	Total Solids
U.S.	United States
ULT	Ultrasonication
USD	United States Dollar
USDA	United States Department of Agriculture
WWTP	Wastewater Treatment Plant

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Chapter 1: Introduction

The cannabis plant is part of the Cannabaceae plant family. There are three types of cannabis plant used for different purposes: *Sativa* (medicinal/recreational), *Indica* (medicinal/recreation or hemp for fibre and seed), and *Ruderalis* (hemp for fibre and seed). When the cannabis plant is grown for fibre and seed, it is classed as hemp, an agricultural crop, but when it is grown for medicinal or recreational purposes, it is classed as a horticultural crop and referred to as cannabis (termed medicinal cannabis for this study). The separation between hemp and medicinal cannabis has created two different industries for the same plant. While hemp is traditionally grown outdoors (GGS, 2021), medicinal cannabis is cultivated indoors and outdoors (Zheng et al., 2021). This study uses a generalised cannabis plant composition rather than being specific to either industry, except for the experimental work taking place using a hemp and medicinal cannabis plant for the identification of key compounds.

Research has shown that there is a large environmental impact when cultivation takes place indoors (Mills, 2012; Pedrazzi et al., 2021; Smith, 2021; van der Werf, 2004; Zampori et al., 2013). A single indoor cultivation facility in the U.S. in 2012 had a total energy usage of 6,074 kWh/kg yield and a carbon footprint (CF) of 4,600 kg CO₂-eq./kg yield (Mills, 2012). This CF is in the range of 2,283–5,184 kg CO₂-eq./kg yield estimated in a study by Colorado State University (Manning, 2021). The environmental impacts of cultivation do not consider the impact that waste plant material has on the environment after harvesting. In the medicinal cannabis industry, 45% of the plant in the form of leaves and stalks can be considered waste (G. Randall, personal communication, April 20, 2021), and this value is even larger if one includes the wasted roots. In the U.S. in 2019, approximately one million tonnes of waste were produced from cannabis plant cultivation (GAIACA, 2020). The most common end-of-life (EoL) treatment method is landfill, with alternative methods being country-dependent. There is currently no literature comparing the environmental impacts of EoL methods; therefore, this study aims to fill this gap using life cycle assessment (LCA) methodology and software.

This chapter discusses the background and context for the study (Section 1.1); sets out the research problem, research aims, objectives and research questions (Section 1.2); and explains the significance of the study (Section 1.3), its limitations (Section 1.4), and thesis outline (Section 1.5).

1.1 Background, geographic scope, and research problem

When hemp is cultivated for fibre and seed, the leaves and roots are classified as waste (termed residues for this study). However, the stalk is also classed as residue if hemp is solely grown for seed (Aliouche, 2019; Vivek, 2019). The leftover residues in the medicinal cannabis industry are most commonly leaves, stalks and roots, with only the flowers (buds) used as the product (Alaska Legislature, 2019). For this study, the residues of cannabis plant cultivation are considered to be leaves, roots, and stalks for consistency.

Hemp is traditionally grown outdoors (GGS, 2021), and medicinal cannabis is cultivated indoors and outdoors (Zheng et al., 2021). It is estimated that the amount of legal medicinal cannabis grown in California alone each year is approximately 514 tonnes, with an approximate value of \$1.66 billion (Guilhem, 2021). According to the United Nations (2010), 50 countries in the last ten years reported on their cannabis plant cultivation, and more were expected to grow illegally, with seizures and eradications also reported. The global cannabis plant market expanded at a rate of 600-700% between 2020 (estimated at USD 20.5 billion) and 2026 (Wood, 2021). The global industrial hemp market was estimated at USD 3.61 billion in 2020, with an expected annual growth of 16.2% (GVR, 2022).

The landfill EoL treatment is the most common for residues, with technological development creating opportunities for increased sustainability in the industry (Alba, 2020; Ochoa, 2019; Spapens, 2011; Wong, 2018). One development is the anaerobic digestion of residues which allows the heat from the gases produced to be reused for heating in indoor cultivation sites (Alba, 2020; Gorrie, 2018). Other EoL treatments include composting and incineration. These treatments are currently used, but for this study, an additional method will be investigated as a possible treatment: pyrolysis.

Pyrolysis is the thermal decomposition of organic material at high temperatures in the absence of oxygen, although it has a lower process temperature and lower emissions than regular incineration or combustion (Czajczyńska et al., 2017). Research into pyrolysis has also increased over the past decade as one of the by-products, biochar or charcoal, has a high carbon content (Jones et al., 2020; Steiner, 2016). Biochar can decrease the soil bulk density, increase soil porosity, increase soil-specific surface area, and increase soil water retention/water-holding capacity (Guo, 2016). Along with the benefits described, the main reason for biochar research is its use for carbon sequestration (Sykes et al., 2019). Carbon sequestration to soil involves transferring atmospheric carbon dioxide (CO₂) into the soil to be stored (Lal, 2016). When carbon is stored effectively, it can be used to (i) offset emissions of fossil fuel combustion, cement production and deforestation, and (ii) reduce the net increase of atmospheric CO₂ concentration (Lal, 2016). Therefore, biochar is an effective tool to help create a circular economy, with the possibility of keeping residues from the cannabis plant in use as biochar, for as long as possible.

This study is being completed for the growing New Zealand industry with considerations for the methods and literature found on a global scale. Landfill and composting are EoL methods used in New Zealand, whereas anaerobic digestion and incineration are used in Hungary and Canada (Alba, 2020; Celitron, 2021; Gorrie, 2018). Along with studying the environmental impacts, the economic, social, and cultural aspects of the EoL treatments are investigated. The social and cultural aspects consider the impacts that the EoL treatments have on local communities and the link (if any) to the Māori culture of New Zealand.

In the literature, there is no quantitative comparison of the current EoL treatments for cannabis plant residues. It is also unknown which current treatment is more environmentally friendly.

Therefore, this study aims to fill these gaps and compile knowledge for the New Zealand (NZ) industry.

1.2 Research aims, objectives, and questions

This study aims to identify and evaluate the environmental, social, and economic impacts of current EoL treatments used for cannabis plant residues in comparison to a proposed new EoL treatment, pyrolysis, through an LCA lens.

The objectives of this study are:

- To identify the common EoL treatments for residues used by the global hemp and medicinal cannabis industries.
- To evaluate the environmental impacts of the current and potential EoL treatments.
- To collect missing data on pyrolysis as an EoL treatment by testing on both hemp and medicinal cannabis plant residues.
- To compare and contrast the overall economic, social, and cultural aspects and sustainability of all EoL treatments.

The research questions this study seeks to answer are:

- What EoL treatments for cannabis plant residues are used by the global hemp and medicinal cannabis industries?
- What are the environmental impacts of the EoL treatments?
- What economic, social, and cultural aspects are associated with each EoL treatment?
- How do the environmental, economic, social, and cultural aspects of pyrolysis compare to alternative EoL treatments?

1.3 Significance

The study will contribute to the body of knowledge in the hemp and medicinal cannabis industries by evaluating the current and possible EoL treatments available for cannabis plant residues. This will help address the current shortage of research in this area and provide real-world knowledge to organisations operating in this rapidly growing industry.

1.4 Limitations

The limitations of this study include:

- LCA software and dataset specificity
 - There are multiple LCA software options available with access to different databases; however, NZ-specific data is not always available. Therefore, decisions on the software and database used are justified in Chapter 3.
- Licencing to test cannabis plant material at Massey University
 - This limitation is discussed further in Chapters 4 and 6.
- Cannabis plant residue composition

- The composition of the residues varies between the hemp and medicinal cannabis industries; however, it is important to be consistent in a study of this size. Therefore, all findings are presented relative to the functional unit, described in Chapter 3. This limitation is also considered further in Chapter 4 during the pyrolysis experiments.

1.5 Thesis outline

This thesis comprises seven chapters. **Chapter 1** gives a general introduction to the context of the research along with the aims. **Chapter 2** critically reviews the literature on the history, regulation, and laws of the global medicinal cannabis and hemp industries. It also discusses the life cycle of the cannabis plant from cultivation to production of medicinal cannabis and hemp products, and the background behind the LCA methodology. **Chapter 3** describes the current and potential EoL treatments for residues in the medicinal cannabis and hemp industries. A consequential diagram and mass and energy balance are presented in this chapter. **Chapter 4** describes the methodology used for the pyrolysis EoL treatment experiments. It also presents and analyses the results of the pyrolysis experiments along with subsequent testing of the by-products, biochar, and condensate in this chapter. **Chapter 5** presents and analyses the results from the LCA modelling, including utilising the experimental results in a sensitivity analysis. **Chapter 6** undertakes a preliminary economic, social, and cultural analysis of each EoL treatment, as well as investigates the regulations for the cannabis plant and carbon accounting in New Zealand. An overall comparison of the EoL treatments, incorporating the environmental impacts and preliminary economic, social, and cultural analysis results, concludes this chapter. **Chapter 7** concludes this thesis with a summary of the results and comparisons of the EoL treatments, along with recommendations for future work and research.

Chapter 2: Review of the cannabis sector and life cycle assessment

This chapter introduces the cannabis sector (Section 2.1) and the history of cannabis including its origins, laws and regulations, and the growth of the industry (Section 2.2). In Section 2.3, the life cycle of the cannabis plant is assessed. Finally, Section 2.4 introduces the life cycle assessment (LCA) methodology.

2.1 Introduction

The cannabis plant has the opportunity to be one of the world's most useful plants with its ability to be used across multiple industries (Clarke & Merlin, 2013). However, use of the cannabis plant has historically been a controversial topic, most commonly being publicised in a negative light (Earleywine, 2003). As noted in Chapter 1, there are three main types of cannabis plants: *sativa*, *indica*, and *ruderalis* (Clarke & Merlin, 2013). The two most prevalent active ingredients in the cannabis plant that can distinguish between the types are tetrahydrocannabinol (THC) and cannabidiol (CBD). THC and CBD are produced from their precursors Tetrahydrocannabinolic acid (THCA) and Cannabidiolic acid (CBDA), respectively, when they undergo partial or complete decarboxylation (Żuk-Gołaszewska & Gołaszewski, 2018).

Sativa is known for its energizing or psychoactive properties (Pruett, 2021), and it is used for recreational, medicinal, or hemp purposes, with a THC content 0.3-10% (Clarke & Merlin, 2013). *Indica* is known for its relaxing effects (Pruett, 2021); it is mainly used for medicinal purposes but is known to be used for recreational purposes as well. *Indica* has a THC content of 1-20% (Clarke & Merlin, 2013). *Ruderalis* is used for hemp fibre and seeds, and not for medicinal purposes as it has a low THC content of less than 0.3% (Clarke & Merlin, 2013). The THC-to-CBD ratio in cannabis plants is a function of the genetic profiles (Daeninck & Maida, 2018). As with anything, there are side effects to the components of cannabis plants. THC can provoke paranoia and increase anxiety, whereas CBD can negatively impact a developing brain (Robson, 2005; Pizzorno, 2018; Wedman-St. Louis, 2018a).

Medicinal cannabis is regarded as a horticultural crop; it is cultivated for its female flowers (buds), but the leaves and stalks/stems can also be used in the same way as for the hemp plant (Żuk-Gołaszewska & Gołaszewski, 2018). The flowers are mostly used for medicinal and recreational use (Clarke & Merlin, 2013). Hemp, on the other hand, is considered an agricultural crop, and is cultivated for the fibre in its stems and seed produced after pollination (Hemp New Zealand, 2020). The outer layer of the stem is made of high-cellulose low-lignin bark containing long fibres (bast fibre) while the inner layer is made of a low-cellulose high-lignin core containing short fibres (hurd) (van der Werf et al., 1994). The fibres can be used to produce cordage (Clarke & Merlin, 2013), paper, textiles, bioplastics (Britannica, 2022; van der Werf et al., 1994) and as reinforcement in composite materials (Shahzad, 2012). The long

fibres (bast fibre) are generally preferred and can be compared to the mechanical properties of glass fibres (Shahzad, 2012). Both hemp and medicinal cannabis are considered in this study.

The cannabis plant has been used as a medicinal product since ancient times (Kuzdzal et al., 2018). Wedman-St. Louis (2018b) discusses the evidence for cannabis plant use over the past 12,000 years for pain relief, reducing insomnia, treating wasting syndrome (Cachexic), reducing nausea, and reducing seizures, to name only a few. The whole plant contains cannabinoids whose molecules interact with the endocannabinoid system (ECS) in the human body by binding to ECS receptors, which leads to a range of effects on the body and mind (Raypole, 2019). Use of the plant has increased in recent times as it can alleviate some of the biggest medical conditions and diseases we are facing today ranging from Alzheimer's disease to cancer to HIV (Wedman-St. Louis, 2018c). The global cannabis plant industry expanded at a rate of 600-700% between 2020 and 2026 (Wood, 2021). This growth is due to the expansion of the industry into new products and applications (Rehm & Manthey, 2020).

When medicinal cannabis plants are cultivated and ready for harvest, the female flowers are removed, and the remaining plant parts not used for products are regarded as waste residues. Alternatively, the female hemp plants may be pollinated by male plants and once seeds appear after flowering, the stalks/stems are removed along with the seeds and the rest is considered waste residues. In the U.S. in 2019, approximately one million tonnes of waste were produced from cannabis plant cultivation (GAIACA, 2020). According to Alba (2020), 10-24% of the total weight is flowers, which would leave approximately 76-90% as leaves, stalks, and possibly roots. Roots aren't always counted in the mass fraction of the plant due to the difficulty of detaching roots from some growing mediums, such as coir pots. G. Randall (personal communication, April 20, 2021) states, "typically medicinal cannabis plants consist of 55% flowers and 45% leaves and stalks/stems (waste if only the flowers are utilised). Roots are not included in the weight fraction because the growing medium used is coir." The approximate percentages of the parts of the plant given in Randall's values appear to be more realistic based on the plant's structure and flowers being the main product of the plant.

These mass fractions can only be used as an estimate due to the many variables that affect the cannabis plant such as different: cultivars, growing styles, indoor or outdoor cultivation, if defoliation occurs, and if the leaves or stalks are also used (see Section 2.3.1).

In New Zealand, the medicinal cannabis industry is growing in response to the growth of the international market (O'Connor, 2022; Solignac, 2022), and the associated quantity of waste residue grows as well. In New Zealand, under the Medicinal Cannabis Scheme (MCS), any mass from the plant not used as a product must be destroyed (MoH, 2020b). The suggested method to use for destruction is grinding the solids and absorbing any liquid from the plant. The material is mixed with other waste materials (yard debris, wood chips, sawdust, soil, manure, or vegetable-based grease or oils), and this other material must constitute at least 50% of the final quantity. The mixed materials are then sent to a composting facility, anaerobic digester, or a certified landfill. Both industrial hemp and medicinal cannabis have large global markets and the New Zealand industries are growing in response to this potential international

market opportunity (Hemp Wellness NZ, n.d.; Moore et al., 2021). However, although New Zealand is already exporting medicinal cannabis, it is not yet active in the global industrial hemp market with no exports of products occurring (Te Puni Kōkiri, 2022).

This study aims to identify and evaluate the environmental, social, and economic impacts of current EoL treatments used for cannabis plant residues in comparison to a proposed new EoL treatment, pyrolysis, through an LCA lens. This chapter consists of the history of cannabis plant industries (Section 2.2.1); cannabis plant structure (Section 2.2.2); laws and regulations (Section 2.2.3); growth of the modern industry (Section 2.2.4); the life cycle of the cannabis plant including its cultivation (Section 2.3.1), processing of cannabis plant waste (Section 2.3.2), and production of cannabis products (Sections 2.3.3 and 2.3.4); and examination of life cycle assessment (LCA) methodology (Section 2.4).

2.2 Background information on the cannabis plant

2.2.1 Origins of the cannabis plant

Even though the origin of the cannabis plant is hard to determine with accuracy, many believe it to be indigenous to western or central Asia (Clarke & Merlin, 2013; Eynde, 2015; Harmon, 2021; Small, 2016). This was supported through research by Yang et al. (2013) who used chloroplast DNA to determine that Cannabaceae was distributed from Asia to be cultivated overseas. Fossil remains of *sativa* were found in Eurasia dating back almost 10,000 years (Fleming and Clarke, 1998, as cited in Clarke & Merlin, 2013). In 1980, records were found indicating the cannabis plant was harvested by the Chinese 8,500 years ago, although it was uncertain if this was cultivated crops or wild-growing plants (Schultes and Hofmann, 1980, as cited in Small, 2016). Cannabis plant seeds were excavated from a burial mound in Siberia, and the seeds trace back to 3000 B.C. (5,020 years ago) (Harmon, 2021; Wedman-St. Louis, 2018b). Evidence suggests that the cannabis plant has a long history of cultivation and use by humans.

2.2.2 Active compounds in the cannabis plant

The main compounds of interest in the cannabis plant are THC and CBD; they are a part of a group of compounds called cannabinoids (Pertwee, 2005). Cannabinoids were first identified between 1937 and 1940 (Grotenhermen & Russo, 2002). According to Huestis (2005), Cannabis *sativa* contains over 421 different chemical compounds. The cannabinoids begin in an acidic form on the plant before processing occurs, this form is the precursor to neutralised cannabinoids (Żuk-Gołaszewska & Gołaszewski, 2018). Cannabinoids possess a carboxylic acid moiety, which can either decarboxylate when heated or under alkaline conditions (Grotenhermen & Russo, 2002) or oxidise when exposed to acid to produce a cannabinol less potent and 10% less psychoactive (Huestis, 2005). The processing of precursor acid forms of cannabinoids consists of the compounds undergoing partial or complete decarboxylation through drying, storing or thermally processing the plant (Żuk-Gołaszewska & Gołaszewski, 2018).

THC

Tetrahydrocannabinolic acid (THCA) is the precursor cannabinoid of THC (Żuk-Gólaszewska & Gołaszewski, 2018). The decarboxylation reaction converts THCA to THC when heated to 145°C for six minutes (Wang et al., 2016). THC is classed as a psychoactive cannabinoid compound (Sharma et al., 2012). THC was first identified in 1964 by Raphael Mechoulam (Huestis, 2005). A 1988 study showed the average cannabinoid content at different stages of growth for *sativa*, which showed THC at its highest concentration during flowering, 3575.3±1069 µg/100 mg dry wt. ± standard deviation (Vogelmann et al., 1988). Sharma et al. (2012) found approximately 30% of the THC is assumed to be destroyed in pyrolysis. However, a study completed by Repka et al. (2006) quantified it, showing the decomposition of THC occurred at temperatures in the range of 200–250°C; however, at 200°C the degradation of THC was relatively low.

Raphael Mechoulam also discovered the endocannabinoid system (ECS) in humans, a complex cell-signalling system, plays a role in sleep, mood, appetite, memory, reproduction and fertility (Raypole, 2019). The ECS contains three core components: endocannabinoids, receptors, and enzymes (Raypole, 2019). According to Raypole (2019), two key endocannabinoids have been identified: anandamide (AEA) and 2-arachidonoylglycerol (2-AG). The body produces endocannabinoids as required, and they bind to receptors: CB1 receptors (found in the central nervous system) and CB2 receptors (found in the peripheral nervous system) to signal the ECS needs to act. Once the endocannabinoids have completed their functions, enzymes break them down. There are two main enzymes: fatty acid amide hydrolase (breaks down AEA) and monoacylglycerol acid lipase (breaks down 2-AG). Cannabinoids attach to the ECS receptors in the same way endocannabinoids do, which allows for a range of effects on the body and mind to occur (Raypole, 2019).

THC produces a high sensation, but it can also be an effective analgesic for pain relief in HIV and cancer patients (Raypole, 2019; Walker & Hohmann, 2005; Wedman-St. Louis, 2018b). Its interaction with the ECS brings about the effects of THC as it binds to both CB1 and CB2 receptors (Raypole, 2019).

CBD

Cannabidiolic acid (CBDA) is the precursor of CBD (Żuk-Gólaszewska & Gołaszewski, 2018). The decarboxylation reaction converts CBDA to CBD when heated to 145°C for nine minutes (Wang et al., 2016). CBD is classed as an active but non-psychoactive cannabinoid compound (Sharma et al., 2012). CBD offers benefits similar to an antioxidant; it keeps the ECS within the body functioning and balanced, controlling sleep, mood, appetite, memory, reproduction, and fertility (Tishler & Wedman-St. Louis, 2018).

In the ECS, the CBD molecule does not bind to either the CB1 or CB2 receptors like THC (Raypole, 2019). Some believe the CBD molecule stops the breakdown of endocannabinoids, and others believe it binds to a receptor that has not been discovered yet (Abood et al., 2005; Raypole, 2019).

Other cannabinoids

Even though THC and CBD are the most known cannabinoids, there are more than 60 inactive cannabinoids present in the cannabis plant (Sharma et al., 2012), along with other compounds in small amounts (Grotenhermen & Russo, 2002). Other than THC and CBD, Cannabichromene (CBC) and Cannabigerol (CBG) are also found in the cannabis plant in significant quantities with the 1988 study showing they were found at the flowering stage with $127.2 \pm 17 \mu\text{g}/100 \text{ mg dry wt.} \pm \text{standard deviation}$ and $101.8 \pm 62 \mu\text{g}/100 \text{ mg dry wt.} \pm \text{standard deviation}$, respectively (Vogelmann et al., 1988).

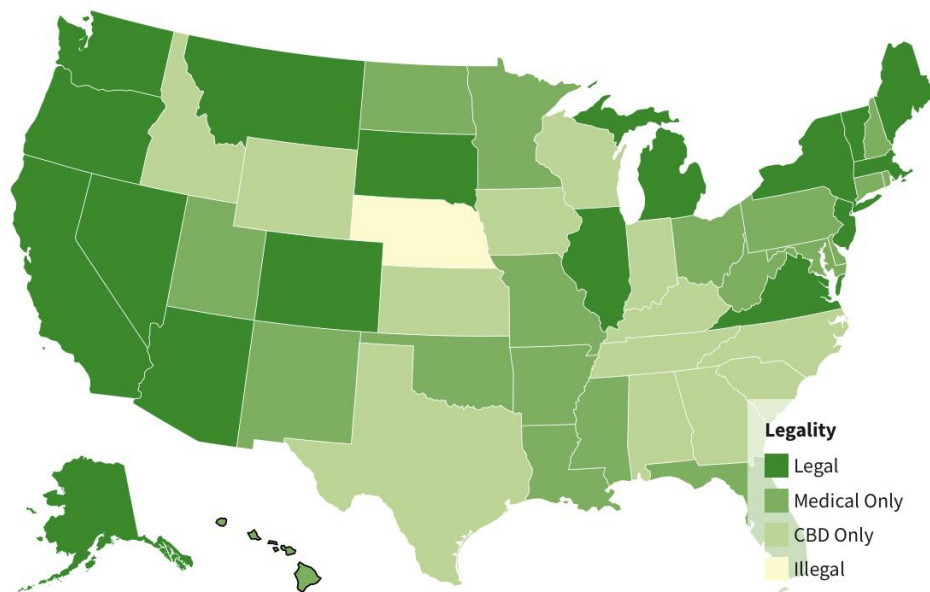
2.2.3 Laws and regulations on cannabis

Laws and regulations on production and supply of medicinal cannabis

Only in the past hundred years have policies on cannabis been made (Spapens, 2011). Laws prohibit the use, possession, cultivation, and supply of cannabis in most countries but, in these countries, cannabis is a widely used drug even though it is illegal (Barratt et al., 2012; Potter et al., 2011; Small, 2016). Uruguay was the first country to legalise recreational cannabis use at a national level in December 2013, with the market being fully regulated and operating under state control (Laqueur et al., 2020). Only citizens and permanent residents of Uruguay who are 18 years or older can register for use and either has a limit of six plants, join a cannabis social club with a limit on members and plants, or purchase from an authorised pharmacy with a limit of 10g/week (Chiaroni-Clarke, 2020a). Canada became the second country to legalise recreational use, with similar state-controlled regulations involving licences for production and provinces being responsible for retail distribution. One difference is that each province/territory controls the limit on their market size/production; therefore, between territories, there is a variation as to whether cannabis can be purchased at privately-owned or government-owned stores (Chiaroni-Clarke, 2020b).

In the U.S, due to its size and the fact cannabis regulation is not applied at a federal level, cannabis for recreational use may be decriminalised or legalised, or only medicinal cannabis may be legalised, depending upon the state (Figure 1). In December 2020, the U.N. reclassified cannabis as a less dangerous drug, removing it from the list which is shared alongside highly addictive drugs, including heroin and cocaine (Rodriguez, 2020). Overall, the current legalisation situation is country dependent on the U.S. leading the charge. President Joe Biden has already expressed his interest to legalise cannabis over the entire country as well as expunging the criminal records of those convicted of possession of cannabis (D'Souza, 2021). A survey in the U.S. completed in April 2021, showed 67% of Americans believed marijuana should be legalised (D'Souza, 2021).

Figure 1: U.S. State Cannabis Laws (from NORML, n.d., Copyright 2022, reprinted with permission)



Cannabis is classed as a soft drug in the Netherlands (Spapens, 2011). Soft drugs are described as causing no physical or psychological addiction or harm but are still unsafe (Government of the Netherlands, n.d.-a). In the Netherlands, cannabis is illegal but in the 1970s the Dutch policy of toleration was written which decriminalised cannabis for personal use, meaning ‘coffee shops’ are allowed to sell cannabis and possess no more than five grams and no more than five plants are allowed by the public (Chiaroni-Clarke, 2020c). At coffee shops that sell cannabis, regulations in place include a minimum purchase age of 18, a limit of 5g/person/day, and sales only to residents (although this is known to be ignored) (Chiaroni-Clarke, 2020c). Similarly in Spain, the approach to cannabis has been much more liberal with cannabis social clubs being formed in the early 2000s; due to the lack of regulation, associations improvise and invent their own solutions to standardise their activities (Chiaroni-Clarke, 2020d). In 2001, Portugal decriminalised all drug use, including cannabis; however, it is still illegal to supply and sell cannabis (Chiaroni-Clarke, 2020e). In Portugal, cannabis social clubs exist where cannabis is illegally consumed; attempts to legalise the sale and cultivation of cannabis in 2019 were rejected (Chiaroni-Clarke, 2020e). Overall, all EU members treat possession as an offence but over one-third do not allow prison as a penalty for minor offences (Figure 2). Legalisation across the U.S. and Europe is becoming more widely discussed, with Cannabis Europa being held in London from 28th–29th June 2022 to ‘push the European cannabis industry forward (Cannabis Europa, 2022).

Figure 2: Cannabis possession penalties in Europe (from European Monitoring Centre for Drugs and Drug Addiction, n.d.)



The success and failures of the medicinal cannabis laws

This section compares and contrasts policies in the Netherlands and the U.S. because they have ended up with quite different approaches to cannabis legislation. In 1906, the U.S. had the Pure Food and Drug Act which required cannabis to be accurately labelled with content, but by 1914 the Harrison Narcotics Tax Act required registration and payment of tax by all persons who imported, produced, dealt in, sold, or gave away narcotics - including cannabis (Patton, 2020). The Netherlands first criminalised the import and export of cannabis when the plant was introduced into the Opium Act in 1928 (Korf, 2002), though this did not criminalise cannabis use within the Netherlands. In 1922 in the U.S., the Narcotic Drug Import and Export Act was passed which made drug possession a federal crime. At this time, the term narcotic was not used in line with its scientific definition; instead, the term was understood to mean any drug used by individuals of low socio-economic standing (Patton, 2020). The U.S. first criminalised cannabis when the Marijuana Tax Act was passed in 1937 (Ministry of Hemp, 2019). However, the Netherlands were slower to criminalise cannabis within the country even though laws against its import and export were in place. In 1938, the U.S. Federal Pure Food, Drug and Cosmetics Act was updated with cannabis being classed as a dangerous drug and the FDA in charge to create and enforce the standards (Allworth, 2020). According to Korf (2002), the 1950s in the Netherlands were seen as the introductory phase of cannabis with the possession, cultivation and sale becoming criminal offences. Cannabis use grew through the 1960s with the number of cannabis users by the end of the decade at 10,000–15,000 (Korf, 2002). The Netherlands first criminalised cannabis in 1953, though this did not last long, with statutory decriminalisation formally came into place in 1976 with the revision of the Opium Act making possession of up to 30g of cannabis a misdemeanour (Korf, 2002).

According to van Ooyen-Houben and Kleemans (2015), since 1976 “coffee shops” have been available for recreational cannabis use in the Netherlands. However, in the US in 1970, the Controlled Substances Act was passed, creating a tier system for drugs, classing cannabis as a Schedule 1 drug, with it carrying the highest penalties (Moore, n.d.). Quickly following in 1972, the Shafer Commission proposed legalising a small amount of marijuana only to be denied; it wasn’t until 1973 that Oregon became the first state to reduce the penalty for cannabis possession (Moore, n.d.). The 1980s were characterised by a ‘war on drugs’ with the Antidrug Abuse Act making life without parole the sentence for offenders who were on their third strike (Moore, n.d.). California became the first state to legalise the cultivation, possession and use of cannabis for medicinal purposes in 1996; by 2013, 20 other states had done the same, with the Justice Department stating they “will not interfere in state laws even with federal policy in place” (Moore, n.d.). The history of cannabis in the U.S. and the Netherlands depicts; the U.S. took a sharp and direct approach to taxation and federal criminalisation; the Netherlands was slower with the regulations and legislations being put in place over vast amounts of time. The Netherlands’ approach was shown with cannabis only being criminalised for 23 years in the 1900s.

Entering the 21st century, the Netherlands’ reputation as the go-to country for tolerated cannabis use grew, so from 2013 coffee shops were required to only have 2,000 members (a membership card was issued to residents) but sale to foreigners was banned (Government of the Netherlands, n.d.-b; Reuters, 2011). However, foreigners still manage to consume and buy cannabis when travelling there with 85% of coffee shops not enforcing the resident criterion in a 2014 survey (Rolles, 2014). Due to coffee shops often relying on the supply from criminal networks due to not enough supply, in 2017, Dutch MPs approved an experiment to regulate the cultivation and sale of cannabis with coffee shops only being able to sell legally produced cannabis, the experiment was set to finish at the end of 2021 (Government of the Netherlands, n.d.-c).

Kuper (2018) calls the Netherlands a ‘success’ as they had straightforward legislation in place by the 21st century whereas the U.S. has three government agencies working federally along with each state having their own regulations as well. While in both countries change is occurring in the cannabis industry, the Netherlands experimented before implementation. However, the U.S. has to make amendments that take years due to the federal government trying to halt any state legislation on cannabis due to it still being classed as a Schedule 1 drug at a federal level. Recent research in the U.S. and the Netherlands has investigated the effects of legalising recreational cannabis in these two countries (Rehm & Mantey, 2020; Spapens, 2011). The U.S. currently has some cannabis products with THC contents above 95%, and this has led to an increase in accidental exposure/overdoses of children from second-hand smoke (Stuyt, 2018), which was unforeseen due to the current policies on cannabis (Spapens, 2011). The debate on policies is also due to the line between medicinal and recreational use being blurred as medicinal cannabis products are essentially the same as recreational cannabis products (Small, 2016).

The production and supply of industrial hemp

Since hemp is specifically grown to have a lower THC content compared to medicinal cannabis, the laws and regulations regarding its production and supply are less stringent. After hemp was introduced to North America in 1606, the first legal stance on it came in the 1700s when farmers were legally required to grow hemp as a staple crop due to its many uses (Ministry of Hemp, 2019). As time went on and more study was done into the agricultural crop, the USDA (United States Department of Agriculture) found hemp produced four times more paper per acre than trees in 1916 (Ministry of Hemp, 2019). As the Marijuana Tax Act began in 1937 for all cannabis sales, this also included hemp, and the benefits of hemp led to the USDA initiating the “hemp for victory” programme, growing more than 150,000 acres (Ministry of Hemp, 2019). In 1970, the Controlled Substances Act classified cannabis (which included hemp) as an illegal Schedule 1 drug with strict regulations being imposed (Moore, n.d.). Since the production of hemp was under strict regulations, the U.S. began importing food-grade hemp seed and oil in 1988; this led to the Drug Enforcement Administration (DEA) appearing in court in 2004 with the Hemp Industries Association and other sellers of hemp food-grade and body care products. The court decision was to permanently protect sales of hemp food and body care products. In 2014, President Obama signed the Farm Bill allowing research institutions to start pilot farming hemp (Ministry of Hemp, 2019). In 2018, the Farm Bill was revised, removing hemp and any strain of cannabis containing less than 0.3%THC by weight from Schedule 1 of the Controlled Substances Act (ENCORE LABS, 2020). A national regulatory framework for hemp production in the U.S. was established with an interim final rule being applied in October 2019 (Nepveux, 2019; USDA, n.d.). After public opinion and lessons learned were reviewed in the 2020 growing season, the final rule of the Farm Bill was published in January 2021 and to be effective from March 2021 (USDA, n.d.). A Hemp eManagement Platform was launched allowing producers, states, tribes, testing laboratories, and sampling agents to manage and submit hemp information and mandatory reports to the USDA (USDA, n.d.). At a federal level under the Farm Bill, licences to grow hemp must be obtained with monitoring and regulations accepted by the USDA before cultivation begins (Nepveux, 2019). At a state level, farmers are unable to grow hemp in states that have not legalised its production within their borders (Nepveux, 2019).

In Europe in 1990, hemp was regulated under the Common Agricultural Framework, which authorised the production of hemp varieties with a THC content not exceeding 0.2% (Dwyer et al., 2020). At a national level, the current cultivation of industrial hemp with 0.2% or less THC is legal in most EU member states (0.3% in Austria and Luxembourg). Still, domestic extraction/production of CBD is regulated (Dwyer et al., 2020). In 2018, the French regulation guidelines were updated so only fibre and seeds of the plant may be used (Dwyer et al., 2020).

Even though the historical uses and benefits of hemp cultivation and products are known worldwide, most laws and regulations have been altered and/or passed in the 21st century. For example, Europe altered the 1990 hemp regulations in 2018; in contrast, the U.S. classed the cannabis plant, including hemp, as an illegal substance in 1970. The U.S. began testing on

hemp in 2014 and revised the federal and state regulations in 2018, removing hemp from Schedule 1 of the Controlled Substances Act.

New Zealand laws on medicinal cannabis and hemp

In New Zealand, the Misuse of Drugs (Medicinal Cannabis) Amendment Bill was passed on the 11th of December 2018. This enabled increasing access to medicinal cannabis for patients through a prescription from a doctor. Under the Misuse of Drugs Amendment Bill, licences can be obtained for cultivation activity, nursery activity, research activity for pharmaceutical purposes, position for manufacture activity, and supply activity (MoH, 2020a). In developing the regulatory framework for medicinal cannabis, the MCS, the government considered cannabis regulations in countries such as Australia, the UK, Canada, Germany, the Netherlands, and the U.S. (Rychert & Wilkins, 2015).

The New Zealand government decided to hold a referendum in November 2020 to decide the fate of the Cannabis Legalisation and Control Bill (CLCB). The public voted 50.7% opposing and 48.4% in support of legalising recreational cannabis, with 0.9% neither for nor against the bill (Kirkness, 2020). According to the New Zealand Drug Foundation, the results were close, but New Zealand tried to take a leap from regulated medicinal cannabis to the legalisation of cannabis which “scared a lot of people” (NZ Drug Foundation, 2020). According to a 2018 survey, 35% said cannabis should be legalised, 32% said cannabis should be decriminalised, and only 33% wanted to keep the current legislation (NZ Drug Foundation, 2018). Therefore, the road to legalisation or decriminalisation is still moving forward for New Zealand; however, it may take years or even decades for change.

In New Zealand, industrial hemp requires a licence for all operations, with the general licence allowing cultivation, processing, possession and supply of low-THC approved cannabis varieties, or a research and breeding licence issued on top of the general licence allowing the cultivation and processing of approved and non-approved varieties (MoH, 2021b). Low-THC hemp seeds can be grown, manufactured, and sold as food products (MoH, 2021b). Hemp grown as industrial hemp is allowed to be 0.35% THC (MoH, 2021b). Under the Misuse of Drugs (Industrial Hemp) Regulations 2006, licence holders can hold no more than 50 seeds and 20 industrial hemp plants for cultivation activities.

2.2.4 Growth of the industry

According to Hasin and Walsh (2021), the global cannabis plant market showed strong growth from 2015 to 2020. The projected worldwide cannabis plant industry is set to reach USD90.4 billion by 2026, whilst the 2020 market was estimated to be valued at USD20.5 billion (Wood, 2021). North America accounted for the largest market share in 2021. The high-concentration THC product segment dominates the industry, and the recreational segment is projected to be the fastest-growing segment. According to Rehm and Mantney (2020), North America is the prime example of the dramatic increase in THC exposure with new products and modes of

administration facilitating the uptake. They state that, “Oil cartridges can contain several hundreds of doses of THC, and regular users may use more of those cartridges a day”¹.

Internationalisation of the cannabis product industry is also occurring due to the UN in 2020 allowing the global trade of medicinal cannabis (Neal, 2020). This has meant there is an opportunity for entrepreneurs to establish at-scale operations in New Zealand focusing on exports and means foreign companies from countries with already established cannabis growing industries have a competitive advantage in the global market (Neal, 2020).

The global industrial hemp market size in 2020 was valued at USD3.61 billion with an expected compound annual growth rate (CAGR) of 16.2% from 2021 to 2028 (GVR, 2022). Hemp seeds held the largest volume share of over 40% in 2020. Specifically, in New Zealand, the opportunity to be involved in the export market is where the largest opportunity for growth lies, to create an approximated NZD2 billion industry by 2030 (Marsh, 2020).

2.3 The life cycle of the cannabis plant

2.3.1 Cultivation

The cannabis plant gene pool is characterised by a restricted number of biotypes and binomials (Clarke & Merlin, 2013). A biotype, binomial and species name are used to distinguish between different plant structures and ancestral use. The main three binomials (types) are *sativa*, *indica*, and *ruderalis* (Clarke & Merlin, 2013; Harmon, 2021).

The cannabis plant is located in the Cannabaceae family, known as the hemp family (Britannica, 2022). Within the Cannabaceae family, the only economically important species are the cannabis plant and humulus or hop plant, commonly used for brewing (McPartland, 2018; Britannica, 2022). Even though all cannabis plants can be grown in similar conditions, the narrow-leaf biotypes, *sativa* and *indica*, are the most commonly recognised, as they are used for recreational and medicinal purposes (Żuk-Gołaszewska & Gołaszewski, 2018).

Different strains and cultivars of cannabis are also present in today's market. A cannabis plant strain is defined as a plant created asexually through colonial propagation. Whereas a cannabis plant cultivar (or variety) is defined as plants created sexually through the propagation of seed (New West Genetics, 2016). The seeds of plants expressing characteristics of interest are selected and improved by humans through generations of selection (Silver, 2020). However, offspring of cultivars are reproduced by cloning to obtain genetically identical replicas; for seed cultivars to be identified, the breeder needs to backdate it through several generations for a reliable result to be obtained (Silver, 2020).

¹ Reprinted from World Psychiatry, 19(2), by Manthey, J., & Rehm, J. Cannabis and public health: A global experiment without control, p.193. Copyright 2020, with permission from John Wiley and Sons.

The cultivation of the cannabis plant has five main stages: cultivation, germination, seedling growth, vegetative growth, and flowering. Each step requires various levels of light, air, water, nutrients, heat, and a growing medium to manufacture food and grow (Cervantes, 2006). According to Clarke and Merlin (2013), most importantly, cannabis plants need well-drained soils or growing mediums, as they don't like to be in moist conditions continuously. The stages of cultivation stated below are averaged, not set standards, because growing styles are different for each facility. According to Cervantes (2006), germination takes 3-7 days and requires moisture, warmth, and air. Seedling growth needs nutrients added and requires 16-18 hours of light. Vegetative growth requires 16-24 hours of light until leaves expand. To trigger flowering, 12 hours of light followed by 12 hours of darkness every 24 hours is required. According to Pedrazzi et al. (2021), it is suggested the vegetative stage runs for 25 days with 18 hours of light/day, and the flowering stage runs for 50 days with 12 hours of light/day before harvesting. The cannabis plant can be cultivated indoors or outdoors (Zheng et al., 2021). The growing styles of indoor cultivation can also implement defoliation. Defoliation is when the leaves of a plant are removed during the cultivation process to allow for better airflow and light penetration since lights in indoor sites are usually only hitting the tops of the plants (G. Randall, personal communication, April 20, 2021). However, hemp is traditionally grown outdoors in large quantities where it is easily harvested, but it is also known to be grown indoors (GGS, 2021). Some growers believe growing hemp indoors for hemp oil makes the plant more terpene-rich, improving the smell and taste (Mallen, 2019).

When seeds reach the vegetative growth stage, it is apparent whether the plant is female, male or a hermaphrodite (i.e. both male and female) (Cervantes, 2006). For medicinal cannabis, only unfertilised female buds are wanted due to their high levels of THCA (a precursor of THC) which are therapeutically valuable (Żuk-Gołaszewska & Gołaszewski, 2018). According to Cervantes (2006), if male plants are grown, they are usually pulled before pollinating the female plants. Żuk-Gołaszewska and Gołaszewski (2018) also state cannabis seeds can be brought from certified sources and bred only to produce female flowers. Medicinal cannabis is grown using the sinsemilla technique, in which only unfertilised female flowers are harvested (Żuk-Gołaszewska & Gołaszewski, 2018).

The yield of the cannabis plant is subjective to many variables including:

- Different cultivars or strains
- Grow styles
 - Indoor or outdoor cultivation
 - If defoliation occurs during indoor cultivation
- What will the end resulting product of the plant be?

Alba (2020) states the content of the marijuana plant is based on the dry weight of 10–24% flowers, 1–2% leaves, 0.1–0.3% stalks, and <0.03% roots. However, these dry-weight mass fractions only add to at most 26.33%. The total mass fraction of the plant should be 100%, and therefore, this literature was disregarded. G. Randall (personal communication, April 20, 2021) discussed around 55% wet weight for flowers with a 45% wet weight fraction as waste

excluding the roots, which is more reasonable, considering flowers are the main product of medicinal cannabis plants. For hemp plants, the weight fractions are approximately 57.8% stem/stalk, 14.3% fibre, 10.1% seed and 17.8% waste residues (Eleni et al., 2021). These mass fractions can only be used as an estimate due to the many variables that affect the cannabis plant, as stated above.

Environmental impacts

Producing cannabis plants indoors is energy-intensive due to the equipment needed to keep the inside environment at optimal conditions (Smith, 2021). The following is the most frequently used equipment to control the cultivation climate: ventilation fans and ducting air-conditioning (dehumidifiers and space heaters), climate control system, high-intensity lighting, CO₂ injection into the environment (usually by burning fossil fuels), and pre-heating of irrigation water. (Pedrazzi et al., 2021; Smith, 2021). Due to the U.S. cannabis plant cultivation being more developed than here in New Zealand, the U.S. has more qualitative and quantitative data on the environmental impact of indoor production facilities. Mills (2012) completed research on the carbon footprint of indoor cannabis plant cultivation in 2012 for a modular growing set-up of four plants. He found the total energy usage was 6,074 kWh/kg yield with a carbon footprint of 4,600 kg CO₂-eq./kg yield. Mills (2012) found the highest energy usage came from lighting (33%), ventilation and dehumidification (27%), air-conditioning (19%), and transportation (12%). In 2020, Pedrazzi et al. (2021) completed research assessing the energy-saving potential of using gasification in indoor hemp facilities for energy, heat and biochar production. Pedrazzi et al. (2021) referenced Mills (2012) and found when a gasifier was used as the main source of energy, it can take 93.7% of the electrical load leaving 6.3% required from the grid.

From the gasifier, gasification biochar is produced, which allows up to 12% of the current anthropogenic CO₂ equivalent emissions to be offset. If the Pedrazzi et al. (2021) gasifier was implemented into the Mills (2012) system, the carbon footprint would reduce to 4,048 kg CO₂-eq./kg yield. Pedrazzi et al. (2021) summarised the current status of indoor cannabis plant cultivation well by stating, “indoor growing systems are affected by high specific energy consumption leading to the high [operational expense] and low overall sustainability”. Due to the cannabis plant industry being one of the fastest-growing markets globally over the last five years (Żuk-Gołaszewska & Gołaszewski, 2018, p.1), research into reducing the environmental impact would help improve the sustainability of the process.

Hemp is primarily grown outdoors, and there are many more studies on the environmental impacts of cultivation compared to medicinal cannabis. According to van der Werf (2004), the environmental impacts of cultivating one hectare of hemp for fibre were: eutrophication potential 20.5 kg PO₄-eq., global warming potential 2330 kg CO₂-eq., acidification potential 9.8 kg SO₂-eq., terrestrial ecotoxicity potential 2.3 kg 1,4-dichlorobenzene-eq., energy use 11.4 GJ, and land use 1.02 ha/year. Zampori et al. (2013) also completed a study on the LCA of hemp cultivation; they discovered that per hectare cultivated by hemp, -26.01 t CO₂-eq. was

produced if the uptake of CO₂ by the plants was considered. If the uptake by the plants was not considered, then 1.57 t CO₂-eq./ha was produced, with the largest area of concern being fertilisation which contributed approximately 37% of the total impact (Zampori et al., 2013). The impact of fertilisation was mainly due to ammonium nitrate phosphate (P₂O₅) production. Even though hemp has been grown indoors under similar conditions to medicinal cannabis, this is mainly when it is cultivated for seed. Therefore, the focus of this study is hemp grown outdoors and medicinal cannabis grown indoors.

2.3.2 Processing of waste residues

Currently, cannabis plant residues are managed differently in different countries (Table 1). Four main EoL treatments are discussed in the literature for the cannabis plant: landfilling, composting, anaerobic digestion, and incineration. Along with these methods, pyrolysis has been discussed in one research article for processing the waste plant fibres of hemp to produce activated charcoal (Vukčević et al., 2015). The methods described here are analysed further in Chapter 3.

Table 1: Cannabis plant residue EoL treatment methods utilised worldwide

Method Name	Method	Country	Reference
Landfill	Shredding and mixing a 50/50 mix of cannabis material and other organic or inorganic material	Canada Netherlands The U.S. Hungary	Alba, 2020; Spapens, 2011; Ochoa, 2019; Celitron, 2021; Wong, 2018
Compost on-site or off-site	Shredding and mixing a 50/50 mix of cannabis material and other organic or inorganic material	Hungary The U.S. Canada	Gorrie, 2018; Wong, 2018; Celitron, 2021; Ochoa, 2019; Alba, 2020
Anaerobic Digestion – large or small scale	Shredding the cannabis material before putting it into the digester. Once digestion is complete, dewatering occurs to obtain the products of solids and liquids.	Hungary Canada	Celitron, 2021; Alba, 2020; Gorrie, 2018
Incineration	The cannabis material is dried before being incinerated producing ash.	Hungary	Celitron, 2021

Regulations on disposal of residues

Under New Zealand laws, the method of disposal/destruction needs to make the cannabis plant material undesirable, unrecognisable, and unfit for human or animal use, as well as being incapable of growth or germination (MoH, 2020b). In other words, the MoH does not want the possibility of any chemicals from the cannabis plant making their way into the food chain, specifically the cannabinoids. In the amendment made to part 4 in the Guideline on the Regulation of Medicinal Cannabis in New Zealand, procedures for destruction must be documented along with any third-party arrangements for the destruction and disposal of waste material (MoH, 2020b). The amendment means that the waste residue does not need to stay

on-site; however, the procedure for destruction needs to be documented. These requirements mean composting with minimal treatment, as done in the U.S. (Ochoa, 2019), is not possible. In New Zealand, under the MCS, any mass from the plant that is not used as a product must be destroyed (MoH, 2020b). The suggested method to use for destruction is grinding the solids and absorbing the liquids of the plant. Then the material is mixed with other materials (yard debris, wood chips, sawdust, soil, manure, or vegetable-based grease or oils), resulting in at least 50% non-cannabis material. This plant mix can then be sent to an off-site composter, anaerobic digester, or landfill off-site.

In Canada, licenced growers must follow the regulations under the Cannabis Act. When the material is disposed of, it must not expose any individual to cannabis plant smoke or vapour, and it must meet all applicable federal, provincial, and municipal environmental potential legislation (Jackiw & Butler, 2019). The destruction of the cannabis plant material must also be completed in the presence of a qualified witness, with security clearance and records kept up to standard (Jackiw & Butler, 2019). Even though Canada's laws and regulations on growing and distributing cannabis are stringent, regulations under the Cannabis Act do not directly address the matter of disposal of cannabis plant waste material, with no mention as to specific methods of disposal that should be used (Government of Canada, 2022).

In the U.S., federally, cannabis is restricted and not regulated; each state develops their own regulations on the disposal of cannabis residues. For example, in Alaska cannabis plant waste is defined under the Marijuana Control Board of Alaska as cannabis plant waste (including roots, stalks, leaves and stems that have not been processed with solvent), solid cannabis sample plant waste (possessed by a cannabis testing facility), and other waste (Alaska Legislature, 2019). The regulations state that cannabis plant waste can be taken to a composting facility or other organic waste treatment facility. Still, the waste should be mixed with at least an equal volume of compostable materials (food waste, yard waste, or vegetable-based oils and grease) (State of Alaska, 2022). The waste can also be landfilled or undergo solid waste incineration, but the waste should be mixed with at least an equal amount of non-compostable materials (paper, cardboard, or plastic) (State of Alaska, 2022).

Australia takes a different route for disposal of cannabis plant waste regulations with destruction methods as follows: high THC plants ($>1\%$ THC) must be destroyed in a monitored incinerator or other tracked destruction. In contrast, low THC plants ($\leq 1\%$ THC) can be destroyed in local incineration or mulching processes - or the plant may be used for fibre if the licensee holds a state hemp licence (Australian Government, 2020). Similar to New Zealand, Australia requires the licence holder to have procedures that ensure all cannabis plant material not used for manufacturing medicinal products is disposed of and destroyed. The details on the destruction method and any arrangements with third parties must be disclosed, and arrangements must be in place with emergency services, police, and local government authorities (Australian Government, 2020).

Countries in Europe have different stances on the treatment of cannabis plant waste. However, the overall regulation on the treatment of cannabis plant waste is dependent on the activity

occurring when the waste is produced, classification is then made from the European Waste List (EWL) published in Decision 2014/955/EU (European Union, 2014). Under this decision from the European Union, cannabis plant waste can be treated using one of the following methods: composting, anaerobic digestion, direct agricultural recovery, landfill, or incineration (European Union, 2014). Although according to Pinto et al. (2022), the European waste hierarchy principle applies to the stated treatment, which promotes the use of recovery operations over disposal operations. Therefore, only special cases will allow the use landfill and incineration to dispose of waste.

2.3.3 Production of products from medicinal cannabis

The current cannabis products on the market around the world are (Nickus, 2022):

- Cannabis flower (bud): after the cannabis plants have been cultivated, the flowers are dried, weighed and packaged before shipping.
- Concentrate (oil): the seeds and roots are removed, and the flowers, stems, and leaves are put into a closed-loop extractor to produce an oil with a high proportion of terpenes and cannabinoids.
- Edibles: are cannabis-infused food or drinks that can be in just about any form imaginable and are made from either the flower alone or oil that has already been produced.
- Tinctures: are solutions produced from steeping cannabis leaves or roots in alcohol.
- Topicals: are cannabis-infused products, such as sprays, lotions, or balms, have complex production processes that vary with the desired product but are typical of those used in the cosmetics industry.

2.3.4 Production of products from hemp

The hemp plant has up to 50,000 uses (Vivek, 2019a). The current hemp products from stalk on the market worldwide are rope, textiles, insulation, paper, and fibreboard. The current hemp products from seeds are cooking/seasoning oil, dietary supplement, body care products, biofuel, flour, beer, granola, and protein powder, to name just a few.

For obtaining fibre from the hemp stalk, the mature plants are cut, and the stalks are baled and left on the field for about five weeks for retting (Vivek, 2019b). Retting is a process that causes the pectin to decay. Pectin is a structural acidic heteropolysaccharide that holds the primary hemp fibre to the core fibre together (Mahapatra, 2018). Retting makes separating the fibre parts of the stem from the non-fibre parts, such as the hurds (for paper and fibre board), easier. The next stage is breaking, which involves separating the dried hemp fibres from the wooden core and is currently done using a machine called a decorticator. Scutching involves beating the stem after breaking to ensure that the fibres and wooden cores are completely separated. The hackling comb separates the line fibres (for fine textiles such as apparel) from the tow fibres (for coarse yarn, pulp, and staffing) before they are twisted together and put on spinning bobbins.

Seeds are generally assumed to be ready when they begin to shatter. The seeds are taken indoors to be carefully cleaned, dried, mechanically screened (sieved), graded, and gravity separated. The seeds are separated according to their grade depending on what further processing is required; they may be left as either a shelled seed for sale or processed into hemp seed oil. The hemp seed oil can be extracted using several different techniques (Aliouche, 2019): the Soxhlet (SOX) extractor process requires a co-solvent added, the Percolation (PER) process requires the dissolution of solute, the Supercritical fluid extraction (SFE) processes uses solvent CO₂, the Ultrasonication (ULT) process uses an ultrasonic bath, and Pyrolysis (PYR). It's interesting that pyrolysis can be used to extract hemp seed oil through the collection of condensate and separation of the oil phase, but it is not a common method for disposal of the plant. The common by-product from oil extraction is hempseed cake which is used to make hemp-based protein powders and livestock feed (Bezzeccheri, n.d.).

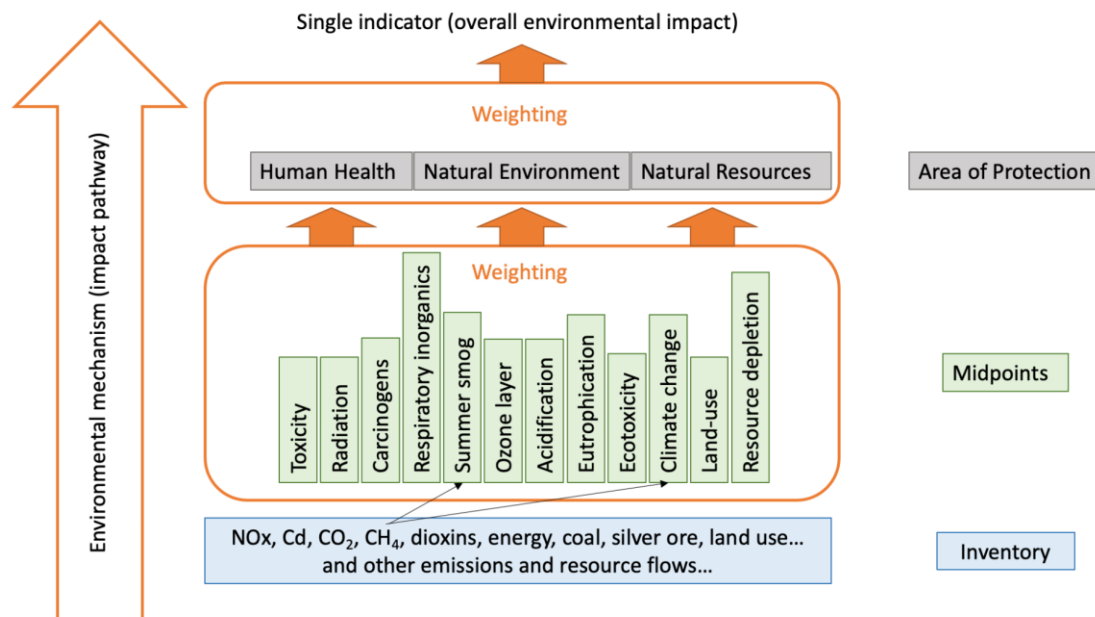
2.4 Life cycle assessment

Life cycle assessment (LCA) is the “compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle”² (International Standards Organisation, 2006). According to Bjorn et al. (2018), there are four main characteristics of LCA: takes a life cycle perspective, covers a broad range of environmental issues, is quantitative, and is based on science.

Four phases make up an LCA: the goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal and scope phase determines the scale and scope based on a well-defined functional unit (FU) (Eynde, 2015). The scope is defined by the system boundaries, which determine what activities will be considered in the study (Eynde, 2015). The inventory analysis quantifies the input of resources, products and materials and the outputs of products, emissions, and waste (Hauschild, 2018). Once all the inventory data has been collected, the impact assessment translates the information into environmental impacts through classification into impact categories (midpoints), characterisation, normalisation, and grouping or weighting (Figure 3). The results from the impact assessment are then interpreted to answer the underlying question(s) (Hauschild, 2018). The final steps of an LCA are a sensitivity and uncertainty analysis which enable the robustness of the conclusions to be verified and identifies areas that can be studied or improved upon in the future. However, Hauschild (2018) describes the iterative nature of LCA as feedback loops, using insights from the impact assessment to refine the inventory analysis. Therefore, the sensitivity and uncertainty analysis are not only completed in the interpretation but throughout the LCA, identifying key assumptions and data with the largest uncertainties.

² Reprinted from International Standards Organisation, 2006, *ISO 14040:2006(en) – Environmental management – Life cycle assessment – Principles and framework*, with permission. © ISO All Rights Reserved.

Figure 3: Inventory data to impact assessment transition (adapted from 238.700 course material, McLaren, 2021a)



In the scope definition phase, when system boundaries are created, either attributional or consequential modelling can be used for the LCA. According to Anaya de la Rosa (2013), system boundaries are defined by the scoping of the LCA, commonly, the system is split into processes in the foreground system and processes in the background system. The foreground system includes the processes controlled by the user and impact the background system. In comparison, the processes in the background system include those affected by the system but not under the direct control of the user. At a broad scale, an attributional modelling approach estimates what share of the global environmental burdens belongs to the output by assigning elementary flows and potential environmental impacts to a specific product system typically based on the history of the product (Ekvall, 2019). This is done in an attributional analysis by only accounting for direct environmental impacts produced by the processes in the foreground system (Anaya de la Rosa, 2013). The attributional diagram contains all inputs and processes necessary to produce a given output. In contrast, a consequential approach at a broad scale estimates how the global environmental burdens are affected by the change in a process or activity in the system by studying the environmental consequences of possible future changes (Ekvall, 2019). The consequential diagram shows the inputs and processes of the system relative to the functional unit and a change in the system. Although the attributional and consequential approaches are the two most prominent types of LCA, there are other factors that play a part such as the inclusion of system expansion and the consideration on the time perspective in place. System expansion is when system boundaries are expanded to include processes that wouldn't be classed within the typical attributional or consequential LCA but can be included in either approach. The time perspective assesses the impacts of the system in the past, present, or future. A retrospective LCA is completed for a past system and a prospective LCA is for a future system (Schaubroeck et al., 2021).

Chapter 3: Life Cycle Assessment of Alternative Options for Management of Cannabis Plant Residues

Medicinal cannabis and hemp plants are grown for different purposes, as discussed in Chapter 2. Typically, medicinal cannabis is grown for its flowers (buds); once these are removed, the residues include leaves, stalks, and roots. Medicinal cannabis is assumed to be grown indoors for this study; the growing mediums used include normal soil, coco coir, perlite, and rock wool (RQS, 2020). For this study, hemp is assumed to be grown outdoors in soil, and the residues are leaves, stalks, and roots (i.e. the seeds are harvested). If hemp is grown for both seed and fibre, the residues would be just leaves and roots. However, for consistency throughout this study, both medicinal cannabis and hemp plant residues are modelled as - stalks, roots, and leaves.

In this chapter, a life cycle assessment was undertaken of five alternative EoL management options for a medicinal cannabis plant cultivation facility operated by Zymbi Pharma Ltd (currently in the planning phase). The goal and scope of this study is defined with the functional unit (Section 3.1.1), system boundary (Section 3.1.2), case study (Section 3.1.3), modelling software and datasets (Section 3.1.4), LCA and modelling approach taken (Section 3.1.5), and data quality described (Section 3.1.6). The LCA modelling of the EoL treatments include a flow diagram, process description, mass and energy balance, and GaBi model description. The modelling begins with landfilling (Section 3.2), followed by composting (Section 3.3), anaerobic digestion (Section 3.4), incineration (Section 3.5), and finally, pyrolysis (Section 3.6).

3.1 Goal and scope of the study

The aim of this study is to identify and evaluate the environmental, social, and economic impacts of current EoL treatments used for cannabis plant residues in comparison to a proposed new EoL treatment, pyrolysis, through an LCA lens. Completing a life cycle assessment model for each of the EoL treatments used for cannabis plant residues will allow for the environmental impacts of each treatment to be assessed.

3.1.1 Functional unit

A functional unit (FU) is the unit of analysis for an LCA study and is based on the delivery of the same function across different scenarios. For this study, the FU was defined as ‘the management of one tonne of fresh cannabis plant residue’. The residue was composed of the leaves, stalks, and roots of the cannabis plant.

Depending upon which growing medium is used, small amounts of it may be attached to the roots and therefore, contribute small additional weight in the residue mixture. However, for this study it was assumed to be absent due to the wide variety of mediums available, and the small amount of absence of it in the residues. [Note: In the practical pyrolysis experiments reported in Chapter 4, the material for testing medicinal cannabis was a mixture of rock wool

and coco coir, and so small amounts of it were present in the tested samples. However, the material when testing hemp was soil which was able to be shaken off easily.]

It was assumed that the material entering the EoL treatment was at an ambient temperature of 20°C with a specific heat capacity of 1.6 kJ/kg.°C. The cannabis plant residues have an assumed moisture content of 71% on a wet weight basis which was calculated from a ratio obtained in the 2006 World Drug Report (United Nations, 2006).

3.1.2 System boundaries

The system boundary starts when the cannabis plant residue is collected and requires EoL treatment. The EoL treatments are described as:

- Landfilling: a shredded blend of fresh cannabis plant residue and green waste is mixed with bleach and sent to a landfill (Section 3.2).
- Composting: a shredded blend of fresh cannabis plant residue and green waste is sent to compost (Section 3.3).
- Anaerobic digestion: shredded fresh cannabis plant residue is added along with water to the digester, and the resulting sludge is dewatered before the solid by-product is sent to compost and the liquid by-product goes down the drain as trade waste (Section 3.4).
- Incineration: fresh cannabis plant residue is shredded, dried, and incinerated before the resulting ash is sent to a landfill (Section 3.5).
- Pyrolysis: fresh cannabis plant residue is shredded, dried, and put in a pyrolyser to produce biochar which is used as a soil amendment (Section 3.6).

Landfilling is a common EoL treatment method in New Zealand. Landfilling and composting are used by the U.S., the Netherlands, Canada, and Hungary. Canada and Hungary also use anaerobic digestion but only Hungary practises incineration. Pyrolysis is an alternative method that destroys psychoactive compounds and produces biochar. Depending on the quality of the biochar, it can be used for drinking water filtration, sanitation of human and kitchen wastes, and as an amendment to soils. When biochar is added to soils it modifies the soil function and offers a carbon sequestration benefit. The production and use of biochar is currently occurring in the Nandi district of Western Kenya, Costa Rica, Egypt, and India to name a few; research is also occurring in universities throughout the world (International Biochar Initiative, 2018; King, 2013).

A foreground and background systems are considered in this study which is shown in the flow diagrams (Figures 4, 6, 8, 11, and 14). The foreground system includes the activities which occur at the cannabis plant cultivation facility such as cannabis waste collection, shredding, mixing, anaerobic digestion, and thermal processes, depending on the EoL treatment being assessed. The background system includes activities that are occurring outside of the cultivation facility but are still within the system boundary so are still assessed for their environmental impacts. The background system can include landfilling, bleach production, composting, land spreading, wastewater treatment, heat generated, synthetic fertiliser production. However, for the landfill EoL treatment, organic waste that is used within the

foreground system is moved from its intended destination of composting, so the background system allows for the intended activity to be displaced. A similar method is used for the other EoL treatments, so that a comparison can be made through the addition and displacement of activities. This study does not include infrastructure creation such as buildings, equipment, or the creation of a mobile unit. It also does not include any activities occurring to the cannabis plants before the cannabis plant residues are collected such as cultivation, harvesting, or processing the plants to obtain the residues.

In summary, the system boundary begins when the cannabis plant residues are collected and ends when it gets to its final destination of being destroyed and unusable. For the EoL treatments, this includes landfill (landfill), composting (compost land spread), anaerobic digestion (compost land spread and trade waste treated at wastewater plant), incineration (ash to landfill), pyrolysis (biochar land spread).

3.1.3 Case study

Zymbl Pharma Ltd (Zymbl) is a new medicinal cannabis company in the process of being set up in Rotorua. Zymbl anticipates that approximately 30 tons of cannabis plant residues will be produced by the facility each year, with an eight-week cultivation cycle for each crop. Several assumptions are made for this case study, including the maintenance and harvest timeframes. It is assumed that after the eight-week cultivation cycle, there is one week of harvest and waste processing to reset the facility for the next cultivation cycle to start. However, the time to process the residue is completely dependent on the EoL treatment method being used. It is also assumed that two weeks per year are left for unexpected maintenance and breakdowns in the facility; this leaves 50 weeks per year for cultivation/harvesting cycles. The 9-week cultivation/harvest cycle with 5 cycles/year gives approximately 6 tonnes of residue produced per cycle for this study. However, as discussed in the literature review the amount of cannabis plant waste is dependent on several factors such as cultivation method, growth styles, defoliation, and cultivar (Section 2.3.1). The cannabis plant residue for medicinal cannabis consists of leaves, stalks, and roots.

In New Zealand, any cannabis plant residue is required to undergo EoL treatment on-site at the cultivation facility before being landfilled or composted (or any other further treatment). There are two options for the processing unit: it can either be stationary at the cultivation site, or the processing unit could be built inside a container and be mobile so that it can travel between different cannabis plant cultivation sites. The pros and cons of each option are set out in Table 2.

The mobile unit can process waste and from a business planning point of view, bring in revenue all year round. A stationary unit has reduced set-up time and no scheduling and waiting is required. For the landfill and composting treatments, fixed on-site at the cultivation facility is likely to be more suitable due to the small amount of equipment required for the operations. The residue can then be put into a dump truck for transport to either a landfill or composting facility. The composting EoL treatment assumes that when the residues arrive at the

composting facility, they would be one of many feedstocks due to the large scale of composting with minimal downtime. The anaerobic digestion EoL treatment would normally be similar with other feedstocks entering the digester to create minimal downtime. For a study of this size, calculating the emissions of solely cannabis plant residues and water entering the digester is the easiest option. The benefits of digestion occurring at the cultivation facility include utilising the biogas created to displace heating in the facility. However, anaerobic digestion is also a scale business, which leaves room for the cultivation facility to obtain further customers to use the digester during downtime. This is out of the scope of this study but should be investigated in the future.

The thermal treatments of incineration and pyrolysis are more likely to be mobile because it is not feasible to have the expensive thermal processing equipment only utilised for 5 weeks of the year. Rather, incorporating the thermal treatments into mobile units allows for their use throughout the year. As a result, this study modelled the landfill, composting, and anaerobic digestion - EoL treatments for permanent units, and the incineration and pyrolysis EoL treatments for mobile units. It was assumed that each mobile unit weighed 15.96 tonne, and it was transported 100km; the weight was based on the average load for a EURO6 lorry with a lorry size class larger than 32 tonnes in the ecoinvent database.

Table 2: Pros and cons of stationary versus mobile unit for cannabis plant residue EoL treatments

	Stationary	Mobile
Pros	• Minimal set-up time • No scheduling or wait time to process waste • Minimal transportation costs	• Can be used all year round • Can be relocated • Able to have employees working full-time • Meets the requirement to be destroyed on-site without needing transport permits
Cons	• Is only unused for a few weeks at a time depending on the EoL treatment* • Restricted to one location • Requires a trained employee but only on a part-time basis • Requires transport permits • Economic demands of running an entire plant • Demand from other residues in the region unknown	• It is uncertain if regulations would allow a mobile unit • Set-up time • Moving costs • Relocation time • Requires a transport vehicle • Requires power supply at every location or a generator

Note. *Landfill and composting treatments would take 5.33 days each. Anaerobic digestion would take 2.67 days to shred the waste and an assumed 30 days to digest it before being dewatered in 2 hours. The thermal treatments would each take 3 days. See Appendix A for calculations.

Throughout this study, on-site and off-site activities are discussed. On-site activities include any that occur at the cultivation and processing facility including the production and transport of the main materials (bleach or green waste) to be used on-site. The off-site activities include any that do not occur at the cultivation facility, for example, activities occurring at the landfill

or composting facilities. However, there is the exception of bleach produced off-site but used on-site which is still classed within the on-site activities.

3.1.4 Modelling software and datasets

While there are many other LCA software options such as OpenLCA and SimaPro, the GaBi Sphera (GaBi) was chosen because Massey University already held a licence for the software.

In the GaBi software, several different databases can be used. Using a single database for all EoL treatments allows for consistency and clarity when comparisons are made. The ecoinvent database and the GaBi databases were reviewed to assess their suitability for use in this study (Table 3). GaBi databases are much easier to use with straightforward processes that easily connect directly to one another for fast system creation. The ecoinvent database uses markets and market groups as connections between processes and uses partially aggregated datasets that require more system modelling by the user. However, due to the variety of technology processes available that were relevant to this study, it was decided to use the ecoinvent database.

Table 3: Pros and cons of databases available in the GaBi LCA software

Database	Pros	Cons
ecoinvent	• Well-documented and reviewed • A wide variety of technology options are available • There are NZ-specific datasets for electricity and technology mixes are available	• The use of markets and market groups makes it more complicated to use • Mostly only country-specific data for Europe or China is available • Must use rest-of-world (RoW) data for most processes
GaBi	• Easy to use • Simple to understand • Plenty of country-specific data for NZ electricity, technology mixes, slaughtering and processing, and soybean cultivation	• Minimal technology options available

In the GaBi database, three common types of datasets can be used: aggregated (agg), partly aggregated (p-agg), and unit process, single operation (u-so). Agg datasets are essentially a single output with collated environmental impacts of the dataset. P-agg datasets indicate a partly linked process which contain all environmental impacts of the dataset except for one or more flows that require additional modelling. The u-so datasets have a single output with several inputs and are used so that the impacts of specific input for the activity such as a ‘diesel production’ input for ‘diesel, burned in building machine’ activity can be modelled separately to see its specific impact. U-so datasets are also good if the system does not consider all the inputs for a specific activity (e.g. infrastructure creation in the form of ‘building of hall’ in a ‘drying of grass’ activity).

Several different impact assessment methods can be used when assessing the environmental impacts of a system. The ReCiPe framework has the broadest set of midpoint impact categories

(*ReCiPe*, 2016), using midpoint indicators from CML and endpoint indicators from Ecoindicator (*ReCiPe*, n.d.). For this study, *ReCiPe* 2016 v1.1 was used to present the environmental impact results of the LCA models. The *ReCiPe* framework has three different cultural perspectives: individualist (I) looking at short-term interests, hierarchist (H) the consensus model, and egalitarian (E) the most precautionary perspective. The hierarchist perspective was used in this study as it is the most commonly used perspective in LCA studies.

3.1.5 Expanding the LCA approach, and modelling approach taken

In a typical life cycle assessment (LCA), only the environmental impacts of the product system are assessed but for this study a wider approach was taken, incorporating the cultural, economic, social, and governance issues. A broader approach was taken because the feasibility of future systems such as these EoL treatments requires implementation that cannot be assessed solely based on environmental sustainability; implementation involves communities which brings culture and social impacts into account as well as the government legislation for the cannabis plant, and the economic feasibility of implementing a new EoL treatment.

The cultural perspective can be used alongside the consequential LCA approach for this study because Māori culture, at least takes interactions with the surrounding activities into account in a similar way to the LCA itself. The economic, social, and governance aspects can utilise either an attributional or consequential approach. Cultural considerations in research are important because this allows for a wider range of knowledge to be gathered as well as contributing to improving relations and collaboration between different cultures. The New Zealand indigenous people are the Māori. The Māori worldview incorporates the interconnectedness of everything living and non-living - and this defines the quality of life within ecosystems. Arguably, from this worldview, a consequential approach should be taken for the study as it aligns with the Māori view i.e. a focus on the impact that processes have and the need to balance that impact using other processes. The attributional approach utilises a more Western way of thinking i.e. considering the way things are in the system without considering the processes that must be added or displaced to balance the overall background environment. The cultural aspect of the study is discussed further in Chapter 6 along with the economic, social, and governance aspects.

According to Schaubroeck et al. (2021), a consequential LCA assesses the environmental consequences of a decision compared to a baseline scenario which is deducted to see the resulting difference. It was first thought that this study may have fallen into this LCA approach when taking the cultural perspective into account, but as no decision is currently being made about a future activity relative to an existing baseline, it was not considered appropriate to subtract the baseline scenario. However, this study also does not fall under the classic definition for an attributional LCA approach which assesses the environmental impacts of a system in the present (Schaubroeck et al., 2021). This study assesses the future environmental impacts of alternative EoL treatment systems that are not being utilised at present (Chapter 5). Therefore, a prospective attributional LCA is appropriate i.e. modelling the EoL treatment systems as they will be in future (Chobtang et al., 2017). However, this study also includes system expansion

as the background system processes account for additional or displaced activities when background products/materials are used in the future foreground EoL treatment systems. Therefore, the modelling approach used in this study can be described as a prospective attributional LCA with system expansion.

3.1.6 Data quality

Data required for modelling the EoL treatments were sourced from literature, engineering calculations and the ecoinvent database of the GaBi software. The mass of all processes was determined using a mass balance produced for each EoL treatment. The transport required in all treatments was calculated using mass balance calculations and used a default distance of 100km for any unknown distances.

For this study, inventory data was collected through:

- Primary data collection (directly by the researcher)
 - Pyrolysis system data was collected via experimental trials on medicinal cannabis and hemp.
 - Transport distances between locations for all EoL treatments were obtained from research and assumptions.
- Publications, open literature, LCA software and LCA libraries (secondary data)
 - All processes involved in the following process systems were obtained using literature data, mass and energy balances and LCA software:
 - Landfilling
 - Composting
 - Anaerobic Digestion
 - Incineration
 - Pyrolysis (secondary data was found for this, so a comparison to the primary data collected could be made)

An energy balance was completed for all treatments which allowed for comparison against the electricity requirements of activities such as ‘drying of grass’ inside the ecoinvent database. Any discrepancies between the engineering calculations and dataset electricity values are discussed in Appendix F for landfill (Appendix F.1), composting (Appendix F.2), anaerobic digestion (Appendix F.3), incineration (Appendix F.4), and pyrolysis (Appendix F.5) EoL treatments. Processes that occur “off-site”, i.e. not at the cultivation facility, such as landfilling and composting, utilised the electricity values given in the ecoinvent database. Within the ecoinvent database, there are New Zealand-specific electricity datasets in three different voltage levels: low, medium, and high. According to Itten et al. (2014), the high voltage level is above 24 kV, specifically for large-scale industries; the medium voltage level is between 1 kV and 24 kV, specifically for a medium to small-scale industry, service sector, or public building; finally, the low voltage level is below 1kV, usually for households. For existing process/process datasets, the electricity voltage dataset is specified. The ‘market for electricity’ NZ-specific datasets (for all three voltage levels) are valid from 2014 through to the end of 2017, since this is the most recent dataset in the ecoinvent database it was used.

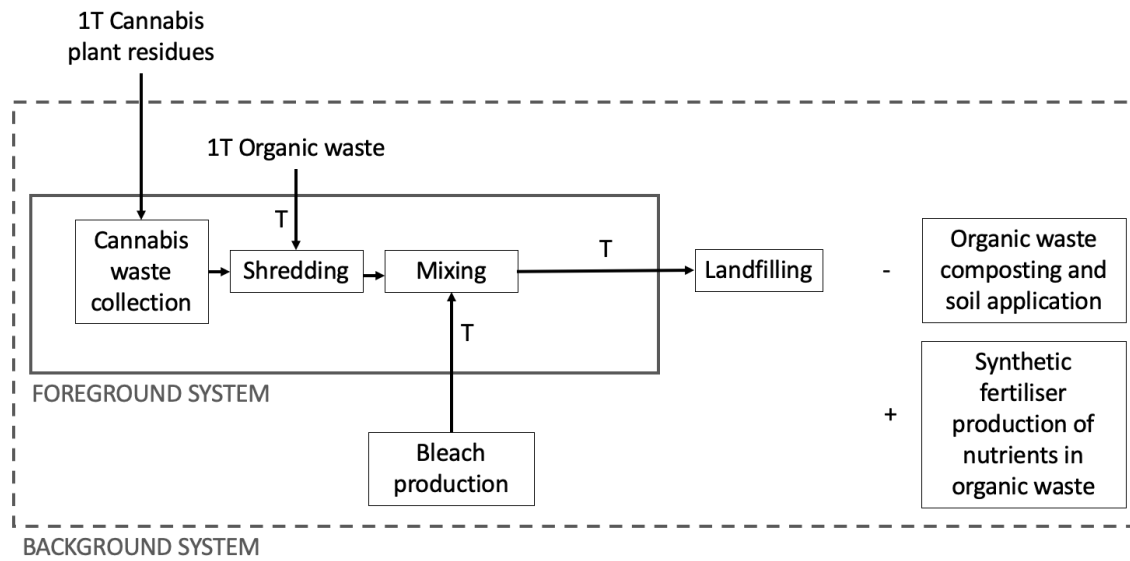
Emission data for all processes in all treatments were supplied in the ecoinvent datasets, except for the carbon sequestered and the N₂O suppressed in the pyrolysis treatment which were calculated using literature values.

For transport, the truck size for transport in the EoL treatments is determined based on the available size within the ecoinvent database as well as the required size based on the mass and energy balance for one cycle. The available sizes of freight transport trucks are 3.5-7.5, 7.5-16, 16-32, and >32 metric tons gross vehicle weight (GVW) and EURO6 emissions class. The GVW is the maximum total loaded weight allowed on the vehicle which can translate directly into the required mass to be transported by the vehicle. The EURO6 emissions class represents the legal emission standard requirement that the vehicle must meet (Appendix B). In the ecoinvent database, there are EURO1 through to EURO6 vehicles; however, transport vehicles are usually diesel based. While the European Union made all sales of new vehicles mandatory to be EURO6 compliance in 2015 (Dow, 2022), New Zealand was much slower to change their emission standards compliance requirements. As of July 2022, New Zealand requires new and used vehicles to meet EURO5 and EURO4 standards, respectively, when entering the country (Metcalf & Kuschel, 2022). According to Metcalfe and Kuschel (2022), the EURO6 standard was assessed in 2022 to estimate the air quality implications that would occur with its introduction between 2021 and 2050. However, the NZTA states that the EURO6 standard is mandatory for used vehicles when imported from Singapore; diesel vehicles first registered in Singapore on or after 1 January 2018, and petrol vehicles first registered in Singapore on or after 1 September 2017 (NZTA, 2022). For this study EURO6 vehicles will be used because New Zealand appears to be heading in that direction and there are many uncertainties if the vehicles are imports and if they are used or new. It should also be noted that the transport datasets used in this study are valid from 2009 through to the end of 2013 because since a EURO standard dataset is used, the emission data is unlikely to have changed since 2013 for New Zealand.

3.2 Landfilling

Landfilling is the most common EoL treatment method for any waste due to its convenience, enabling large quantities to be disposed of fast and at a low cost. Figure 4 shows the flow diagram for the landfill EoL treatment. It was assumed that organic waste was already present in the background system and if the organic waste was not being used in this process, it would have been composted. The original fate of the organic waste (organic waste composting and soil application) therefore was deducted as it was no longer taking that route. Furthermore, in the process of organic waste composting and soil application, the nutrients in the organic waste would have been returned to the soil. Therefore, the production of synthetic fertiliser nutrients equivalent to that in organic waste needed to be modelled to replace the nutrients no longer contributing to soil quality. It should also be noted that the organic matter content of the soil was not modelled as it was assumed that a negligible contribution was made to maintaining the organic matter in the displaced system.

Figure 4: Flow diagram of the landfill EoL treatment for cannabis plant residues



3.2.1 Process description

On the cannabis plant cultivation site, an industrial shredder (modelled using an ‘industrial wood chipping’ dataset), and a high-shear in-line mixer are used to combine the cannabis plant material with other organic material and sometimes sodium hypochlorite (NaOCl). The addition of NaOCl, which is commonly found in bleach, renders the material unsafe for human or animal consumption. This process ensured the cannabis plant material is unusable and unrecognisable (Celitron, 2021). Figure 5 shows the wet cannabis plant material (Stream 1) and organic material (Stream 2) fed into the shredder after which it enters the mixer. The non-cannabis material can consist of cat litter, plastic waste, sand, sawdust, or green waste (Government of Alberta, 2018). For this study, the non-cannabis material is assumed to be green waste added at a 1:1 ratio. The cannabis plant and green waste material must be shredded to the same consistency, so separation does not occur. When bleach is used as a disinfectant, the final bleach solution should have a NaOCl concentration of between 0.5 and 2% (Virginia Tech, n.d.). Therefore, to ensure the final mixture has a NaOCl concentration of 1.25%, approximately 25 kg of NaOCl is required. Bleach solution is purchased at a NaOCl concentration of 5.25–8.25% and so using an average of 6.75%, 375 kg of bleach is required per tonne of cannabis plant residues to obtain disinfection (Appendix C).

The purpose of mixing bleach into the cannabis plant mixture is to denature proteins and attack bacteria, breaking down the structure of the mixture (Bleach, 2022). When mixing is complete, the resulting mixture is put into a heavy-duty dump truck. Once the truck is full or all the cannabis plant material is used up, it is transported to the landfill. Bleach has a shelf life of six months, and then it starts to degrade; for this study, it is assumed that the bleach is transported to the landfill within six months. NaOCl decomposes at a second-order decay (Gray, 2014; Lister, 1956), as decomposition occurs H^+ ions are released which increases the pH of the mixture accelerating the rate of decay. According to *Sodium Hypochlorite* (2022), the

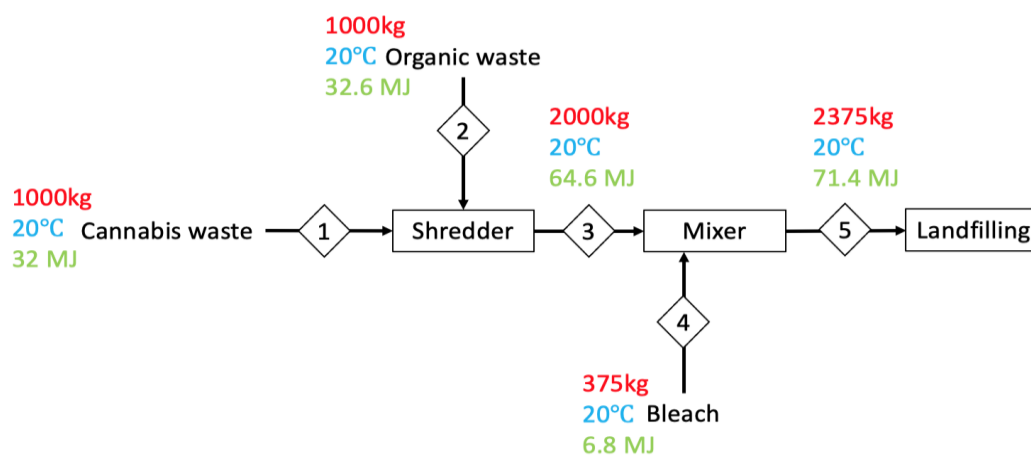
compound decomposes rapidly at room temperature. Therefore, it is assumed for this study that the decomposition of sodium hypochlorite has no environmental impact and therefore it is not modelled.

An assumed specific heat capacity of the cannabis plant material, green waste, and bleach was used to calculate the sensible heat flow of each stream and create an energy balance (Appendix D.1). The balanced streams allow for the EoL treatment to be modelled in GaBi.

It was assumed that the Rotorua cultivation facility treats the material before it is sent to the Ngāpuna transfer station, assumed to be 100 km away; the material is then transported from the transfer station to the Tirohia landfill, 119 km away (Rotorua Lakes Council, n.d.). The Guideline on the Regulation of Medicinal Cannabis in New Zealand under the Ministry of Health (MoH) and Medicinal Cannabis Agency (MCA) does not specify an EoL treatment method, location or what mixed cannabis plant material would be classed as at a landfill. It was assumed to be classed as general refuse. Even though the decomposition of NaOCl was not modelled in this study, the landfill site would still need to be made aware of the presence of bleach in the mixture.

According to the MfE (2020), the Tirohia landfill has landfill gas recovery (LGR). According to *Tirohia landfill* (n.d.), the technology used at Tirohia captures more than 95% of the methane gas and converts it into electricity to be sent back into the national grid. Another concern when modelling landfills is leaching. Leaching is when the water has flowed through a solid and the liquid leaches out of the landfill; the leachate is a highly concentrated mix of chemicals that can contaminate groundwater leaving it not suitable for domestic water use (Renou et al., 2008). As Tirohia is a Class 1 landfill, which must follow the Technical Guidelines for the Disposal to Land from WasteMINZ it also requires a leachate collection system to be in place. Therefore, an ecoinvent dataset modelling both landfill gas and leachate collection was used in this study.

Figure 5: Summary of mass and energy flows in the landfill EoL treatment



Note. See Appendix D.1 for mass and energy balance calculations and Appendix E.1 for energy requirement and consumption calculations.

3.2.2 GaBi Model

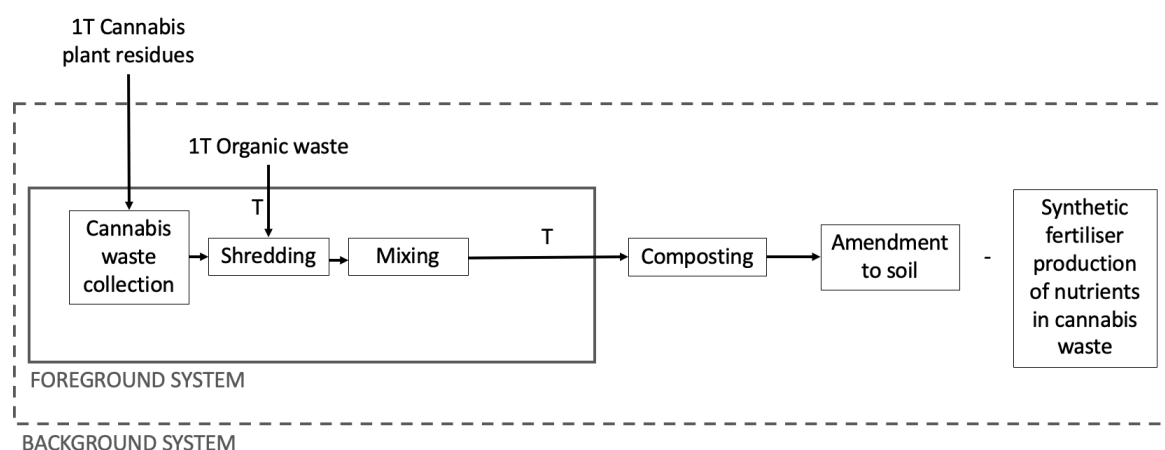
The landfill EoL treatment was broken into five sections: on-site activities (Appendix F.1, Figure 29), transport activities (Appendix F.1, Figure 30), off-site activities (Appendix F.1, Figure 31), organic waste composting and soil application (Appendix F.1, Figure 32), and synthetic fertiliser production (Appendix F.1, Figure 33). On-site processes consisted of shredding, mixing, and obtaining green waste and bleach. Off-site activities consisted of processes occurring after mixing on-site, i.e. transport and landfilling. Appendix F.1 describes the data decisions for this EoL treatment.

To account for the consequential scenario, the addition and subtraction of processes were made and are shown in Figures 32 and 33 (Appendix F.1). The note in Figure 32 describes the assumed mass loss of 19.4% from the initial weight due to composting from Breitenbeck and Schellinger (2004). The ecoinvent database only has two fertiliser production datasets: NPK (26-15-15) and NPK (15-15-15). A nitrogen mass balance was used to find the amount of fertiliser required to displace the volume of organic waste compost in this scenario. According to Biala and Wynen (1998), green waste compost has a nutrient content of 1%dm N, 0.18%dm P, and 0.83%dm K. The NPK (26-15-15) fertiliser production process dataset was used as it was the closest to the green waste nutrient value ratios. Therefore, approximately 12.4 kg of fertiliser per functional unit was required (Appendix G.1). It was assumed that all fertiliser inputs were produced in Germany except for dolomite which was produced here in New Zealand. Therefore, all transport from Germany or the New Zealand manufacturer had to be modelled as well. All material transported over land would be transported in larger quantities than specifically required for this study. Therefore, a >32-ton GVW transport is required using an assumed 100km for each transportation leg. The emissions for each transportation leg are allocated amongst the different materials being transported in each load so that emissions per functional unit can be obtained. For sea transport, a container ship would be used to transport the material. While many fertiliser inputs do come from Europe, they also come from other locations; however, Germany was the assumed location for this study.

3.3 Composting

Composting the cannabis plant material uses a similar method to the landfill scenario, involving shredding and mixing as shown in Figure 6. As discussed earlier, organic waste is assumed to exist already and would have been composted if it was not used in this process. Therefore, only synthetic fertiliser with equivalent nutrients to cannabis plant waste that would be applied to soil, needs to be subtracted because the organic waste is still composted and applied to the soil in this system.

Figure 6: Flow diagram of the composting EoL treatment for cannabis plant residues



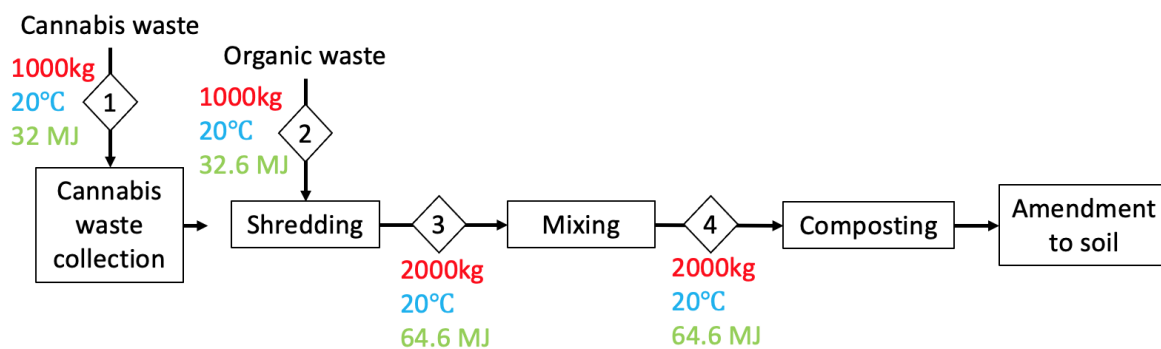
3.3.1 Process description

In the composting process, an industrial shredder, and a high-shear in-line mixer are used to combine the cannabis plant material and other organic material. Figure 7 shows the wet cannabis plant material (Stream 1) and organic material (Stream 2) fed into the shredder and then conveyed into the mixer. No bleach or other chemicals are added to the mixture as it would become unsuitable for use as compost (Commendatore, 2019). The non-cannabis material may consist of leaf and yard waste, food waste, animal manure, wood chips, grease, or other compostable oil waste (Government of Alberta, 2018). For this study, the non-cannabis material is modelled as green waste. The cannabis and green waste are added at a 1:1 ratio and shredded to the same consistency so separation does not occur. The final material is collected in a heavy-duty dump truck and transported to an off-site composting facility (assumed to be 100km away from the processing facility). Once the mixed material arrives at the off-site facility, water is added to obtain the recommended optimum moisture content of 50–70% (Richard et al., 2002). The mixture is stirred regularly to ensure oxygen oxidises the carbon in the organic matter and sparks the process; the carbon produces energy and heat (Logan, 2019). The mixture is also stirred because bacteria and fungi need oxygen to survive which manages the decomposition by converting the materials into compost, heat, carbon dioxide, and ammonium (Logan, 2019). Water maintains the microbes and fungi needed to carry out the decomposition. The fungi often break down the structures that contain the types of carbon rings found in THC and CBD-11. This complex interplay of factors means that well-performing compost systems are constantly monitored and protected from rainfall. Along with rainfall or stormwater management, leachate management, dust control and odour control are required in the management of composting facilities (MfE, 2009). There is also a potential liability associated with APIs (Active Pharmaceutical Ingredients) in waste discharge (Wong, 2018). APIs include THC and CBD-11, and they, therefore, need to be destroyed (Tucker, n.d.). A study completed by King and Hopkins (2020) produced three test compost piles with a starting THC content of 5.21%; after one month, the concentrations had decreased to 0.14%, 0.19%, and 0.47%; after two months, the THC could not be detected with a detection limit of 0.1% or lower. The THC testing looked for THCA-A, Delta-8-THC, and Delta-9-THC (King &

Hopkins, 2020). The minimum composting time recommended by King and Hopkins (2020) and the Nelson City Council (n.d.) was 8 weeks and 6-8 weeks, respectively, if the compost was well maintained and turned over regularly. The recommended optimal temperature inside the heap was 30°C–60°C (Nelson City Council, n.d.) and 55°C–65°C (King & Hopkins, 2020). Therefore, it was assumed for this study that the composting facility was managed to avoid the liabilities associated with APIs in the composted product.

The sensible heat flows of each stream were calculated from the mass flow of cannabis plant residue and assumed specific heat capacities of the cannabis plant material and green waste (Figure 7).

Figure 7: Summary of mass and energy flows in the composting EoL treatment



Note. See Appendix D.2 for mass and energy balance calculations and Appendix E.2 for energy requirement and consumption calculations.

3.3.2 GaBi Model

The composting EoL treatment method was broken into four sections: on-site activities (Appendix F.2, Figure 34), transport activities (Appendix F.2, Figure 35), off-site activities (Appendix F.2, Figure 36), and synthetic fertiliser production (Appendix F.2, Figure 37). On-site activities consisted of shredding, mixing, and obtaining green waste. Off-site activities consisted of composting. Appendix F.2 describes the data decisions for this EoL treatment.

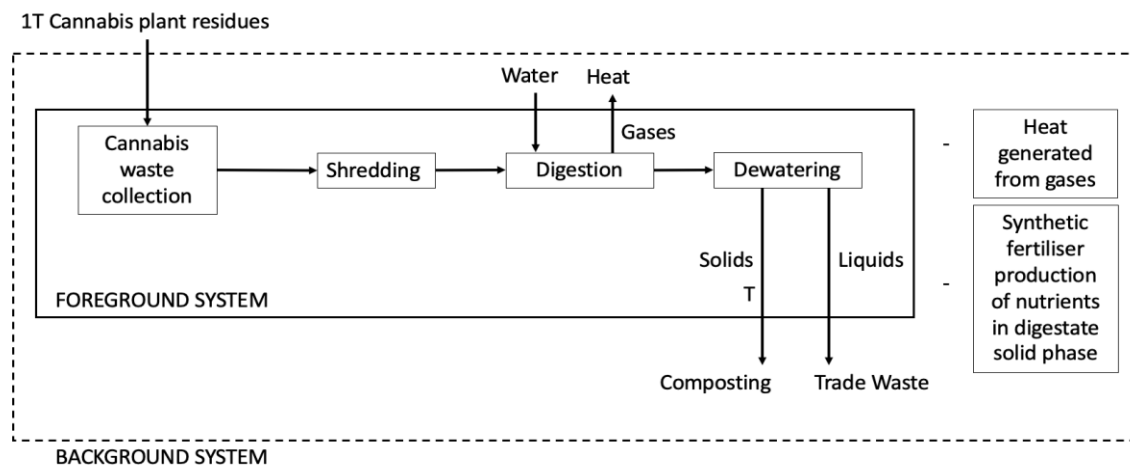
The synthetic fertiliser production of nutrients equivalent to the cannabis plant material needs to be accounted for (Appendix F.2, Figure 37). The cannabis plant waste was estimated using the average nutrient content of six common weeds: 3.64%db N, 0.52%db P, 6.20%db K, and 2.35%db Ca (Harper et al., 1934). However, due to the age of this publication only the nitrogen value of 3.64%db. was used to estimate the nitrogen nutrients in the cannabis plant material, and a fertiliser dataset was used to obtain the environmental impacts. The NPK (26-15-15) fertiliser production dataset was used as it represented the nutrient ratios of the cannabis plant the closest. Therefore, 40.6 kg of fertiliser was required to provide the soil with the same quantity of nitrogen (Appendix G.2). It was assumed that all fertiliser inputs such as potassium chloride were produced in Germany except for dolomite which was produced in New Zealand. Therefore, all transport from Germany or the New Zealand manufacturer was required to be

modelled as well. It was assumed that for the freight transport of fertiliser inputs large trucks would be required because of the distance and quantity that companies would be transporting. Therefore, >32-ton GVW trucks would be used to transport on land an assumed 100km on each route. Sea transport was assumed to be completed by a container ship. While many fertiliser inputs do come from Europe, they also come from other locations; however, Germany was the assumed location for this study.

3.4 Anaerobic digestion

Anaerobic digestion (AD) is described in the literature as being used in Canada and Hungary (Alba, 2020; Celitron, 2021; Gorrie, 2018). Figure 8 shows the flow diagram of the anaerobic digestion EoL treatment. The useful outputs of heat from anaerobic digestion and compost-containing nutrients from the solid phase of the digestate, need to be displaced for a comparison to other EoL treatments to be made.

Figure 8: Flow diagram of the anaerobic digestion EoL treatment for cannabis plant residues



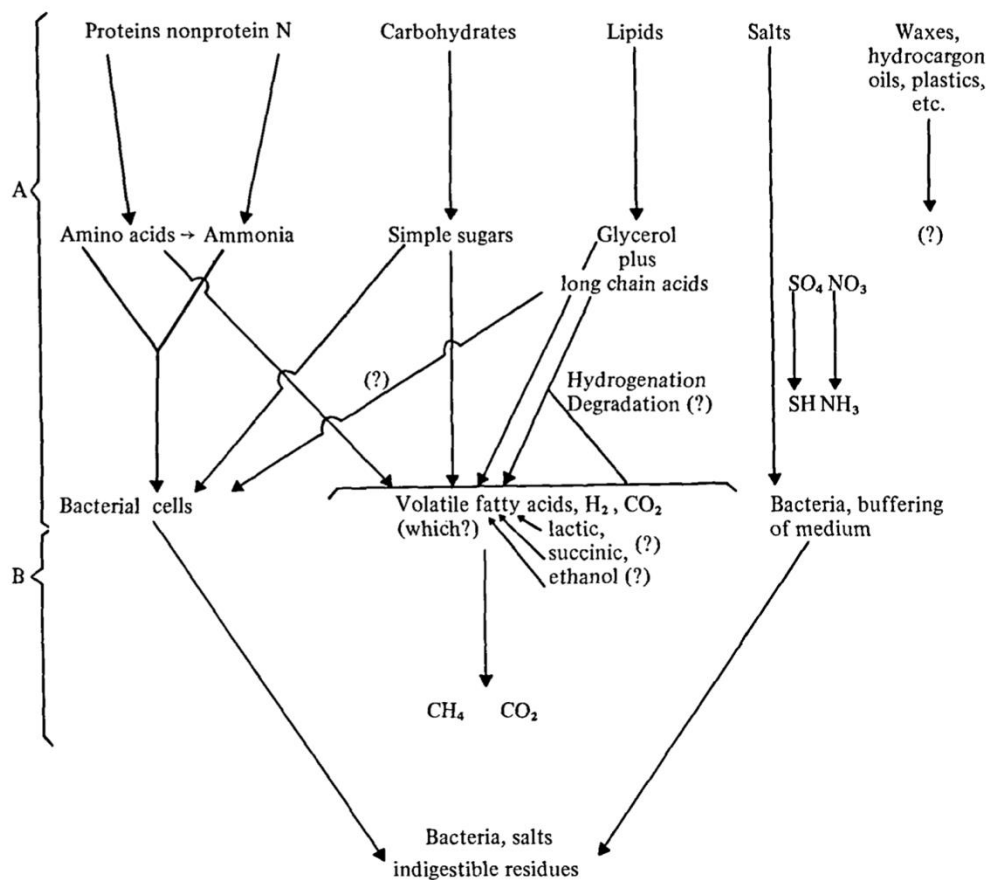
3.4.1 Process description

The cannabis plant waste is initially shredded to reduce its substrate size, but caution must be taken because, if the particles are too fine entering the digester, acidification can occur due to high waste solubility (Meegoda et al., 2018). The shredded cannabis plant is then put into the digester along with water (if required). Studies on hemp being anaerobically digested by Kreuger et al. (2011) and Kortekaas et al. (1998) do not discuss the addition of water into the digester. AD is when microorganisms break down waste material without requiring oxygen (Ward et al., 2008). There are four successive stages to AD: hydrolysis, acidogenesis, acetogenesis and methanogenesis. Figure 9 shows the pathways taken. Hydrolysis has an optimum temperature of 30–50°C with a pH level of 5–7 (Meegoda et al., 2018). According to Ward et al. (2008), the optimal temperature for reactors to be run at is 35°C and 55°C, for mesophilic and thermophilic temperatures, respectively. According to Yi et al. (2014), methane production increases with a total solids content between 5–20%, while in wastewater treatment

plants the typical feed solids percentage is 5–7% with a solids retention time (SRT) of 15–20 days (Coyne et al., 2017). At the end of digestion, bacteria, salts, and indigestible residues are the solid percentage of the sludge (Hobson et al., 1974; Logan, 2019). As the sludge is dewatered through the belt filter press, the solid and liquid phases separate. The solid phase is likely to only reach 50–80% solids without further drying. The solids are composted as they are unable to be land spread for soil amendment without further drying. The liquids or leachate on the other hand yields a BOD which incurs a trade waste cost when sent down the drain to the local wastewater treatment plant. Biogas is also produced by AD which is made up of approximately 65–70% methane and 25–30% carbon dioxide, with other gases such as hydrogen and nitrogen, making up the difference (Coyne et al., 2017).

One major question for this process option is if the cannabinoids in the cannabis plant residues would have been destroyed or not. Literature such as Alba (2020) did not describe whether this occurs but states that cannabis plant cultivation companies are using this process in Canada where the law, like New Zealand, requires the destruction of cannabis plant material in a manner for it to be unrecognisable and unusable.

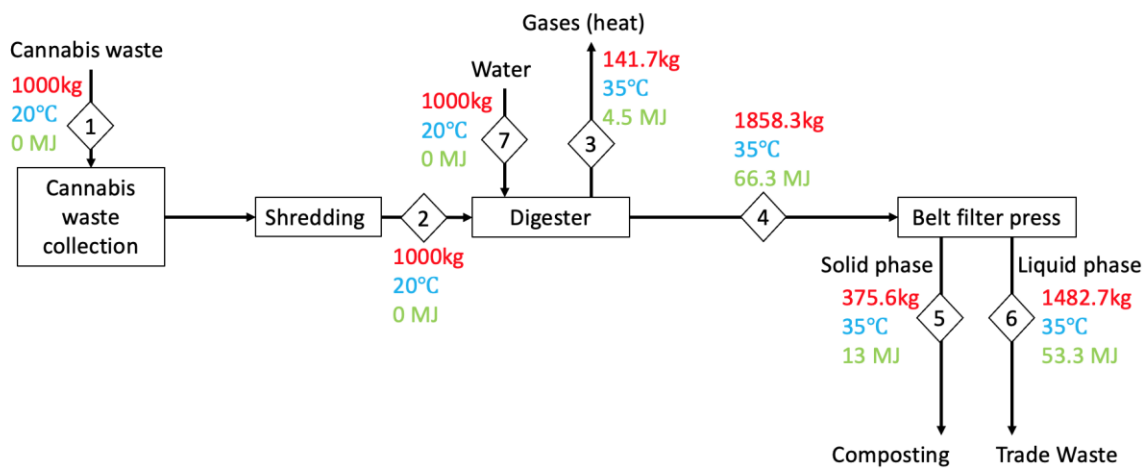
Figure 9: Reactions occurring in the anaerobic digestion process (from Hobson et al., 1974, see note)



Note. From *Anaerobic digestion of organic matter* (p.135), by Hobson, P., Bousfield, S., Summers, R., & Kirsch, E., 1974, CRC Critical Reviews in Environmental Control. Copyright 1974. Reprinted by permission of Informa UK Limited, trading as Taylor & Taylor & Francis Group, <http://www.tandfonline.com>.

Due to the cannabis plant material having a moisture content of 71%, the AD technology that would work with such a feedstock is modern dry with a total solid (TS) content greater than or equal to 20% (Yi et al., 2014). The anaerobic digester is assumed to run as a single-stage batch reactor using the mesophilic method, allowing for the cannabis plant waste to be loaded simultaneously with all processes occurring sequentially (Meegoda et al., 2018). Figure 10 shows the sensible heat flows of each stream which were calculated from the mass flows and assumed specific heat capacities of the cannabis plant material (Appendix D.3). Further information and testing is required to conclude the process parameters as many assumptions are made.

Figure 10: Summary of mass and energy flows in the anaerobic digestion EoL treatment



Note. Enthalpy was calculated at a baseline temperature of 20°C. See Table 24 (Appendix D.3) for a mass balance, Table 25 (Appendix D.3) for an energy balance, and Appendix E.3 for electricity consumption calculations.

3.4.2 GaBi Model

The anaerobic digestion (AD) EoL treatment was broken into five sections: on-site activities (Appendix F.3, Figure 38), transport activities (Appendix F.3, Figure 39), off-site activities (Appendix F.3, Figure 40), heat displaced (Appendix F.3, Figure 41), and synthetic fertiliser production (Appendix F.3, Figure 42). On-site activities consisted of shredding, AD, and pressing the digestate. The digestate solid phase was transported and composted in the transport activities and off-site activities, respectively. Appendix F.3 describes the dataset decisions made for this EoL treatment.

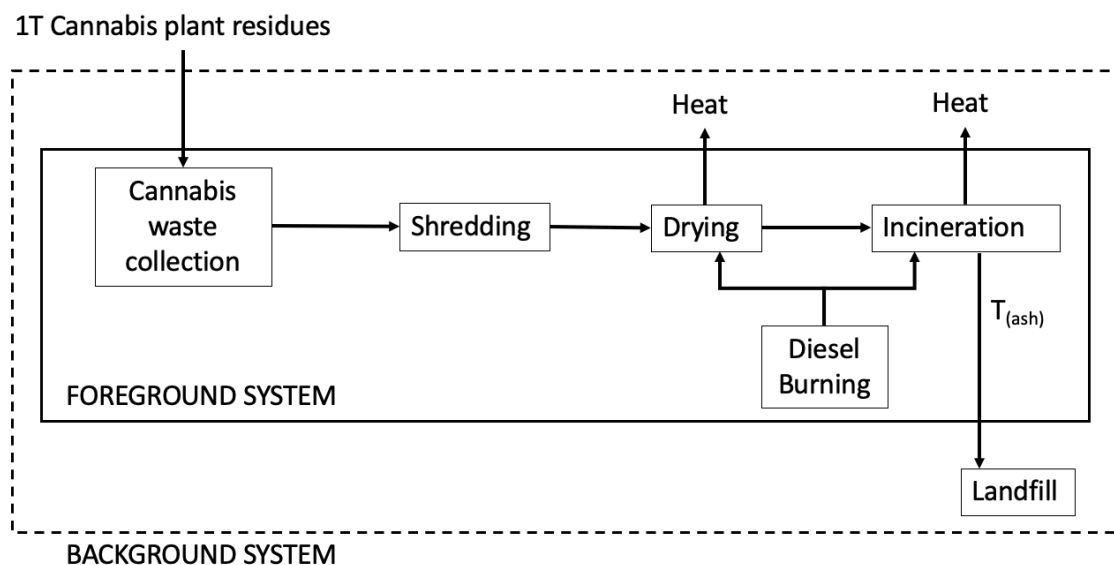
The NPK (26-15-15) fertiliser production dataset was used to show the fertiliser production that would be displaced if the solid phase of digestate was composted and put back into the soil (Appendix F.3, Figure 42). From the belt filter press, 375.6 kg of solids per functional unit were produced. According to NNFCC (n.d.), digestate solids have an average nutrient content: 0.325%db N, 0.085%db P, and 0.325%db K. The digestate solids have an 80% moisture content, therefore, 0.939 kg of fertiliser per functional unit was required (Appendix G.3). It was assumed that all fertiliser inputs were produced in Germany except for dolomite which

was produced in New Zealand. Therefore, all transport from Germany or the New Zealand manufacturer had to be modelled. It was assumed that large freight trucks would be required for all material transported over land. Therefore, a >32-ton GVW truck is required using an assumed 100km for each transport leg. The emissions for each transportation leg are allocated amongst the different materials being transported in each load so that emissions per functional unit can be obtained. For sea transport, a container ship was assumed to be the most appropriate. While many fertilisers do come from Europe, they also come from other locations; however, Germany was the assumed location for this study.

3.5 Incineration

Incineration is less documented but was still mentioned in Celitron (2019) as an EoL treatment method for cannabis plant material in the U.S. Figure 11 shows the flow diagram of the incineration EoL treatment. Since incineration is assumed to occur in a mobile unit for this study, the heat is unable to be captured. However, the potential heat captured could displace the use of natural gas on-site, therefore, it is investigated in the sensitivity analysis in Section 5.2.3.

Figure 11: Flow diagram of the incineration EoL treatment for cannabis plant residues



3.5.1 Process description

A garden chipper and industrial in-direct dryer are used to shred and dry the cannabis plant material before incineration, the resulting ash is then transported to a landfill. Incineration ensures that the cannabis plant material is unusable and unrecognisable (Celitron, 2019). Figures 12 and 13 show the mass and energy flow summaries for the start-up and operation of the incineration system. A one-hour start-up period uses a diesel burner to initially run some material through the dryer before assisting with the ignition of the incinerator (Figure 12). The cannabis plant material is dried to 20% moisture content before being conveyed into the

incinerator. MMIS (2010) describes destroying medical material in an incinerator operating at 600°C–900°C; this temperature range is also assumed to destroy the key compounds of interest in the cannabis plant, cannabinoids. From the incinerator, ash is produced along with flue gas. Ash is assumed to have no nutritional value and is sent to a landfill as inert waste. During operation, a portion of the flue gas is recycled to continue the drying and incineration processes (Figure 13). The energy requirement for the diesel burner, dryer, and incinerator is based on the estimated process time of the cannabis plant material calculated as two tonnes per day (Appendix E.4).

Figure 12: Summary of mass and energy flows of the start-up phase in the incineration EoL treatment

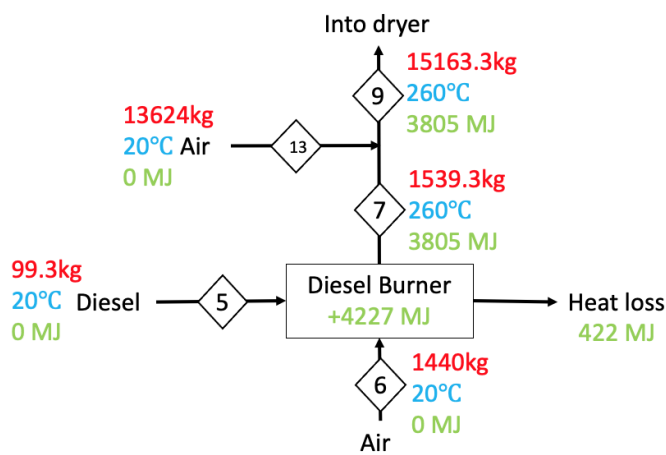
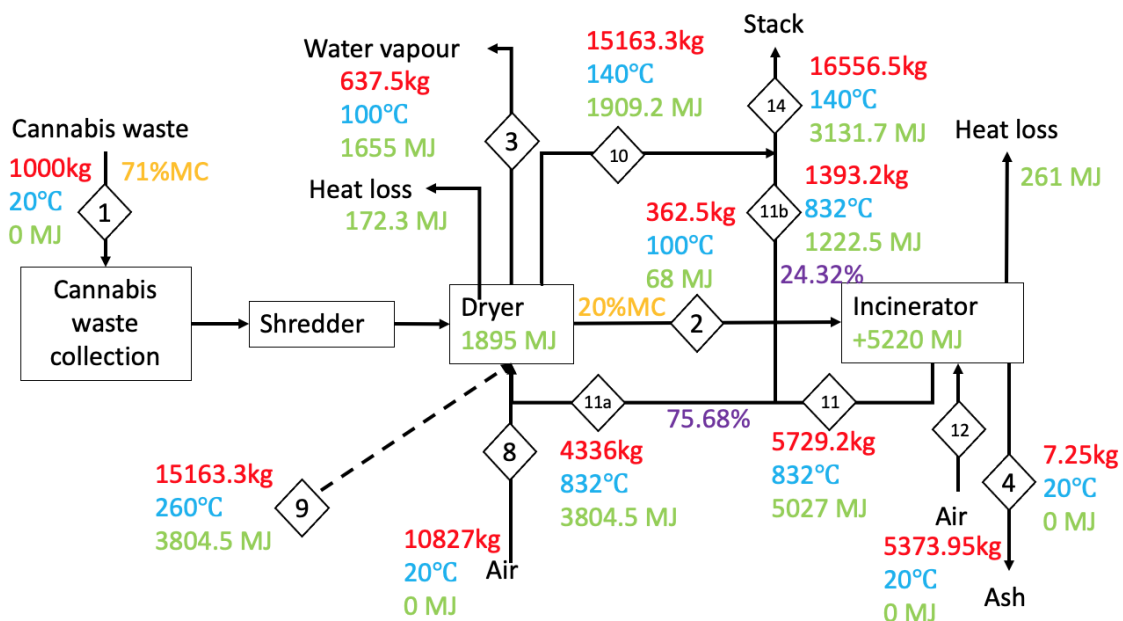


Figure 13: Summary of mass and energy flows of the operational stage in the incineration EoL treatment



Note. Enthalpy was calculated at a baseline temperature of 20°C. See Appendix D.4 for mass and energy balance calculations and Appendix E.4 for energy requirement and consumption calculations. Ash is assumed to fall through a grate and is removed at room temperature.

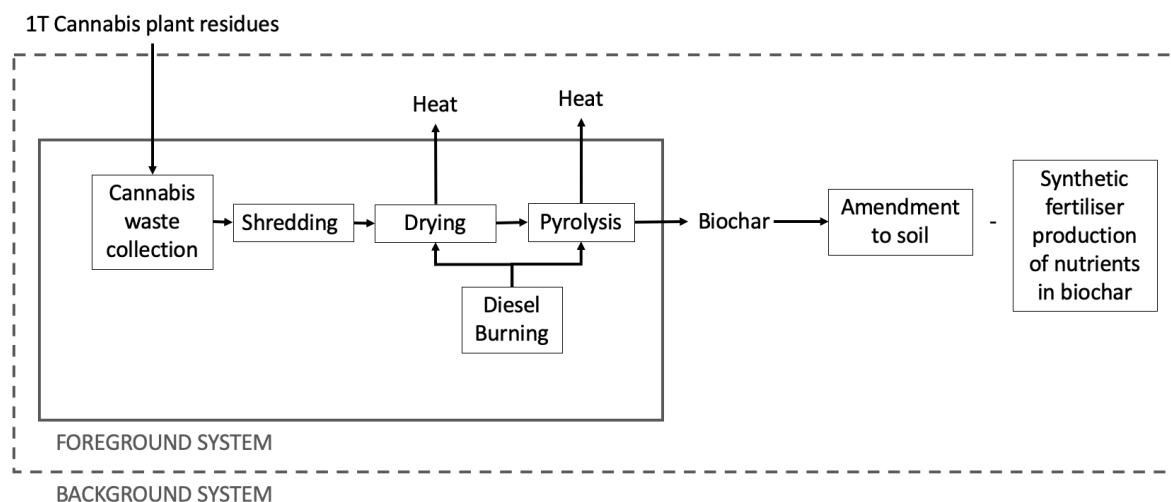
3.5.2 GaBi Model

The incineration EoL treatment was broken into four sections, transport of the mobile site (Appendix F.4, Figure 43), on-site activities (Appendix F.4, Figure 44), transport activities (Appendix F.4, Figure 45), and off-site activities (Appendix F.4, Figure 46). The mobile unit is required to be transported on-site before EoL treatment occurs. On-site activities consist of shredding, drying and incineration. The ash is transported to a landfill in transport activities. Finally, off-site activities included the landfill of the ash. Appendix F.4 describes the dataset decisions for this EoL treatment.

3.6 Pyrolysis

There is little to no literature on the use of a pyrolysis system for the EoL treatment of cannabis plant material. A flow diagram was created based on the literature on other biomass pyrolysis systems (Figure 14). Since pyrolysis occurs in a mobile unit, the heat is unable to be captured for reuse. However, the potential heat displacement that could occur if the heat is captured and reused instead of natural gas on-site is investigated in the sensitivity analysis in Section 5.2.3. The production of a synthetic fertiliser with an equivalent amount of nutrients to biochar which was added to the soil was displaced with this EoL treatment.

Figure 14: Flow diagram of the pyrolysis EoL treatment for cannabis plant residues



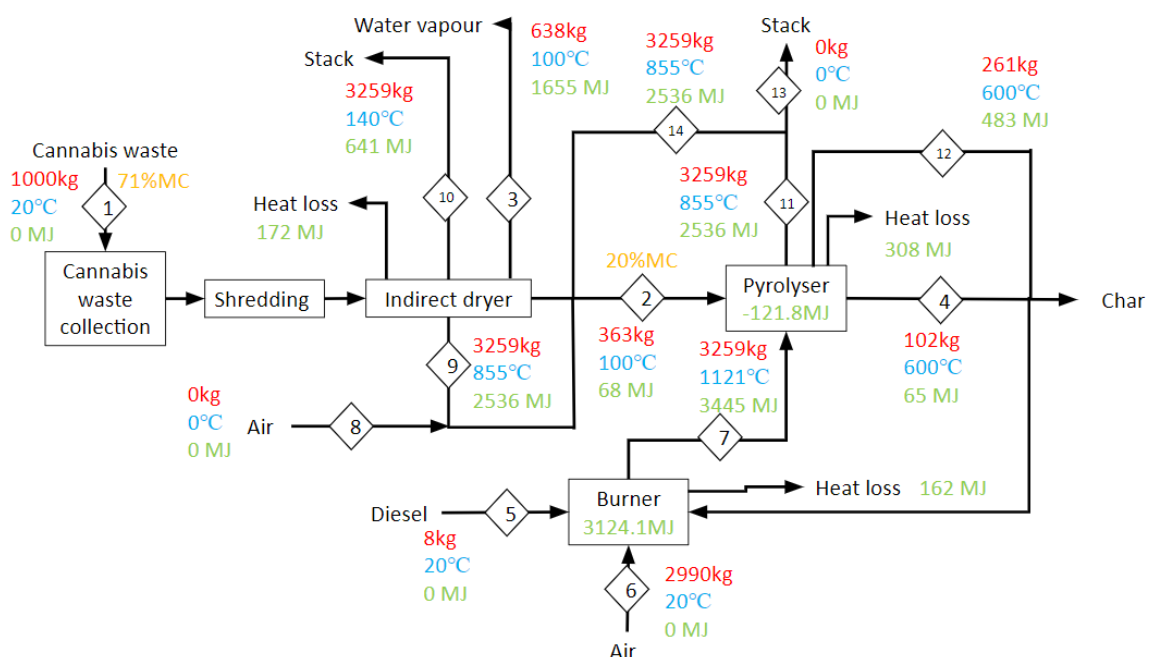
3.6.1 Process description

In the pyrolysis EoL treatment, a garden chipper, and an indirect dryer, are used to shred and dry the cannabis plant material before it is pyrolysed in an indirect pyrolysis unit into charcoal (biochar). A diesel burner is used to activate and consistently hold the heat energy required for the treatment. Pyrolysis can be completed fast or slow. Fast pyrolysis favours the formation of the condensable phase, and slow pyrolysis maximises solid char production (Jones et al., 2020; Steiner, 2016). Pyrolysis produces solid char, condensable liquid and non-condensable gases, the proportions depend on the rate of heating and the residence time of the vapours in the reactor (Jones et al., 2020). The wet cannabis plant material (Stream 1) and heat from the diesel

burner (Stream 9) enters the dryer during start-up. The dried material is then augured into the pyrolyser (Stream 2). Once the operation phase occurs (the required temperature is reached), the diesel burner switches and begins flowing through the pyrolyser; the flue gas from the pyrolyser then enters the dryer. Figure 15 shows the operational period, but the same amount of heat is assumed to be needed during the start-up except the heat goes directly into the indirect dryer instead of through the pyrolyser. The same process parameters were applied to both the start-up and operation of this EoL treatment as the same amount of diesel and heat is being used and produced during the two stages. To use the least amount of diesel, the volatile gases and water vapour that came off the material when it goes through the pyrolyser are recycled back into the diesel burner and used in conjunction with diesel to run the system. Therefore, the non-condensable gases exit through the flue gas pipes entering the gas stack where they are emitted along with the diesel emissions. Due to the unknown composition of the non-condensable gases, they were unable to be modelled in this EoL treatment. It was assumed for modelling that the dried material entering the pyrolyser had the resulting proportion of outputs, 35% char, 30% condensable volatiles, and 35% permanent or non-condensable gases.

Using the FU, the process was modelled using engineering calculations on GaBi. The sensible and latent heat of each stream was calculated using assumed specific heat capacities (Appendix D.5). The calculated capacities and flow rates allowed for the entire system to be modelled as accurately as possible; the environmental impacts were then calculated. The pyrolysis EoL treatment required the displacement of the fertiliser value added to the soil by the biochar to be accounted for. The land where the biochar was spread was assumed to be 100km away from the cultivation facility.

Figure 15: Summary of mass and energy flows in the pyrolysis EoL treatment



Note. The values in this diagram have been rounded to the nearest whole number. Enthalpy was calculated at a baseline temperature of 20°C. See Appendix D.5 for mass and energy balance calculations and Appendix E.5 for electricity consumption calculations.

3.6.2 GaBi Model

The pyrolysis EoL treatment was broken into five sections for modelling; transport of the mobile unit (Appendix F.5, Figure 47); on-site activities (Appendix F.5, Figure 48); transport of biochar to land (Appendix F.5, Figure 49); land spreading of the biochar (Appendix F.5, Figure 50); and the production of a synthetic fertiliser with equivalent nutrients to biochar (Appendix F.5, Figure 51). The mobile unit is required to be transported on-site before EoL treatment can occur. On-site activities include drying and pyrolysis. The char is then transported to be land spread, it is assumed that the biochar was spread over 2 km of land. Appendix F.5 describes the dataset decision for this EoL treatment.

The heating capacity of the diesel burner, dryer, and pyrolyser was calculated to be 0.24MW each, when the processing rate of the cannabis plant material per cycle was two tonnes of cannabis plant residues per day. The system was expanded to account for the avoided synthetic fertiliser production of nutrients equivalent to those in biochar. It was assumed that the nitrogen was not carried into the biochar from the cannabis plant material. The phosphorus and potassium content of cannabis plants or weed-like plant material can range from 0.1–0.8%db. P and 1.08–6.20%db. K (Bernstein et al., 2019; Harper et al., 1934; Kumar et al., 2012). The average was taken and used as the amount of phosphorus (P) and potassium (K) in the biochar material was assumed to carry into the land. The amount of fertiliser required to displace the nutrients that biochar would add to the soil was calculated to be 0.43 kg of P fertiliser and 6.94 kg of potassium chloride (KCl) (Appendix G.4). Both fertilisers were assumed to be produced in Germany and were modelled as such (Figure 51). It was assumed that the fertiliser inputs would be transported in bulk, therefore, required >32-ton GVW trucks to carry the weight over the assumed 100km for each transportation leg. The emissions for each transportation leg are allocated amongst the different materials being transported in each load so that emissions per functional unit can be obtained. For sea transport, a container ship was assumed to be the most suitable.

3.6.3 Management of condensable and non-condensable volatiles

The volatiles that come off the dried cannabis plant material during pyrolysis, Stream 12, consists of condensable oils, water, and non-condensable gases. While this stream was used in this model to reduce the amount of diesel required to run the thermal processes, there is an opportunity to capture the volatiles and water. The condensable oils are likely to contain cannabinoids which may be of value to a cannabis plant cultivation facility. To capture the streams an approximated system would consist of two condensers running at approximately 180°C and 90°C, to condense the oil volatiles and the water from the non-condensable gases.

3.6.4 Biochar

When char is produced from biomass, it is commonly known as biochar. The char produced from pyrolysis can be used for several applications due to its high carbon content and good adsorption nature (Antal & Gronli, 2003). The International Biochar Initiative standard states that biochar must contain at least 10% organic carbon (C_{org}), have an H: C_{org} molar ratio of less

than 0.7, not contain any toxic components, and be made from sustainable resources (Miles et al., 2016). The primary characteristics of the biochar produced from feedstock at different temperatures using different production technologies were analysed (Steiner, 2016); the closest matched feedstock to the cannabis plant was green waste and its characteristics are shown in Table 4.

Table 4: Basic characteristics of biochar produced from green waste at different temperatures (adapted from Ronsse et al., 2012, see note)

Feedstock	Carbon		Volatile Matter (%)	Ash (%)	pH
	Total %	Dry ash-free %			
Green waste					
300°C	64*	69*	49	6.8	8.1
450°C	73*	83*	19	12	10
600°C	77*	88*	8.8	13	11.3
750°C	81*	93*	1.9	13	11.6

Note. *Value calculated from dry and ash-free basis or total sample, respectively. Reprinted from GCB Bioenergy, 5(2), by Ronsse, F., van Hecke, S., Dickinson, D., & Prins, W. Production and characterization of slow pyrolysis biochar: Influence of feedstock type and pyrolysis conditions, p.107. Copyright 2012 Blackwell Publishing Ltd, with permission from John Wiley and Sons.

The impact that biochar amendment has on the physical properties of soil, regardless of soil type, remains consistent. Biochar decreases the soil bulk density with increasing biochar added, increases soil porosity, increases soil-specific surface area, and increases soil water retention/water-holding capacity (Guo, 2016). Similarly, when compost is mixed with biochar (40–50 wt.% of biochar) and then applied, greater nutrient availability is seen (Guo, 2016). Although this was not modelled in the pyrolysis EoL treatment.

3.6.5 Accounting for long-term storage of carbon and the suppression of N₂O emissions

The long-term storage of the carbon in biochar and the biochar's ability to suppress N₂O emissions was also accounted for in this EoL treatment. There are many ways for carbon to be accounted for in LCAs with a variety of methods and frameworks that are recommended (Chapter 6).

Long-term storage of carbon

Based on the engineering calculations 101.5 kg of biochar (BP) was produced per functional unit (Appendix D.5). For this study, it was assumed that 1% of the biochar was lost (BL) during transport. This left about 100.5 kg of biochar to be land spread per tonne of cannabis plant material. The calculated value to be land spread was similar to Anaya de la Rosa's (2013) value of 127 kg of biochar per tonne of biomass collected. To account for the land spreading of the biochar, the dataset 'transport, tractor and trailer' was used to account for the emissions of running agricultural equipment.

According to Lal (2016), carbon sequestration is the transfer and secure storage of atmospheric CO₂ into carbon (C) pools instead of being emitted or remaining in the atmosphere. If biochar was used in the soil as sequestered carbon, conditions must be met for a net carbon sink to be considered (Appendix H). Based on the same assumptions made in the engineering calculations, 82.50% of the biochar mass is carbon (CC). Of this total carbon content, a fraction is considered labile, increasing this fraction increases the likelihood that the carbon will turnover faster in the soil. Charcoal components are considered to have the smallest labile fraction, making up the stable soil organic matter pool in the soil which takes hundreds to thousands of years to turnover. The labile fraction of the total carbon pool must be calculated and not assumed to be sequestered within the standard 100-year considered when making estimations on climate change (Favoino and Hogg, 2008 as cited in (Colón et al., 2010)). The labile fraction was calculated using the carbon stability factor (CSF) as done in Anaya de la Rosa (2013). The CSF is the percentage of carbon contained in biochar that would remain in the soil longer than 100 years. One of the variables that affect the CSF is the pyrolysis temperature, which also determines the quantity and quality of biochar produced. Some articles discuss using a different CSF based on the pyrolysis temperature used, while others only describe the CSF without stating the temperature at all. Table 5 lists the CSF values available in the literature review, however, unspecified CSF values were left out of the table. Another variable that affects the CSF is the feedstock material, which varies from manure to wood chips to green waste to plant residue. Therefore, the feedstocks were also stated in Table 5 and the sewage sludge feedstock which was not applicable to this study was removed.

Table 5: Biochar carbon stability factors (adapted from Matušík et al., 2020, see note)

Reference	Feedstock	Pyrolysis temperature	CSF used
Hamedani et al. (2019)	Pig manure, willow woodchips	500°C	80%
Oldfield et al. (2018)	Oak residue	650°C	80%
Thers et al. (2019)	Oilseed rape straw	400°C	85.1% (after 20 yrs.), 57% (after 100 yrs.)
Uusitalo and Leino (2019)	Oat seed side flows, willow woodchips	Unspecified	50-90% C stable range (willow); 70% (oat side flows)
Bartocci et al. (2016)	Miscanthus, sorghum, hemp, black locust	Unspecified	Unspecified
Peters et al. (2015)	Poplar woodchips	Unspecified	Base case 90% stable after 100 yrs.
Llorach-Massana et al. (2017)	Tomato plant residue	400°C	3 scenarios C stable: 20%, 50%, and 80%
Ibarrola et al. (2012)	Urban biodegradable waste = sewage sludge, green waste, food waste, used cardboard, materials derived from waste treatment; paper sludge, poultry litter, whiskey remains	Unspecified	68% stable over 100 yrs.

Hammond et al. (2011)	Wheat straw, barley straw, oilseed rape straw, sawmill residue, forestry residue chips, wood chips, short rotation coppice chips, short rotation forestry chips, miscanthus, forestry residue chips from Canada	Unspecified	68% carbon stable after 100 yrs.
Brassard et al. (2018)	Switchgrass	459°C and 591°C	50% for 459°C biochar and 70% for 591°C biochar
Miller-Robbie et al. (2015)	Yard trimmings	450-500°C	80%
Muñoz et al. (2017)	Oat hulls, pine bark	300, 400, 500°C	80% stable after 100 yrs.
Clare et al. (2015)	Rice straw	Unspecified	80% after 100 yrs.
Sparrevik et al. (2014)	Cocoa shells	300-400°C	80% after 100 yrs.
Robb and Dargusch (2018)	Oil palm waste	280°C	Model equation: 350°C – 14.21%; 500°C – 58.57%; 600°C – 70.27%
Mohammadi et al. (2016a)	Rice straw, rice husk	Unspecified	69% stable fraction (over 1000 yrs.)
Mohammadi et al. (2016b)	Rice straw, rice husk	Unspecified	69% stable fraction (over 1000 yrs.)
Sparrevik et al. (2013)	Maize cobs	Unspecified	80%

Note. Reprinted from Journal of Cleaner Production, 259, by Matušík, J., Hnátková, T., & Kočí, V., Life cycle assessment of biochar-to-soil systems: A review, 120998, Copyright 2020, with permission from Elsevier. Reprinted from The Lancet, 259, Life cycle assessment of biochar-to-soil systems: A review, 120998, Copyright 2020, with permission from Elsevier.

Based on the range of literature CSF values found from 14%–90%, a mid-range conservative biochar carbon stability factor (BCSF) of 68% was assumed for this study as it was used for urban biodegradable wastes such as green waste in Table 5. This meant that 32% of the 100.5 kg of biochar produced per functional unit, 32 kg, was considered labile and lost within 100 years, leaving 68 kg of biochar per functional unit remaining long-term in the soil beyond 100 years. Using the gathered data, the following equation from Anaya de la Rosa (2013), was used to determine the avoided CO₂ due to carbon sequestration in soils for ≥ 100 years per functional unit:

$$CSQ = BP * (1 - BL) * CC * BCSF * CCR$$

$$\begin{aligned}
 CSQ &= 0.1015 * (1 - 0.01) * 0.825 * 0.68 * \left(\frac{44}{12}\right) \\
 &= 207 \frac{kg CO_{2-eq}}{t \text{ fresh cannabis plant material}}
 \end{aligned}$$

Where:

CCR = carbon to CO₂ conversion rate

Suppression of N₂O emissions

When applying biochar to soils there is also the opportunity for suppression of N₂O emissions from soils (Hammond et al., 2011). The rate at which biochar was applied to land, as well as the crop used for biochar, the crop is grown on the land biochar was applied to, and the CSF value used affected the amount of N₂O emissions that were suppressed (Hammond et al., 2011; Ibarrola et al., 2012; Roberts et al., 2010). However, further testing would be required to determine the rate at which biochar from cannabis plant material would need to be applied to obtain certain N₂O suppression levels due to the literature not being available.

When calculating the suppression of N₂O emissions, a case study of soil must be applied; for this study, the average N₂O field emissions from a non-organic apple orchard of 102 kg CO₂-eq. per ha per year were used (McLaren et al., 2009). The assumptions from Roberts et al. (2010) are that approximately 8.8 tonnes per ha would be required to suppress soil N₂O emissions by 50%. It was found that the incorporation of 100.5 kg of biochar into the orchard soils would suppress N₂O emissions by approximately 1.1 kg CO₂-eq. per functional unit (Appendix I). The calculated N₂O suppression is in line with the calculated value by Anaya de la Rosa (2013) of 1 kg CO₂-eq. per tonne of fresh pruning biochar.

The carbon sequestered in soils and the suppression of N₂O in soil was calculated and accounted for in the LCA modelling of the pyrolysis EoL treatment. Since experimental testing was being completed for this EoL treatment, a more accurate carbon content and biochar yield were found and used in a sensitivity analysis undertaken in Section 5.2.1.

Chapter 4: Pyrolysis Experiments on Cannabis Plant Residues

Pyrolysis experiments were completed to determine if the pyrolysis EoL treatment was viable for cannabis plant residues. Under New Zealand regulations, cannabis plant residues must be unusable and unrecognisable after EoL treatment. However, the New Zealand Government is also concerned with cannabinoids entering the ecosystem and food cycle. Therefore, during these experiments, the by-products from pyrolysis, biochar and condensate, were collected and tested to determine if cannabinoids were present. Biochar is the main product of concern as it has the potential to be utilised in further activities. However, the condensate was also investigated as potentially it could be captured and combusted to supply heat to drive the process.

This chapter describes the experimental research along with the results obtained, including: research design (Section 4.1), residue selection and collection (Section 4.2), data analysis techniques (Section 4.3), and the methodology and results for the pyrolysis trials (Section 4.4), proximate analysis (Section 4.5), and Py-GCMS experiments (Section 4.6). The methodological limitations are outlined and justified in Section 4.7 before recommendations for future research (Section 4.8), and a summary concludes the chapter (Section 4.9).

4.1 Research design

Zymbl were unable to supply medicinal cannabis plants, as was originally arranged. Therefore, an alternative supplier was sought who could supply medicinal cannabis plants that used rock wool as the growing medium – to keep the samples as representative as possible of what Zymbl were planning to use. After considerable efforts, Puro, a company that is New Zealand's largest cultivator of medicinal cannabis, was identified as a supplier of medicinal cannabis residues.

4.2 Experimental cannabis plant residue selection

Cannabis plant material was sourced from two different locations:

- Hemp plants were collected from an outdoor cultivation plot run by a PhD research student at Massey University. The hemp seeds were established for 23 days before being transplanted into the field on 26th November 2021; 66 days later, on 31st January 2022, the plants were harvested for this study. The hemp plants collected were from 12 different half-sib families, meaning they have one parent in common and are generated from one cultivar, Ferimon.
- Medicinal cannabis plants cultivated indoors in a mixture of rock wool and coco coir were sourced from Puro. Puro is a medicinal cannabis company based in the Marlborough region. The cannabis plants were collected when they exhibited bud growth and were determined by the cultivators to be ready for harvest. The cultivar

used for the medicinal cannabis testing was “Indoor dried THC variant cannabis - harvested 13/10/2022”.

The collection of the cannabis plants was completed by removing each plant from the majority of its growing medium either by pulling it out of the ground (hemp) or removing the root system from a pot (medicinal cannabis). When collecting the samples, an attempt was made to remove the growing medium from the roots. Hemp plants grown in the soil had the growing medium gently shaken off since the soil wasn't stuck in a root ball. However, the medicinal cannabis growing medium was much harder to remove because the root ball was much firmer in the pots. Therefore, effort was taken to remove a similar amount of growing medium as previously obtained in the hemp collection. In reality, at a commercial scale, separating the root balls from the growing medium would not be feasible.

Hemp collection

The hemp plants were pulled out of the ground instead of being dug out as the plants were extremely close to others that were required for another research project. A representative of the largest and the smallest plants based on height and stalk diameter, were each weighed whole, and each section of the plant (root, stalk, leaves) was weighed individually to establish a mass fraction ratio of the sections of the plants. Secateurs were used to remove the roots from the stalk just above the last outward root. The leaves and buds containing the seeds were clipped using scissors or hand-picked. Each part of the plant was separated into paper bags for pre-treatment drying, and the seeds were put into a paper bag for disposal by the plant growth unit technicians; as they are a product, they were not required for this study.

Medicinal cannabis collection

The medicinal cannabis plants were cut above the root system and processed by Puro to separate the buds (product) from the stalks and leaves. The stalks and leaves collected were weighed and those required for the experiments in this study were put into trays for drying while the rest was composted. The roots were removed from the pots and the growing medium was teased out before being sectioned with secateurs and put onto trays for drying. The roots were dried separately from the other plant sections because of the possible contamination from the growing medium.

4.3 Data analysis techniques for the pyrolysis trials and subsequent experiments of by-products

The data analysis techniques for this study included descriptive statistics and inferential statistics. The data obtained from the drying yields, pyrolysis unit yields, and proximate analysis components were analysed using descriptive statistics where the mean, median, mode, etc. were considered to be a good representation of the industry. The Py-GCMS results used

inferential statistics by correlating the data obtained with secondary data inside the GCMSsolution software, which allowed for chemical compounds to be identified.

4.4 Pyrolysis trials on cannabis plant residues

The pyrolysis trials for hemp were conducted at the Plant Growth Unit (PGU) at Massey University's Manawatu campus where licences were already held. The pyrolysis trials for medicinal cannabis were conducted at Puro. Trials were conducted in a semi-outdoor setting due to the temperatures being reached by the pyrolysis unit and the requirement of running water for the condensing unit. The pyrolysis unit was designed by the FIET Smoke Generator Research team and fabricated in the Massey University workshop (Figure 16). A condenser unit was then designed and fabricated in the Massey University workshop; the unit was added to the top of the unit to catch water, condensable gases, and oils emitted during pyrolysis. There was also a gas outlet, which let the non-condensable gases escape. The pyrolysis unit was connected through thermocouples to the National Instruments VI analyser software, which allowed for remote access to control the temperature as well as saving the data directly onto the Massey University servers.

Figure 16: Pyrolysis unit used during experimentation in this study



Pre-treatment

Due to the small size of the pyrolysis unit, the material had to be mulched or chopped small enough to fit inside the area around the furnace. For the hemp trials, after the plant material was chopped using secateurs, it was put back into its separate paper bags to be weighed before

going into a vacuum oven overnight at 60°C. The next morning the bags were weighed so that the initial moisture content could be determined. Each pyrolysis trial took one full day. As the plants were all mulched, separated into bags and put into the dryer oven on the same day, some plants were in the dryer longer than others. Therefore, all bags were weighed each day to keep consistent records of moisture content when entering the pyrolyser.

Due to Puro's harvesting process, the leaves and stalks were already mulched to a usable size and only the roots had to be chopped using secateurs. The leaves, stalks, and roots were dried to approximately 10% moisture content; the buds that were inside the drying room with the leaves and stalks used for this study, was tested using Puro's moisture content machine.

Samples

As the hemp industry uses the seeds and fibre (stalk), the leaves and roots were individually tested in the pyrolysis unit followed by a mixed sample of leaves, roots and stalks. The mixed sample was used to represent cultivation in the hemp industry for the sole production of seed. For the medicinal cannabis trials, the leaves and stalks were individually tested in the pyrolysis unit followed by a mixed sample of leaves, roots, and stalks. The leaves and stalks were tested separately because the medicinal cannabis root structure was bound in pots, which made their separation from the growing medium difficult. Commercially, the root balls would be shredded or crushed and mixed with the rest of the residues. The mass fraction of the mixed trials depended on the material available as much as obtaining a similar mass fraction to the plant's structure.

Start-up

First, the condenser section was unclipped from the unit and placed aside. Second, the material to be pyrolysed was then put into the kiln, approximately 245 ± 75 g, taking care to spread it evenly. Third, the condenser section was clipped back on top of the unit. Fourth, the thermocouple from the condenser and the pyrolyser power plug were then connected to the data box. Fifth, the hose from the water supply tap was connected to the inlet of the condenser and the outlet hose from the condenser was put into either a bucket or toward a drain. Sixth, the power cord from the side of the data box was plugged into a power socket and the unit was switched on and left for an initialisation period of around 10 minutes was run so the temperature of the thermocouples could stabilise. Seventh, the temperature profile was then set up through the VI analyser software. Once stable, the temperature profile was started.

Operation

The temperature profile set out in Table 6 is based on the recommendation of Dr Qun Chen and Professor Jim Jones; based on their pyrolysis experience where 250°C is just below the pyrolysis range, and 300°C, 350°C, and 420-450°C represent early, mid, and late extents of the pyrolysis reaction. The maximum temperature of the unit ranged from 420°C-450°C,

depending on the wind and atmospheric temperature on the day. There was no specific hold time at this highest treatment temperature (HTT) because once smoke stopped coming out, or no gas flow was detected, pyrolysis was deemed to be finished.

Table 6: Temperature profile of pyrolysis experimental trials

Temperature (°C)	Holding time (mins)
Room temperature	0
250	30
300	30
350	30
420-450	--

The products of pyrolysis were biochar collected in the kiln, and a mixture of tar and water (condensate) collected in the condenser. The biochar was weighed and placed in sample bags, and the condensate was collected in a glass jar. The bags and jar were stored in a fridge between 2–4°C, to preserve the sample for testing over the period of this study. Testing on the biochar required sample sizes ranging from 2-10 mg, so a coffee grinder run for 10 seconds allowed for an appropriate sample size to be taken. The condensate only required 2-3 mg sample sizes, so a pipette was used.

4.4.1 Hemp

Before drying, the average mass fraction of the fresh hemp plant when the seeds were not included was found to be 25.08%±0.01% roots, 53.69%±0.01% stalks, and 21.22%±0.02% leaves, on a total weight basis.

The root, leaf, and stalk were partially air-dried and then dried in an oven at 60°C for at least 24 hours; it was assumed that the samples reached equilibrium. The partial air drying obscured the ‘fresh-at-harvest’ moisture contents. The dried material was kept in the oven at 60°C until it was used for the pyrolysis experiment; the first trial of leaf sample bags 1-10 were dried for 36 hours, the second trial of root sample bags 1-3 were dried for 48 hours, and the third trial of leaf bags 7 and 11-13, stalk bag 3, and root bag 5 were dried for 60 hours (Table 7).

The masses on a total weight basis that were put into the pyrolysis unit were 218 g of dried leaves in the first trial, 181 g of dried roots in the second trial, and in the third trial 79 g of dried roots, 119 g of dried stalks, and 104 g of dried leaves were put into the unit. Even though the third trial mass fractions are outside the uncertainty levels for the fresh hemp plant, they are still reasonable estimations, with the stalk having a more significant mass fraction. To maintain consistency throughout this study, the same approximate mass fractions were used for the medicinal cannabis pyrolysis experiment. Figures 52-54 (Appendix J) show the specific pyrolysis temperature profiles for the leaf, root, and mixed residue experiments with the maximum temperatures reached.

Table 7: Weight records of the plant parts in the hemp pyrolysis trials (days of air drying before weight was measured)

Weights at harvest and air dried (g)													
Sample Bag Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Roots	132.03 (0)	150.91 (0)	133.65 (0)	122.82 (0)	156.11 (0)	10.88 (0)							
Stalks	301.4 (0)	221.95 (0)	301.43 (0)	72.64 (1)	98.5 (2)								
Leaves	74.53* (0)	56.82 (0)	49.57 (1)	47.94 (1)	47.47 (1)	67.2 (1)	48.48 (1)	65.95 (1)	42.06 (1)	33.65 (1)	48.68 (2)	46.13 (2)	45.91 (2)
Weights after drying, when used (g)													
Sample Bag Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Roots	56.50	63.73	60.75		78.79								
Stalks			118.89										
Leaves	21.71	19.7	25.54	24.21	21.95	33.34	22.43	29.71	19.28	15.14	35.54	31.21	29.96
Moisture content fresh (% wet)													
Sample Bag Number	1	2	3	4	5	6	7	8	9	10	11	12	13
Roots	57.21%	57.77%	54.55%		49.53%								
Stalks			60.56%										
Leaves	70.87%	65.33%	81.76%	82.13%	83.63%	82.44%	83.63%	84.06%	83.78%	84.08%	80.97%	82.36%	82.99%

Note. Not all samples dried were used in experiments, these dry weights are not included. *A calculation example is set out below.

Calculation example of moisture content for leaves sample bag number 1

$$\text{Moisture content \%} = \frac{\text{mass at harvest} - \text{mass after oven}}{\text{mass at harvest}} * 100$$

$$\text{Moisture content \%}_{\text{Leaf}(1)} = \frac{74.53 - 21.71}{74.53} * 100 = 70.87\%$$

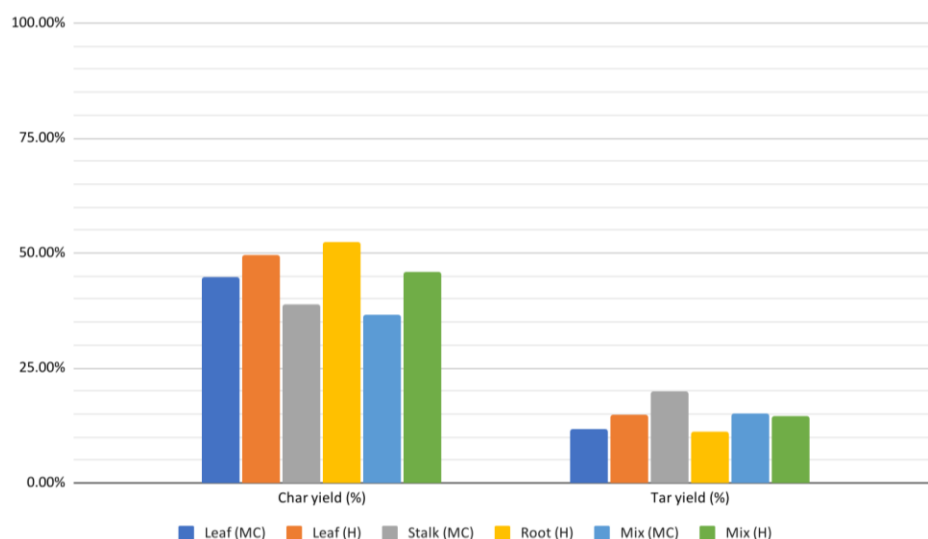
4.4.2 Medicinal cannabis

Figures 55-57 (Appendix J) show the specific temperature profiles for the leaf, stalk, and mixed residue experiments and the maximum temperatures reached. The masses on a total weight basis that were put into the pyrolysis unit were 230 g of dried leaves in the first trial, 206 g of dried stalks in the second trial, and in the third trial 91 g of dried roots, 137 g of dried stalks, and 114 g of dried leaves were put into the unit; this is a similar ratio to that used in the hemp trials.

4.4.3 Comparison of pyrolysis trial results

Figure 17 shows the biochar yields, which range from 35.6-52.5% on a dry basis. These yields are higher than many biomass pyrolysis yields (Hammond et al., 2011; Anaya de la Rosa, 2013) but within the range of others (Hasan et al., 2019; Al-Rumaihi et al., 2022), although there is no comparable data for cannabis in the literature. Interestingly, Figure 17 shows that the medicinal cannabis had lower yields than hemp, with the mixed pyrolysis trial having the lowest char yield for both hemp and medicinal cannabis. Also, a blue tinge was found on the collected biochar samples, with the medicinal cannabis stalk biochar having more blue presence than the hemp stalk biochar. The reason for these two observations is unknown.

Figure 17: Hemp and medicinal cannabis yields of biochar and condensate (tar) on a dry basis obtained from the Massey University pyrolysis unit



Note. The basis used for yield calculation is the mass of oven-dried feed to pyrolyser. The remainder is the non-condensable gas.

4.5 Proximate analysis of biochar collected from pyrolysis trials of cannabis plant residues

The proximate analysis study was performed using a NETZSCH STA 429 thermal analyser and following the ASTM E1131-08 standard test method. A baseline for each testing crucible was completed initially, which allowed for a temperature profile to be set up for the biochar tests (Table 8). Nitrogen was used as the purge gas to ensure that the sample does not combust during the first 4 stages of the analysis. The sample was heated at approximately 10°C/minute until the 105°C plateau, which removes the equilibrium moisture and establishes the dry biomass weight for future calculations. Subsequent heating was at 20°C/min to 900°C. In the ramp to 900°C, volatiles are evolved during anoxic decomposition. The residue is the fixed carbon. After a holding period at 900°C, the purge gas is swapped to air which reacts with the carbon to create CO₂, which is vented from the sample, leaving ash. Each sample size was between 5–10 mg.

The proximate analysis identified the biochar samples' initial moisture content, volatile matter, fixed carbon, and ash contents. Three duplicates were completed for each sample.

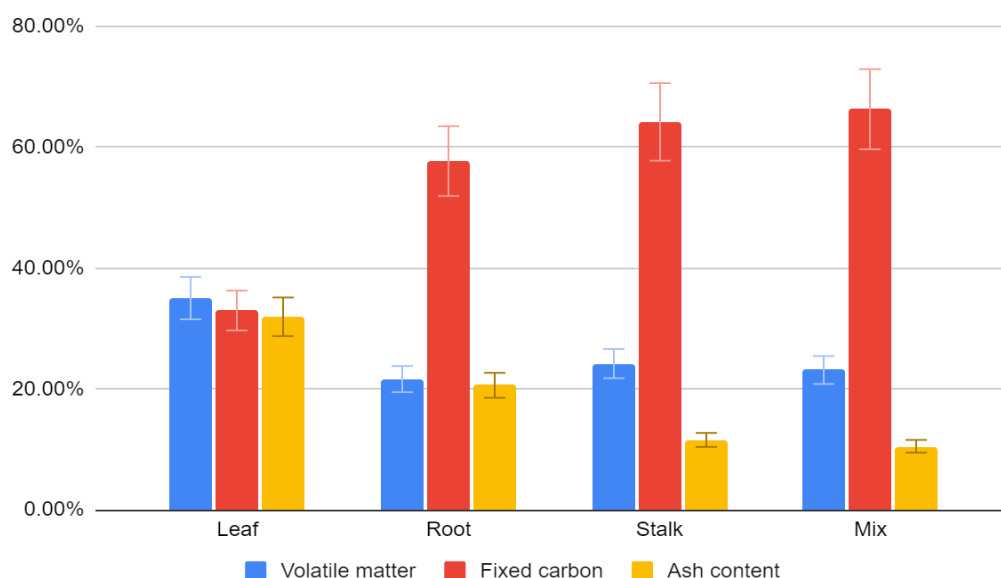
Table 8: Proximate analysis temperature profile

Gas type	Temperature (°C)	Holding time (mins)
Nitrogen	Room temperature	0
Nitrogen	105	40
Nitrogen	900	10
Air	900	30
Cooling		

4.5.1 Hemp

Figure 18 shows the results from the hemp experiments averaged over the three trials with the standard error calculated in EXCEL. The stalk was obtained from the mixed pyrolysis test as it held its structure and could be tested separately. A comparison with the medicinal cannabis results is made in Section 4.5.3.

Figure 18: Proximate analysis results of hemp cannabis plant residue biochar

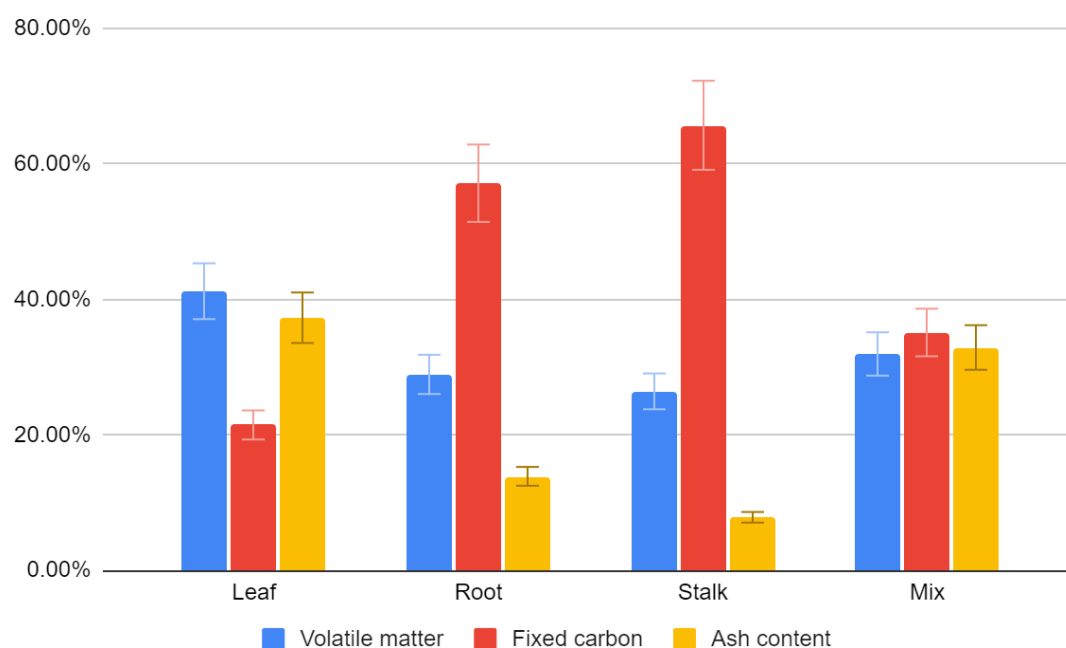


Note. Values are given on the basis of the dry biomass measured at the 105°C holding step during the temperature ramp (Table 8).

4.5.2 Medicinal cannabis

Figure 19 shows the results for medicinal cannabis with the standard error calculated in EXCEL. The root sample was obtained from the mixed pyrolysis experiment, as it held its structure and could be separated for testing.

Figure 19: Proximate analysis results of medicinal cannabis plant residue biochar



Note. Values are given on the basis of the dry biomass measured at the 105°C holding step during the temperature ramp (Table 8).

4.5.3 Comparison of proximate analysis results

Within the standard error in Figures 18 and 19, there are no discernible differences between the medicinal cannabis and hemp results. Across both, roots and stalks had more fixed carbon than the leaves, whereas the leaves had significantly more ash and volatile matter.

These results for roots and stalks are not dissimilar to the proximate analysis of green waste biochar at a pyrolysis temperature of 450°C obtained 73% fixed carbon, 19% volatile matter, and 12% ash (Ronsse et al., 2012 as cited in Steiner, 2016). Given the leaves were somewhat different and the reference is for a generic mixed species green waste, it is clear the composition of the initial plant material plays a large part in the final composition of the biochar; with the literature values not being for cannabis plants, the difference is expected.

The average range obtained from this analysis for both hemp and medicinal cannabis was then used to conduct a sensitivity analysis on the pyrolysis variables (Section 5.2.1).

4.6 Py-GCMS experiments on biochar and condensate from pyrolysis trials on cannabis plant residues

A pyrolysis unit on the front of a gas chromatography-mass spectrometer (Py-GCMS) heats 2-3 mg samples, decomposing them to produce smaller molecules that are then separated through gas chromatography. Biochar and tar were tested with up to three duplicate samples. After pyrolysis, the volatiles passed through a SHIMADZU GCMS-QP2010 using the following temperature profile (Table 9). The sample inside a crucible was inserted into the auto-sampling machine and held out of the heat, 250°C was reached, and the crucible was injected inside. The temperature climbed at a rate of 5°C/min. Once the chamber had cooled back down to room temperature, the crucible was removed and weighed in case any residue was not injected and remained. The results were saved on the computer connected to the Py-GCMS and the results were then able to be analysed.

Table 9: Py-GCMS temperature profile

Temperature (°C)	Holding time (mins)
40	4
250	0
280	20
Cooling	

The components could be identified from a Py-GCMS analysis of the biochar and condensate. Figures 58-70 (Appendix K) show the results from the Py-GCMS analysis, and Tables 27-32 (Appendix K) state the compounds identified using the libraries inside the GCMSsolution software. The resulting compounds identified were accepted when the similarity index (SI) was 80% or higher or if the only results presented by the libraries in the software had a SI of 70% or higher.

4.6.1 Hemp

Four biochar and three condensate samples were completed for the Py-GCMS analysis. Figures 58-61 (Appendix K) show the leaf, root, stalk, and mix biochar samples, with three duplicates constructed for each sample. Several similar compounds were identified through all the samples, including Tridecanoic acid, Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester, Diisooctyl phthalate, and Eicosane, 2-methyl- to name a few. Table 27 (Appendix K) shows the identified compounds in all the hemp char samples, with the outliers found by comparing all the hemp char samples shown in Table 28 (Appendix K).

Figures 62-64 (Appendix K) show the condensate samples for the leaf, root, and mixed pyrolysis trials, with three duplicates completed for each. Several similar compounds were identified in the condensate samples, including 2-Pentadecanone, 6,10,14-trimethyl-, Cannabidiol, and Octadecane, 2-methyl- (Appendix K, Table 29). The condensate results showed more variation than the char, with many more outliers occurring (Appendix K, Table 30). It should be noted that both collated outliers include repeated retention times; this is where multiple possible compounds were identified for a single retention time peak as one was unable to be determined.

The key compounds that were of interest in the GCMS analysis are cannabinoids which are discussed below as a comparison to the medicinal cannabis results where higher concentrations of cannabinoids are expected.

4.6.2 Medicinal cannabis comparison to hemp

Figures 65-67 (Appendix K) show the leaf, root, and stalk biochar samples for medicinal cannabis, with three duplicates completed for each sample. These results were compared to those of hemp's leaf, root, and stalk char (Appendix K, Table 31). The compounds that were found in both the hemp and medicinal cannabis char samples were:

- 1,1,1,3,5,7,9,11,11-Decamethyl-5-(trimethylsiloxy)hexasiloxane, found only in the stalk samples
- 2-Bromotetradecane, found in the leaf and stalk samples
- 2-methyloctacosane, found in the leaf and stalk samples
- 7,7-Diethylheptadecane, found only in the leaf samples
- Eicosane, 2-methyl-, found in the leaf and root samples
- Eicosane, 7-hexyl-, found in all samples
- Eicosane, 9-octyl-, found in the leaf and stalk samples
- Hexacosane, 9-octyl-, found in the leaf samples
- Nonadecane, 2-methyl-, found in the leaf and stalk samples
- Squalene, found in the leaf samples
- Sulfurous acid, pentadecyl 2-propyl ester, found in the leaf and root samples
- Tridecanoic acid, found only in the root samples.

Figures 68-70 (Appendix K) show the condensate samples of the leaf, stalk, and mixed pyrolysis trials for medicinal cannabis, with three duplicates of each sample, completed. The results obtained were compared against those found in the hemp analysis (Appendix K, Table 32). Since there are many similarities between the identified hemp and medicinal cannabis compounds, only the compounds present in all the condensate samples for both hemp and medicinal cannabis and the key compounds of interest are stated below. It is noticeable that the main cannabinoids of interest in the cannabis plant, CBD, and THC, are present in the condensate.

- 2-methylhexacosane
- 2-Pentadecanone, 6,10,14-trimethyl-
- Cannabichromene (CBC) - found in only the leaf
- Cannabicyclol (CBL)
- Cannabidiol (CBD)
- Cannabinol (CBN)
- Dronabinol (Δ^9 -THC)
- Heptadecane
- Morphinone, 7,8-dihydro-3-desoxy-
- Octadecane, 2-methyl-
- Phenol, 3-methoxy-2-methyl-
- Squalene
- Tetratetracontane

The concentration of a compound within the samples is determined by comparing the results to concentrated standards and calculating the area under the peaks. Due to the size of this study, this was unable to occur but comparing the size of the key compounds showed that THC had a much larger peak in medicinal cannabis compared to hemp, indicating the possibility that a more significant concentration is present. CBD, at a retention time of 45.75 minutes, had a possibly more minor concentration in the medicinal cannabis samples than hemp. At the retention time of 43.069 minutes, either CBD or CBL were identified. All samples show a similar peak size for CBD, CBL, and CBC.

Cannabinoids were only found in the condensate samples; this indicates that the pyrolysis system removed all the cannabinoids leaving a char free of cannabinoids. Char is the most likely by-product of pyrolysis that would have further purposes, options include its use as a soil amendment, filter, or to increase the porosity of a growing medium. The main concern of the Medicinal Cannabis Agency (MCA) and the Ministry of Health (MoH) is if cannabinoids have the potential to enter the food cycle within New Zealand or exposure to the ecosystem. This risk is avoided if the condensable fraction is combusted rather than collected so that all cannabinoids are destroyed. It is possible that the condensate could also have potential uses, including separating it into its water and oil phases. However, it would have to be an additional licensed activity which is out of the scope of this study.

4.7 Methodological limitations

The methodological limitations and trade-offs in this study included: sampling issues, selection bias, licencing and regulation requirements, analysis method limitations, and experimental limitations and trade-offs.

Sampling issues, selection bias, licencing and regulation requirements

The Guideline on the Regulation of Medicinal Cannabis in New Zealand states that a license is required for any location where any cannabis plant material will be used for experiments or stored (MoH, 2020b). This meant that a new license was required for the laboratory. After many telephone calls and hours of discussion with both the Medicinal Cannabis Agency (MCA) and the Ministry of Health (MoH), the MoH decided that a licence could not be provided for this study (Section 6.6.1). Therefore, the pyrolysis experiments had to be completed on-site at the cultivation facilities and using plant materials available at times when there was no Covid lockdown in place. A medicinal cannabis plant and hemp plant were tested for this study in order to be more representative of the two industries.

Experimental limitations and trade-offs

In an ideal scenario, the cannabis plant residues would go through a mulcher instead of being chopped by hand, before being dried and pyrolyzed. However, for such a small sample size for the experimental testing being so small, the cost of obtaining and running a mulcher for these experiments was not feasible. To imitate mulching, the cannabis plant material was broken up using scissors and secateurs as an alternative. This choice was justified as the next best option to reduce the material to a size able to fit in the pyrolysis unit's chamber given the budget constraints for this study.

The NETZSCH thermal analyser used to complete the proximate analysis testing ran up to approximately 900°C so the ash content that remained in the crucible was less than what the actual ash content would be due to certain heavy metals, if present, and alkali metals being vapourised at that temperature (Wang et al., 2017). No mitigation can occur for this limitation; therefore, a standard error uncertainty was used when analysing the results obtained from the proximate analysis.

The Py-GCMS machine leaked in the auto-sampling section of the machine. To mitigate the impact that this has on the experimental testing, manual input of samples was required which meant the testing of each sample took longer than expected. This was a justified method as the same outcome will be obtained from the results.

Despite the limitations discussed above, this study still provides value to the global industry as no other studies have created a comparison between EoL treatments.

4.8 Recommendations for future research into the pyrolysis EoL treatment

Replication of pyrolysis trials

This study tested one harvest of hemp and one harvest of medicinal cannabis, with no replicates. Future research should conduct additional pyrolysis experiments for the hemp and medicinal cannabis industries to replicate results and reduce the uncertainty associated with the biochar yields. This would give the industry more accuracy about the feasibility of pyrolysis as an EoL treatment and using biochar to create a circular economy.

Alternative uses of biochar

This study estimated data for modelling end uses of biochar; however, while the composition of the biochar was obtained, no experiments into biochar use were completed. Future research should focus on hands-on experiments to collect and compare quantitative data on the potential use of biochar for drinking water filtration, sanitation of human and kitchen wastes, and as an amendment to soils.

Flaring the pyrolysis by-product, condensate

This study assumed that the condensate was burnt to ensure the condensates do not enter the human food cycle. The cultivation facility can utilise the heat if it is collected from flaring the condensate. This requires further innovation in the pyrolysis mobile unit equipment.

Cannabinoids found in the pyrolysis condensate

This study found that the condensate collected from pyrolysis contained cannabinoids, the key compounds of interest in the cannabis plants. Future research should look into the methods for extracting them and how the industry could utilise them (provided there is enabling legislation in place).

4.9 Summary

To conclude, the experimental work described in this chapter aimed to support the evaluation of pyrolysis as a possible EoL treatment method for cannabis plant residues. In particular, it investigated whether the biochar produced during pyrolysis had any cannabinoids present. While no cannabinoids were found to be present in the biochar, they were present in the condensate. Therefore, this study has identified that pyrolysis is a suitable method for disposing of cannabis plant residues to produce cannabinoid-free biochar. However, the method does require the condensable phase to be combusted to destroy the cannabinoids.

The biochar yield results from the pyrolysis trials were within the range obtained from literature. The moisture and carbon content obtained from the proximate analysis tests are essential for calculating the potential carbon sequestration for the cannabis plant residues. Using these values, a sensitivity analysis was subsequently completed on the effect of the biochar yield on the total climate change impact for the pyrolysis EoL treatment (Section 5.2.1).

Chapter 5: LCA results for alternative end-of-life treatments of cannabis plant material

This chapter presents the LCA results for each alternative EoL treatment (Sections 5.1), and a sensitivity analysis of the climate change impact categories (Section 5.2).

5.1 LCA results and discussion for EoL treatments

This study used the ReCiPe 2016 v1.1 method (Huijbregts et al., 2017b). The method provides 19 impact categories. Four impact categories were omitted in this study as they were less relevant to the product systems under analysis:

- Land use and metal depletion: the processes assessed in the study all use relatively small amounts of land and metals compared to other economic activities. Therefore, these two impact categories are not considered relevant.
- Stratospheric ozone is constantly being created and destroyed; however, certain materials increase its depletion. According to MfE (2021b), ozone-depleting substances include CFCs, HCFCs, HBFCs, halons, methyl bromide, carbon tetrachloride, and methyl chloroform. These have been commonly used to produce refrigerants, foam-blowing agents, components in electrical equipment, industrial solvents, solvents for cleaning, aerosol spray propellants, and fumigants. For this study, none of these is commonly used. Therefore, the stratospheric ozone depletion impact category is outside this study's scope and was not assessed.
- The climate change including biogenic carbon impact category was not assessed in this study. When the climate change impact including biogenic carbon was studied, it was found that the biogenic carbon was not consistently accounted for in the different datasets in the ecoinvent database (see Section 5.1.1). However, the pyrolysis EoL treatment produces biochar which has the ability to store carbon long-term (Sections 3.6.4 and 3.6.5). Therefore, the carbon sequestration of the biochar was accounted for in the climate change excluding biogenic carbon impact category. In this study, the result for the climate change excluding biogenic carbon impact category together with the carbon sequestration of the biochar is referred to as the climate change impact category.

The impact categories assessed in this study are therefore:

- | | |
|--|--|
| - Climate change | - Ionising radiation |
| - Fine particulate matter formation | - Marine ecotoxicity |
| - Fossil depletion | - Marine eutrophication |
| - Freshwater consumption (inventory indicator) | - Photochemical ozone formation (ecosystems) |
| - Freshwater ecotoxicity | - Photochemical ozone formation (human health) |
| - Freshwater eutrophication | - Terrestrial acidification |
| - Human toxicity (cancer) | - Terrestrial ecotoxicity |
| - Human toxicity (non-cancer) | |

A general description of each impact category can be found in Appendix L. This section includes a comparison of the two climate change impact categories that are provided in the ReCiPe 2016 v1.1 assessment method (Section 5.1.1), the results for all the EoL treatments for each assessed impact category (Section 5.1.2), a discussion on the environmental hotspots of alternative EoL treatments (Section 5.1.3), a summary of the environmental impact of the alternative EoL treatments (Section 5.1.4), and a comparison of the synthetic fertiliser production climate change impact results to literature (Section 5.1.5).

As noted at the beginning of Chapter 3, the LCA results presented in this Chapter are generic to both the medicinal cannabis and hemp plants. This is because the modelling was completed on the basis of one tonne of cannabis plant residues - stalks, roots, and leaves.

5.1.1 Comparison of the two climate change impact categories available in ReCiPe 2016 v1.1

The ReCiPe 2016 v1.1 assessment method has two impact categories: climate change excluding biogenic carbon, and climate change including biogenic carbon. Biogenic carbon is the carbon dioxide (CO₂) released from the combustion and decomposition of organisms/organic material (Jan & Vladimír, 2022).

Through analysis of the climate change including biogenic carbon impact category, it was found that when transport and electricity activities are considered there is little to no difference between the climate change excluding biogenic carbon and climate change including biogenic carbon impact results. However, for activities which involve biogenic carbon the difference can be considerable. It was found that the results increased for all the EoL treatments (except for the **landfill** and **incineration** EoL treatments) when assessing climate change including biogenic carbon. The increase is surprising because one would expect, at least for the **composting** and **anaerobic digestion**, that accounting for the biogenic carbon storage would have decreased the overall climate change result.

The **incineration** EoL treatment impact did not change between the two climate change impact categories. The explanation is that all of the biogenic carbon in the cannabis plant residues is released into the atmosphere (as CO₂) during combustion, and this is the carbon that was

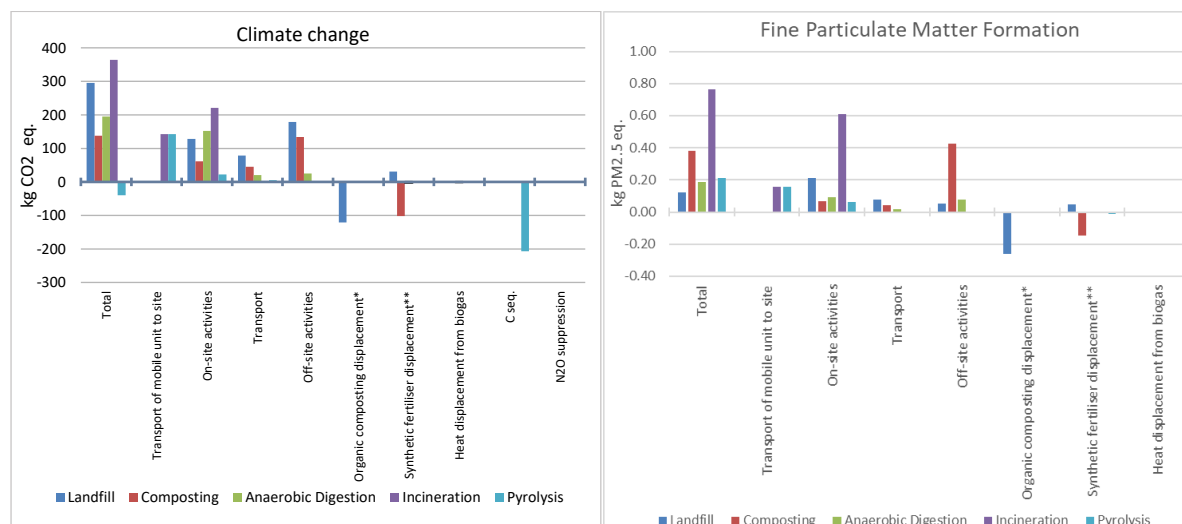
already in the atmosphere a few months previously. Therefore, on the normal timescale that climate change is assessed, there has been no net change in the amount of CO₂ in the atmosphere. The **landfill** EoL treatment climate change impact decreased when biogenic carbon was included; the likely explanation is that the dataset accounted for the biogenic carbon in the cannabis plant residues remaining stored in the material for a significant amount of time after landfilling.

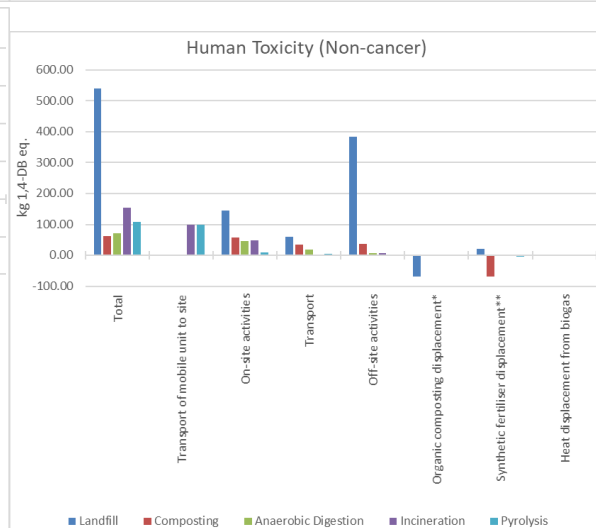
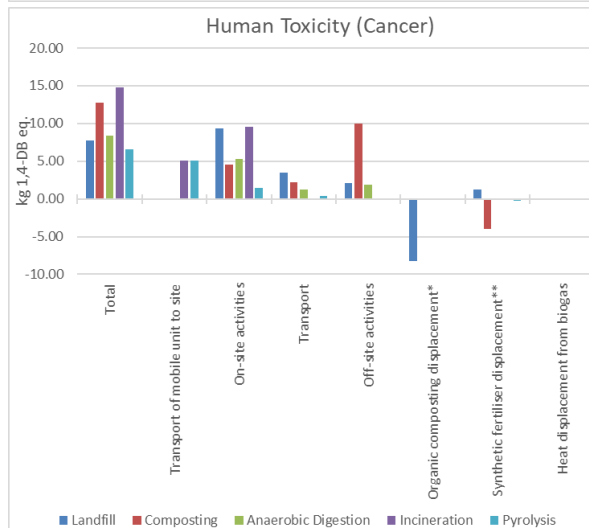
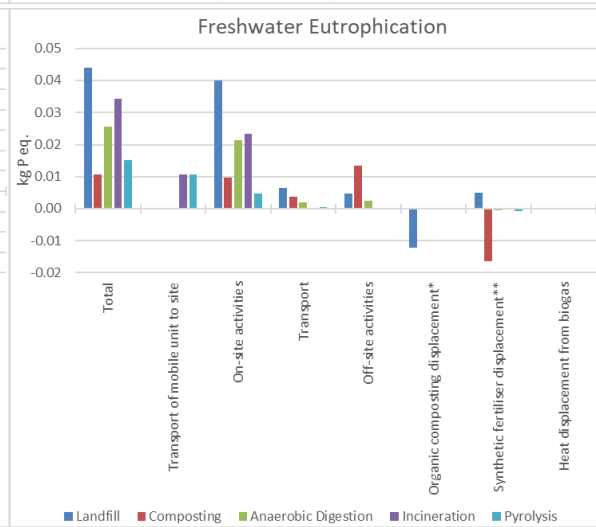
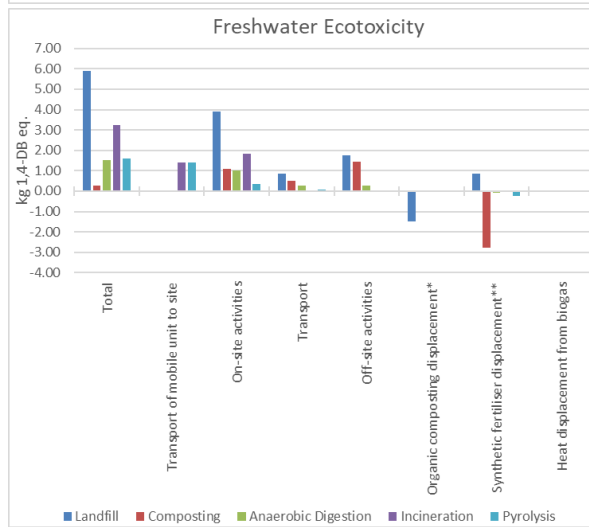
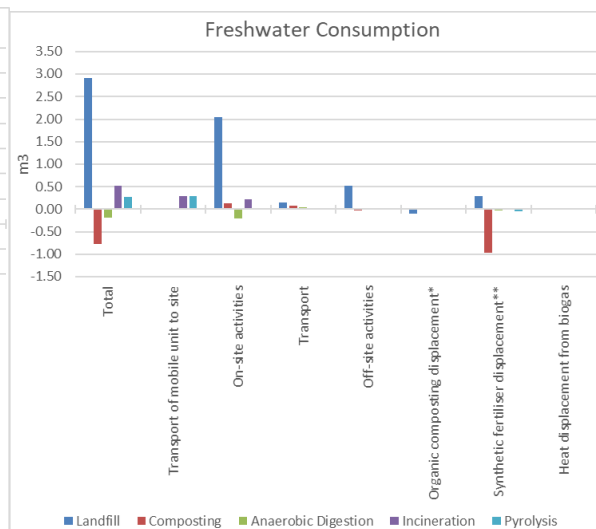
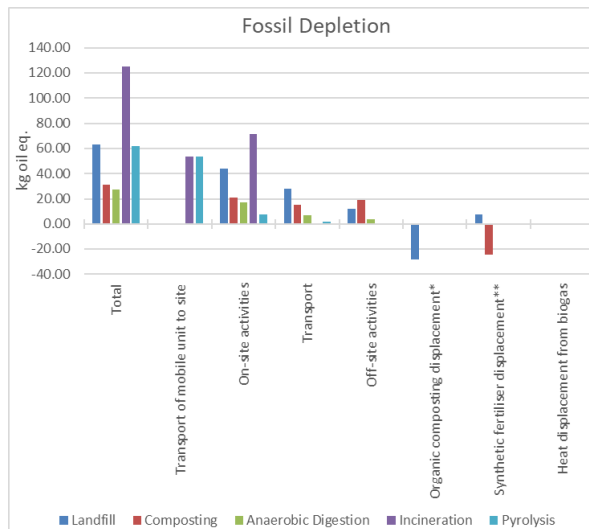
For the **pyrolysis** EoL treatment, a portion of the carbon stored in the biochar is stored for at least 100 years. For this study, the amount was manually calculated through the use of literature values and use of an equation in Anaya de la Rosa's (2013) study.

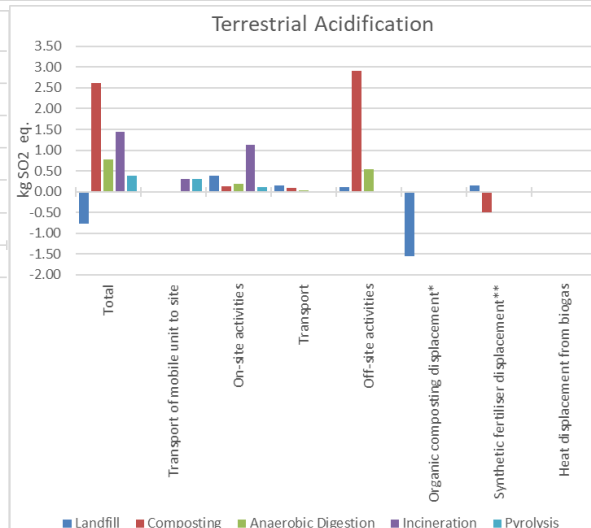
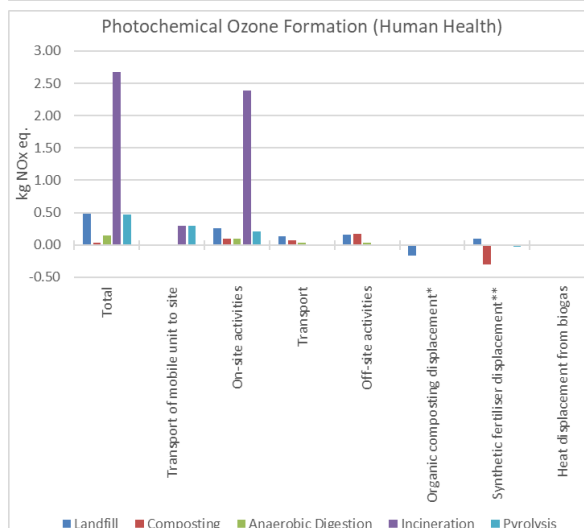
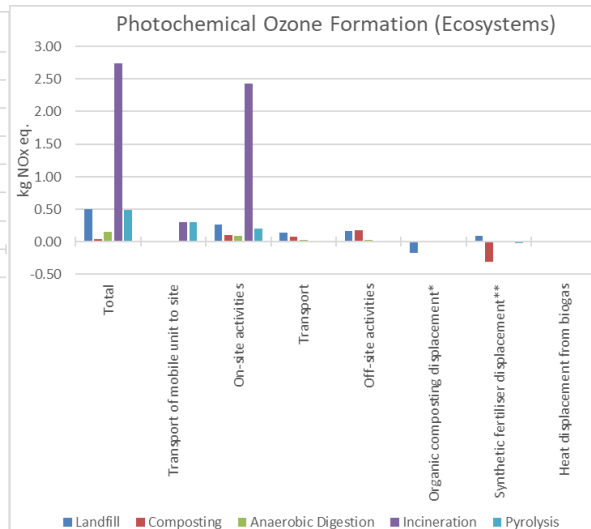
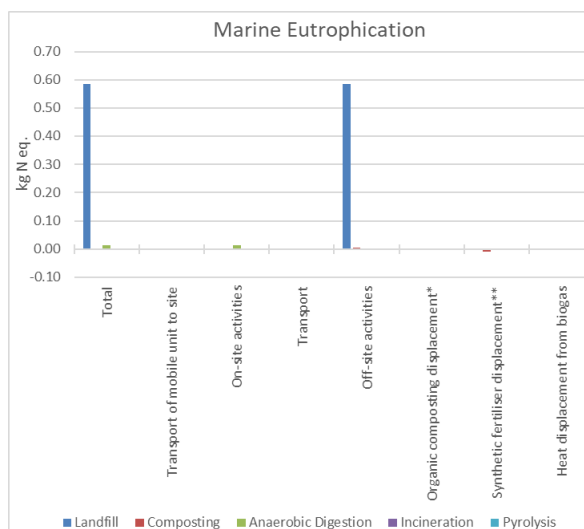
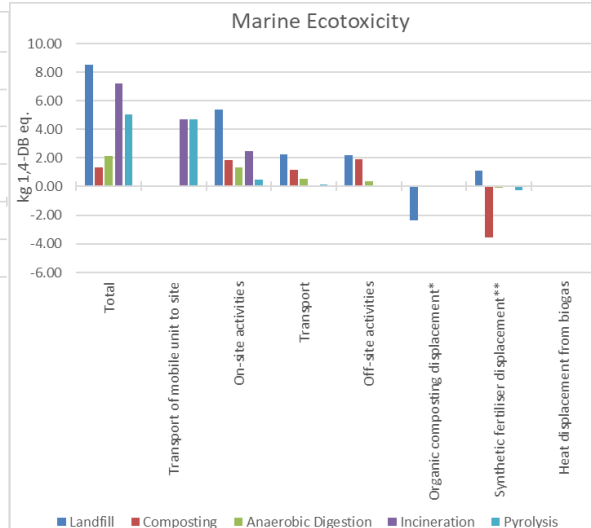
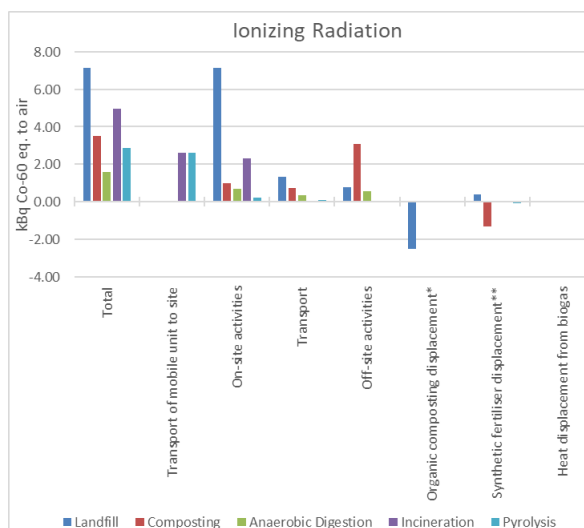
5.1.2 LCA results for alternative EoL treatments of cannabis plant residues

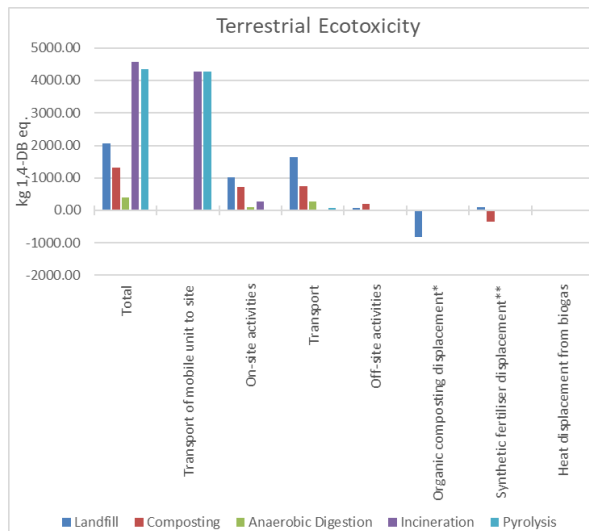
Figure 20 shows the overall results for alternative EoL treatments of cannabis plant residues for all assessed impact categories. It splits the results into ten sections to present the hotspots that are occurring from which activity locations. The sections are: total, transport of mobile unit to site, on-site activities, transport, off-site activities, organic composting and land spreading displacement, synthetic fertiliser production displaced from operations, heat displacement from biogas, carbon sequestration, and N₂O suppression. Carbon sequestration and N₂O suppression were only included in the climate change impact categories. Table 10 presents the specific activities within each section that contribute the largest portion of the total impact for each impact category. An analysis of the results is provided in Sections 5.1.3 with Section 5.1.4 summarising the LCA results across all the impact categories for alternative EoL treatments.

Figure 20: The LCA results of alternative EoL treatments for cannabis plant residues for all assessed impact categories









Note. *Organic composting and land spreading displacement. **Synthetic fertiliser production displaced from operations.

Table 10: Activities contributing above 20% to the total impact in the assessed impact categories for each alternative EoL treatment for cannabis plant residues (the underlined contributing activity is the major activity; the headings below represent specific areas within that activity)

EoL treatment (total impact)	Contributing activity	Impact category (%* of total impact for each alternative EoL treatment)														
		Climate change	Fine Particulate Matter Formation	Fossil depletion	Freshwater Consumption (Inventory indicator)	Freshwater ecotoxicity	Freshwater Eutrophication	Human toxicity (cancer)	Human toxicity (non-cancer)	Ionizing Radiation	Marine ecotoxicity	Marine Eutrophication	POF ** (Ecosystems)	POF ** (Human Health)	Terrestrial Acidification	Terrestrial ecotoxicity
Landfill	Total impact	295	0.12	63	2.91	5.89	0.04	8	541	7.15	8.50	0.59	0.50	0.48	-0.76	2,055
	Total on-site activities impact	24%		37%				38%	21%		41%			32%		28%
	NaOCl production		22%		50%	31%	44%			50%	25%		20%			
	Transport to landfill			23%												45%
	Total landfill activities impact													20%		
	Methane emissions from landfill decomposition	29%														
	Water, turbine use in landfill operations				1340%											
	Water release to freshwater in landfill operations				-1356%											
	Nitrogen organic bond release long-term effect to fresh water from landfill activities										64%					
	Zinc, ion emissions long-term effect on fresh water from landfill activities								37%							
	Total displaced organic composting and land spreading impact	-23%		-24%						-21%			-21%	-21%		-22%
	Total displaced composting activities impact							-20%								
	Ammonia emissions to urban air close to ground from displaced composting activities														-58%	
Carbon dioxide from displaced composting activities	-26% (decomposition)															
Composting	Total Impact	138	0.38	31	-0.78	0.28	0.01	13	62	3.53	1.36	0	0.04	0.03	2.62	1,325
	Total on-site activities impact						22%	22%			22%					
	Transport of green waste on-site			23%					25%							35%
	Transport to composting facility															37%
	Total composting activities impact			24%		25%					22%	27%	27%	27%		
	Methane emissions from composting decomposition	20%														
	Carbon dioxide emissions from composting decomposition															
	Ammonia emissions to urban air close to ground from composting activities		49%												76%	
	Phosphate long-term to freshwater from composting activities						26%									
	Chromium (+VI) emissions long-term effect to fresh water from composting activities							36%								
	Radon-222 emissions to air from composting activities									43%						
	Total displaced synthetic fertiliser production impact		-22%	-31%						-21%			-47%	-48%		
	Ammonia nitrate production from the displaced synthetic fertiliser production	-21.80%			-62%	-30%	-23%		-22%		-26%	-40%				

EoL treatment (total impact)	Contributing activity	Impact category (%* of total impact for each alternative EoL treatment)														
		Climate change	Fine Particulate Matter Formation	Fossil depletion	Freshwater Consumption (inventory indicator)	Freshwater ecotoxicity	Freshwater Eutrophication	Human toxicity (cancer)	Human toxicity (non-cancer)	Ionizing Radiation	Marine ecotoxicity	Marine Eutrophication	POF** (Ecosystems)	POF** (Human Health)	Terrestrial Acidification	Terrestrial ecotoxicity
Anaerobic Digestion	Total Impact	195	0.19	27	-0.19	1.51	0.03	8.33	71	1.61	2.12	0.01	0.16	0.15	0.77	392
	<u>Total on-site activities impact</u>		48%			62%									25%	24%
	Belt filter press wastewater treatment				-508%							69%				
	Total anaerobic digestion emissions (on-site)					26%			40%		25%		42%	42%		
	Methane emissions from anaerobic digestion	41%														
	Carbon dioxide emissions from anaerobic digestion															
	Phosphate long-term to fresh water from anaerobic digestion						41%									
	Radon-222 emissions to air from anaerobic digestion									21%						
	Chromium (+VI) emissions long-term effect to fresh water from anaerobic digestion							30%								
	Heat required for digestion - specifically hard coal being used			25%												
	Tap water added to the digester in on-site activities				382%											
	<u>Transport of digestate solids to composting facility</u>			24%					25%		23%					65%
	<u>Total composting activities impact</u>													20%		
	Total composting emissions from composting digestate solids							22%		34%						
	Ammonia emissions to urban air close to ground in the composting of digestate solids		32%												65%	
Incineration	Total Impact	365	0.77	125	0.51	3.25	0.03	14.72	154	4.94	7.22	0	2.74	2.68	1.43	4,562
	<u>Transport of mobile unit on-site</u>	39%		20%	43%	56%	43%	32%	35%	65%	53%	65%	36%		21%	94%
	<u>Total on-site activities impact</u>															
	Emissions from diesel burnt on-site	53%		71%	49%	30%		48%		44%		23%	88%	37%	75%	
	Electricity for conveyors and air pumps (on-site)					33%	39%					31%				
Pyrolysis	Total Impact	-40	0.21	62	0.28	1.62	0.02	6.6	109	2.86	5.05	0	0.49	0.47	0.39	4,346
	<u>Transport of mobile unit on-site</u>	37%	67%	84%	76%	68%	65%	71%	84%	87%	84%	70%	56%	55%	68%	97%
	<u>Total on-site activities impact</u>		26%					20%				22%	38%			
	Electricity for shredder (on-site)						21%									
	Emissions from diesel burnt (on-site)													36%	37%	
	<u>Carbon Sequestration Potential</u>	-54%														

Note. The underlined contributing activity is the major activity; the heading below it represent specific areas within that activity. Total impacts rounded to the nearest whole number where appropriate. *Percentage of total impact was calculated taking all the impacts for each alternative treatment in the impact category regardless of the impact containing a minus sign or being displaced. **Photochemical ozone formation.

5.1.3 Environmental hotspots for alternative EoL treatments of cannabis plant residues

According to Ecetoc (2016), one general idea of LCAs is to make ‘hotspots’ visible. Figure 20 shows substantial differences between the EoL treatments across the impact categories; this was expected because the alternative treatment’s technologies are very different. Table 10 shows the activities within each treatment that contribute above 20% to the total impact in each impact category. From Table 10 the environmental hotspots were identified with a clear pattern arising for each treatment, these hotspots were compared against other studies on organic matter waste management.

Landfill

The landfill EoL treatment for this study is a special case because incorporating bleach into the organic matter is a worst-case scenario – which is not commonly done in landfill treatment literature LCA assessments. For this study, NaOCl production for use on-site at the cultivation facility was found to be a hotspot contributing 20% or more of the impact in 7 out of 16 of the impact categories. If bleach was not added, the environmental impact of this treatment would improve dramatically

Composting

There is limited literature that compares organic matter waste management options using the same EoL treatments as completed in this study, but one good report compares three out of five of the treatments compared in this study. Jones et al. (2020) compared the carbon footprint of windrow composting, combustion (incineration), and pyrolysis to produce biochar. Jones et al. (2020) found that for the composting of grape marc, decomposition had the largest contribution (77%) to the carbon footprint impact. For this study, the decomposition in the composting EoL treatment found that 20% of the total climate change impact came from the methane emissions of decomposition. Compared to Jones et al. (2020), this study has lower contributions to the impact from decomposition emissions. The contribution difference could be due to Jones et al. (2020) assuming the best-case scenario with 98% of the methane produced in the composting heaps being oxidised and therefore, not being emitted; whereas this study assumes good management but does not assume a best-case scenario. Therefore, if the management of the composting facility improved so more methane is oxidised in the heap, the overall environmental impact of this treatment would decrease.

Saer et al. (2013) completed three emission scenarios: the average, minimum, and maximum. The minimum scenario considered best management practices, while the maximum was the worst scenario. In the average emission scenario, Saer et al. (2013) found that composting decomposition emissions from composted food waste contributed 74% of the climate change impact, this result is similar to Jones et al. (2020) who found that composting decomposition emissions from composting grape marc contributed 77% of the carbon footprint emissions, as

discussed above. In the minimum and maximum scenarios, Saer et al. (2013) found that 2.5% and 94.1% of the impact was due to decomposition emissions. In comparison, the contribution to the climate change impact category for this study (20%) was lower than the average obtained by Saer et al. (2013) and the result obtained by Jones et al. (2020). Compared to Saer et al. (2013) average, minimum, and maximum results, this study sits below the average of 74% but not as low as the minimum 2.5%.

Saer et al. (2013) also completed assessment on the acidification, eutrophication, and ecotoxicity impact categories with the decomposition contributing a range of 12.2% to 87.8%, 14.2% to 89.6%, and 0.0%, respectively. However, for this study the decomposition of composted cannabis plant material was not found to have any significant contribution to these impact categories.

Anaerobic Digestion

Anaerobic digestion has several assumptions made for this EoL treatment that makes a comparison to the literature very difficult. Literature studies require the same software and database for comparison. Therefore, no comparisons to the hotspots found in this study were made to other literature on LCAs of anaerobic digestion. For this study, anaerobic digestion emissions produced on-site were found to be a hotspot and contributed 20% or more of the impact in 12 out of 16 impact categories. However, more research is needed to verify the various assumptions.

Incineration

Jones et al. (2020) also assessed the carbon footprint of a system combusting the grape marc residues. Jones et al. (2020) found the combustion carbon footprint impact was due to operation of a loader (43%), construction of the incineration plant (37%), and transportation (22%). Jones et al. (2020) specified that transportation included transporting the grape marc material from the wineries to a central location, which is similar to this study with the mobile unit being transported to the cultivation facility. This study has a contribution of 39% from transportation of the mobile unit for the incineration EoL treatment climate change impact, which is slightly larger than the contribution found in Jones et al. (2020). However, there are many factors that can affect the emissions from transportation activities including, the truck size, volume transported, and the emission standard which the truck meets. Jones et al. (2020) used a EURO4 24.7t payload capacity truck, whereas this study used a EURO6 transport lorry with a gross vehicle weight (GVW) larger than 32t, this could explain the difference.

A major hotspot for this study's incineration EoL treatment was the emissions from diesel burning to help combust the cannabis plant residues, but no comparison was able to be made to literature. Jones et al. (2020) found that diesel use for operation of the system had minimal contribution to the carbon footprint impact. The environmental hotspot of this treatment could be reduced by optimising the incineration system and reducing the amount of diesel burnt. The

use of diesel could be reduced by optimising the system and increasing the amount of dried cannabis plant residues being burnt to fuel the incineration process.

Pyrolysis

Jones et al. (2020) found the pyrolysis EoL treatment of grape marc carbon footprint impact was largely due to carbon sequestered in the biochar (-94%), NPK synthetic fertiliser displaced (-10%), plant construction (1%), operation of a loader (1%), and transportation (1%). This study had the environmental hotspots of transport of the mobile unit (37%) and carbon sequestration (-54%) for the climate change impact category.

Muñoz et al. (2017) assessed a similar pyrolysis EoL treatment for forestry residual biomass, the only difference being that a system boundary extension was added with the production of biomass waste from agricultural activities also included within the system boundary. Muñoz et al. (2017) found that within the climate change impact category, the carbon sequestered from the biomass contributed -91% to the impact; this is similar to the value found in Jones et al. (2020), and again smaller than that found in this study. Muñoz et al. (2017) also completed assessment on the fossil depletion, freshwater eutrophication, and human toxicity impact categories. For this study, transport of the mobile unit was an environmental hotspot across all impact categories. Muñoz et al. (2017) found that transportation contributed 6%, 20%, and 21% to the fossil depletion, freshwater eutrophication, and human toxicity impact categories. Table 10 shows that transport of the mobile unit contributed 84%, 65%, and 71% and 84%, to the fossil depletion, freshwater eutrophication, and human toxicity (cancer and non-cancer) impact categories. The large difference between this study's results and the results from the Muñoz et al. (2017) study is due to the size of the impact of other activities in the study as well as the different technologies utilised. Muñoz et al. (2017) fossil depletion impact category was strongly influence by the biochar production stage with syngas generation, this study uses diesel instead (at small volumes) and therefore the biochar production (on-site activities system) does not produce a large fossil depletion impact.

There is a large difference in contributions between the literature and this study for both transport and carbon sequestration, this difference could be due to many factors. Transport is affected by the truck size, volume transported, and the emission standard which the truck meets. Jones et al. (2020) used a EURO4 24.7t payload capacity truck, whereas this study used a EURO6 transport lorry with a gross vehicle weight (GVW) larger than 32t. Carbon sequestration is affected by the biochar yield, biochar lost in transport, carbon content of the biochar, and the biochar carbon stability factor. Therefore, it is hard to assess exactly what contributed to the difference.

Even though differences are seen between the contribution amounts, the emissions due to decomposition of composted organic matter and carbon sequestration in biochar were found to be hotspots in the climate change impact for the **composting** and **pyrolysis** EoL treatments, respectively, in the literature and in this study. The emissions from burning diesel on-site were

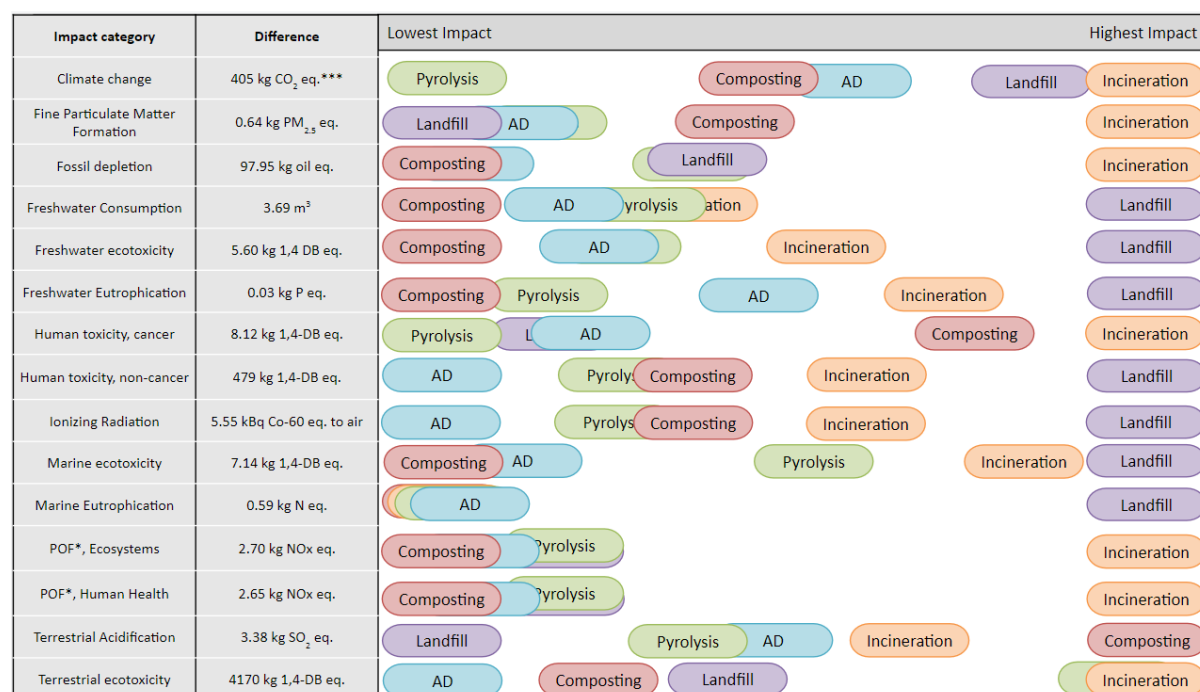
found to be the hotspot in the climate change impact for the **incineration** EoL treatment, in this study but not in the literature.

5.1.4 Summary of the LCA results for the alternative EoL treatments of cannabis plant residues

Figure 20 shows that the **incineration** and **landfill** EoL treatments have the two highest impacts in 7 out of 15 investigated categories. In contrast, the **composting** EoL treatment only has the highest impact in one impact categories (terrestrial acidification). The two treatments that do not have the highest impact in any impact categories are **anaerobic digestion** and **pyrolysis**.

Figure 21 shows a visual representation of the ranking of the different treatments for the assessed impact categories. The ranking order is generally: **composting** (best), **anaerobic digestion**, **pyrolysis**, **incineration**, and **landfill** (worst) EoL treatments. Significant distance between treatment results is seen in some impact categories, e.g. fine particulate matter formation, fossil depletion, marine eutrophication, POF (ecosystems), and POF (human health). The large gaps indicate that, while a ranking for each treatment in each category from one to five can be given, it needs to be set in context of the actual magnitude of difference across all the results.

Figure 21: Summary of the total impact for the alternative EoL treatments for the assessed impact categories



Note. The difference between the highest and lowest impacts for each impact category is stated in column two.

*Photochemical Ozone Formation **Equivalent to driving an average gasoline car 2350 km.

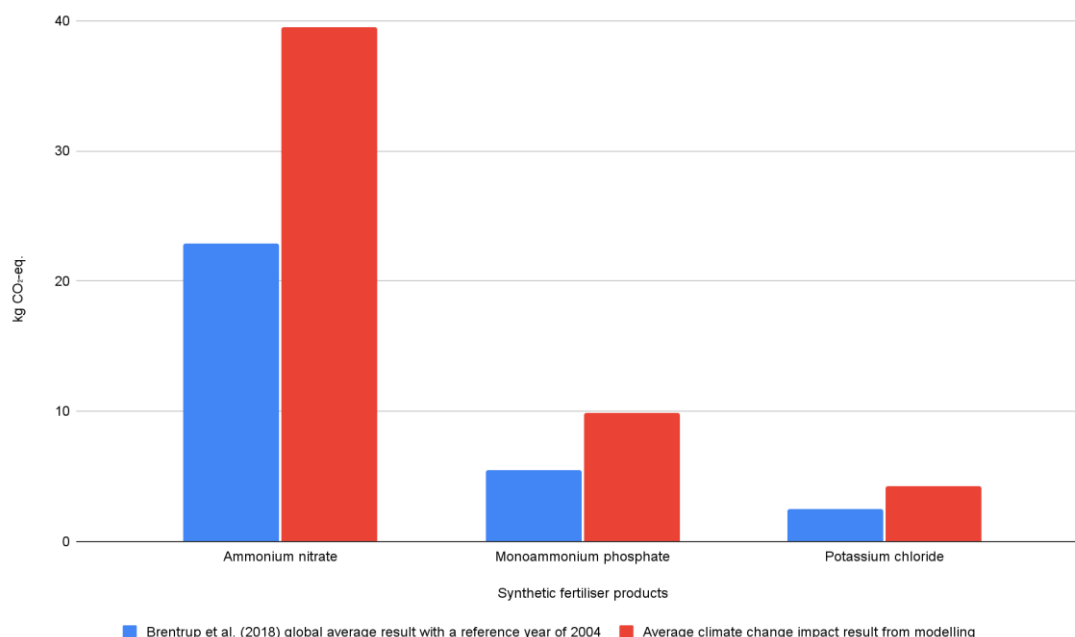
5.1.5 Synthetic fertiliser production comparison to literature

The **composting**, **anaerobic digestion**, and **pyrolysis** treatments involved modelling the displacement of synthetic fertilisers, whereas the landfill treatment required the addition of synthetic fertilisers into the soil. Therefore, a comparison was undertaken of the synthetic fertiliser production climate change impact calculated in this study (based on the ecoinvent database) with other literature values.

The obtained values for synthetic fertiliser production used in this study were compared to the Brentrup et al. (2018) study results which provide climate change impact values for specific fertilisers across different regions. Since the synthetic fertiliser production carbon footprint results from the LCA are based on rest-of-world (RoW) datasets, the Brentrup et al. (2018) values were averaged across the different regions in the study (Figure 22). Only the ammonium nitrate, monoammonium phosphate, and potassium chloride fertilisers were able to be compared to literature because they were the only ones modelled with similar nutrient contents to that in Brentrup et al. (2018).

The comparison indicates that for all fertilisers compared, the ecoinvent results were larger than the Brentrup et al. (2018) results (almost doubled) when an equivalent amount of fertiliser product was produced. Future research should be conducted on what climate change impact values are most appropriate to use for fertilisers in New Zealand.

Figure 22: Comparison of modelling and literature results for the synthetic fertiliser production climate change impact for selected of fertiliser products (using data from Brentrup et al., 2018)



5.2 Sensitivity analysis

This section considers the impact on the climate change impact category results of changing specific aspects of the EoL treatments: several ranges of values for the pyrolysis EoL treatment (Section 5.2.1), the distance to landfill (Section 5.2.2), the potential heat captured from thermal EoL treatments to displace natural gas (Section 5.2.3), and comparison to the Ministry for the Environment (MfE) country-specific emission factors (Section 5.2.4) for the diesel use emissions, transport fuel emissions, landfill emissions, composting emissions, anaerobic digestion emissions. Only the climate change impact category was assessed in this section because the MfE New Zealand specific data only provided emission factors to estimate the climate change impact. Therefore, no other impact categories could be compared to country-specific data for New Zealand.

5.2.1 Pyrolysis treatment variables

The pyrolysis treatment was originally modelled using assumed values for the biochar loss (BL), carbon content (CC), and biochar carbon stability factor (BCSF) (Section 3.6.5). The CC and biochar yield (BY) are directly associated with the pyrolysis temperature. Therefore, the literature and experimental values were used to complete this sensitivity analysis. A range of values for the BL, moisture content of the biochar (MCB), BCSF, and N₂O suppression were also used to understand the potential difference in the results (Table 11). For the modelling, it was assumed that when one parameter was changed, the other variables remained constant. The original assumption was used as either the maximum or minimum when it was not in the range obtained from experimental or literature sources. The climate change impact category was assessed in this sensitivity analysis.

The increase in the climate change impact was largest when the BCSF decreased from 68% to 14%; it led to a +415% increase in total climate change impact. Another increased impact change was due to the CC of the biochar decreasing from 82.50% to 21% (the lowest average obtained from proximate analysis), creating a +390% increase in the total climate change impact. The largest decreased impact change was due to the increase in BY from 10.15% (originally assumed based on engineering calculations) to 59% (the largest literature and experimental result obtained), creating a -2468% decrease in the total climate change impact. An increase in biochar losses led to a reduced amount of carbon being sequestered in the soil; for equations see Section 3.6.5.

Table 11: Sensitivity analysis for the pyrolysis EoL treatment per FU for the climate change impact category

Parameter	Original assumption	Range	Impact of variability on the total climate change impact
Biochar yield	10.15%*	10 to 59%**	+11 to -2468%
Biochar losses from production to use/collection	1%	1 to 22%**	0 to +116%
Moisture content of biochar	5%	4 to 6%**	-3 to +3%
Carbon content of biochar	82.50%	21 to 83%	+390 to -2%

Biochar carbon stability factor (BCSF) for ≥ 100 years	68%	14 to 90%***	+415 to -168%
Suppression of N ₂ O from soil	50%	0 to 100%***	+3 to -3%

Note. Values are rounded to the nearest whole number. *Obtained from engineering calculations. **Obtained from literature in conjunction with averages from experimental testing of biochar. ***Obtained from literature.

Care should be taken when interpreting the sensitivity analysis results in Table 11 because the variables are interdependently and non-linearly related. Each variable was changed independently, and no two variables were changed together; however, there is an interrelationship between the BY, BSCF, CC, and BL variables. Therefore, changing any two of them in further studies could create large changes in results. Further research into these variables should occur to get more accurate results since the pyrolysis experiments were only completed twice.

5.2.2 Distance to landfill

For consistency, a default distance of 100km was used for unknown distances. As Rotorua does not currently have a landfill close to it, waste is sent to a transfer station (Rotorua Lakes Council, n.d.), whose distance from the proposed cultivation and processing facility is currently unknown. However, the distance from this transfer station to the Tirohia landfill is known to be 119 km. Therefore, from the processing facility in Rotorua, the total distance that the waste travels to the landfill is modelled as 219 km. This distance is only temporary until a more permanent solution for Rotorua is found. In 2021, New Zealand had 327 legally operating landfills, with 40% serving populations of fewer than 1,000 people (MfE, 2021a). The distance of communities to their closest landfills has yet to be published for New Zealand. However, based on the map from Land Information New Zealand (2011), 40 km appears to be an average distance. Therefore, a sensitivity analysis was undertaken, assuming that the landfill was located 40 km from the cultivation facility.

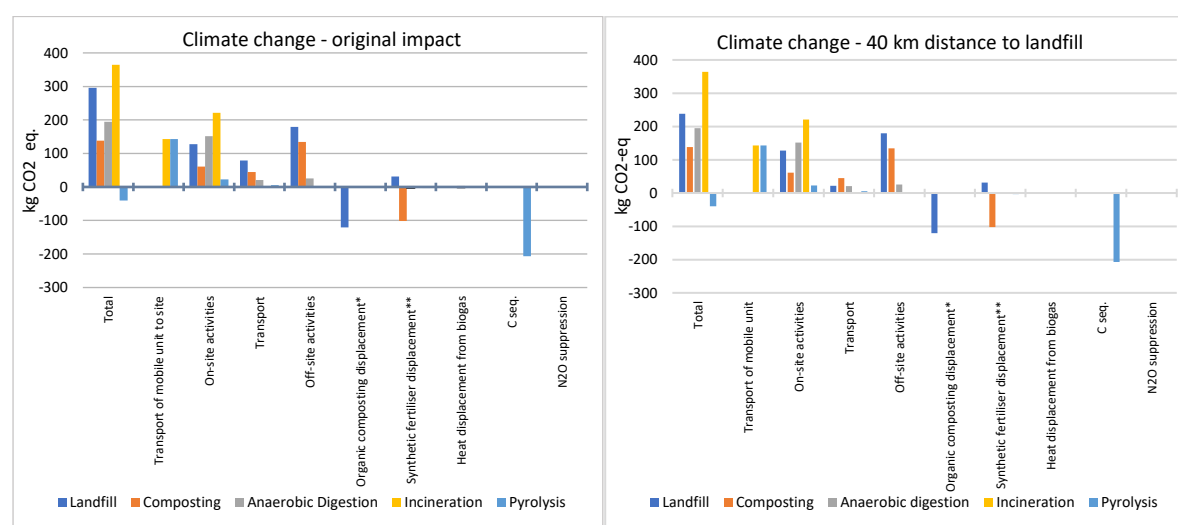
Only two EoL treatments involved transporting material to a landfill: landfill and incineration. Table 12 shows that reducing the distance to landfill caused a decrease in the climate change impact of -19.4% and -0.1% for landfill and incineration EoL treatments, respectively. Figure 23 shows that altering the distance to the landfill did not change the rankings of the different treatments but increased the gap between the first (incineration) and second (landfill) EoL treatment climate change impact results.

Table 12: Sensitivity analysis for the landfill and incineration EoL treatments considering the distance to landfill

	Original assumption (km)	New assumption (km)	Impact of variation on the total climate change impact
Landfill	219	40	-19.4%
Incineration	219	40	-0.1%

Note. The minus sign (-) indicates a further reduction in the climate change impact category from the original result in Section 5.1.2.

Figure 23: Breakdown of the climate change impact per FU for landfill and incineration EoL treatments with comparison of the original impact to the altered distance to landfill



Note. *Organic composting and land spreading displacement. **Synthetic fertiliser production displaced from operations.

5.2.3 Potential heat captured from thermal EoL treatments to displace natural gas

Due to the thermal treatments being undertaken in a mobile unit, it was assumed that capturing the heat created in the systems was impossible. This section explored the potential displacement of natural gas that could occur if a way was found to capture the heat and reuse it at the cultivation facility.

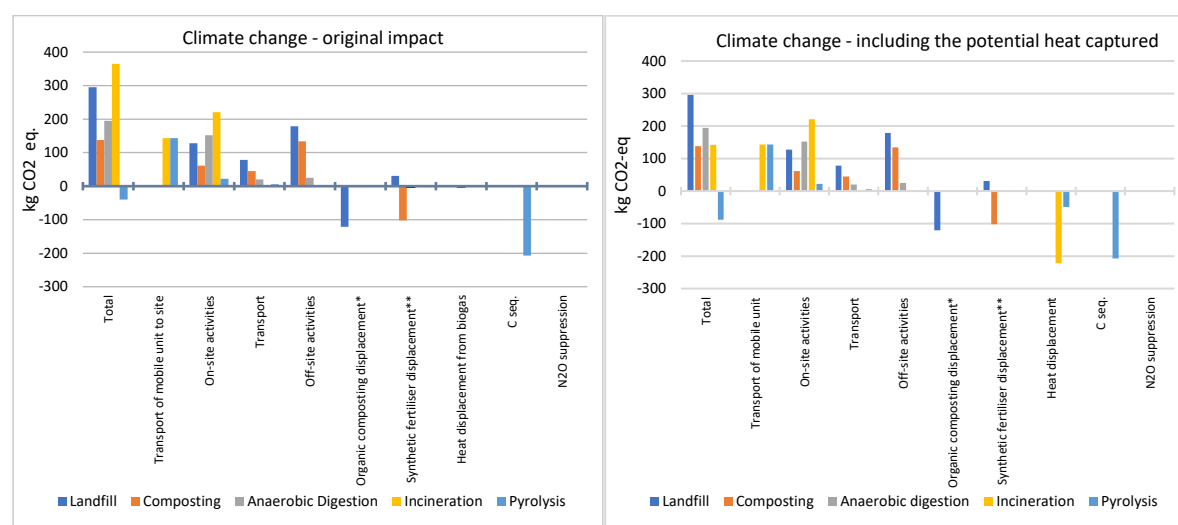
The potential heat that could be captured was determined by modelling the heat being released as flue gas and quantified as energy in MJ. The potentially displaced climate change impact of heat from natural gas was subtracted from the original climate change impact results. Table 13 shows that capturing all of the excess heat from the thermal treatments decreased the climate change impact by -61% and -29% for incineration and pyrolysis EoL treatments, respectively. Figure 24 shows that the rankings were altered by capturing 100% of the excess heat produced by the thermal treatments. The incineration EoL treatment showed the most variation when 100% of the potential heat was theoretically captured and used to displace natural gas in the cultivation facility (-61%).

Table 13: Sensitivity analysis considering the potential heat displacement of thermal treatments when excess heat captured, per FU for the climate change impact category

	Original assumption	New assumption	Impact of variation on the total climate change impact
Incineration	0% captured	100% captured	-61%
Pyrolysis	0% captured	100% captured	-29%

Note. - indicates a further reduction in the climate change impact from the original result in Section 5.1.2.

Figure 24: Breakdown of the climate change impact category per FU for the incineration and pyrolysis EoL treatments with comparison of the original impact to the altered potential heat displaced



Note. *Organic composting and land spreading displacement. **Synthetic fertiliser production displaced from operations.

5.2.1 New Zealand-specific emission factors comparison

The MfE (2022) guide on measuring emissions provides emission factors for calculating the climate change impact of activities. The MfE emission factors for diesel use, transport fuel, landfilling, composting, and anaerobic digestion were compared to the LCA values used and results obtained in this study. The climate change impact was used to compare to all MfE (2022) results.

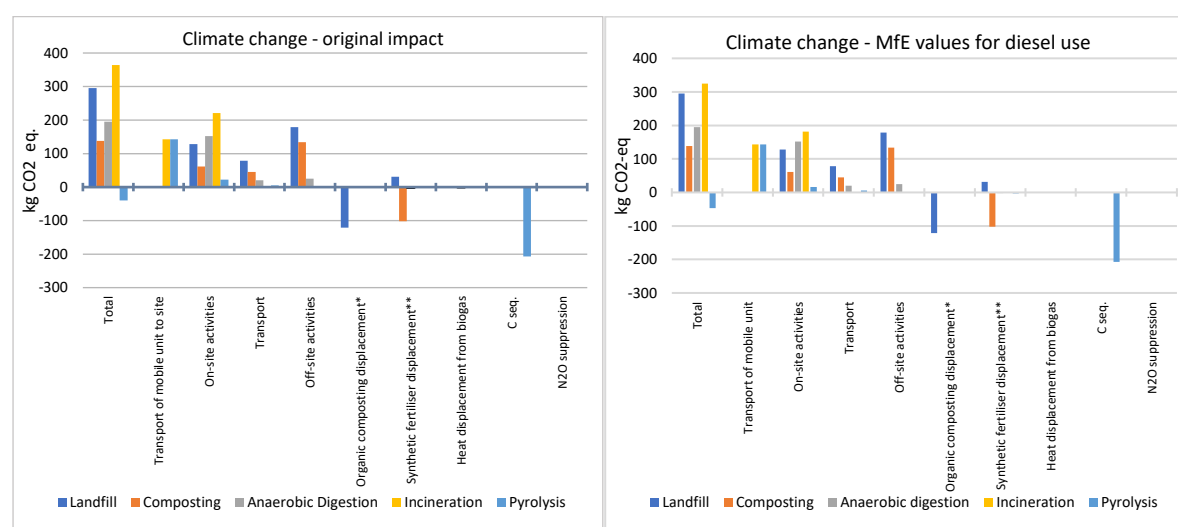
Diesel use emissions

Diesel was only modelled for use in two EoL treatments: incineration and pyrolysis. The comparison of results specifically for the burning of diesel/diesel use can be found in Table 14. The MfE (2022, p.23) emission factor is 2.67 kg CO₂-eq per litre of diesel, and this value was converted to per kg of diesel using a density of 860 kg/m³. The differences between this study's climate change result and the MfE emission factor-based climate change results for incineration and pyrolysis were both approximately -20.5% when solely considering diesel emissions. This caused a -11% and -4% change in the total incineration and pyrolysis EoL climate change results. Figure 25 shows that the rankings of the treatments did not change when the MfE emission factors were used instead of the GaBi diesel dataset in the modelling. The change in results is most likely due to the MfE dataset not including the extraction and processing of the diesel – which is included in the ecoinvent datasets. However, the difference could also be due to the MfE carbon dioxide values being based on the carbon and energy content of the fuel and not accounting for how the fuel is combusted – which will affect the quantities of non-carbon dioxide greenhouse gas emissions (methane and nitrous oxide) (MfE, 2022, p.20).

Table 14: Sensitivity analysis on diesel use emissions of LCA results to MfE emission factors, per FU for the climate change impact category

EoL treatment	Diesel required (kg diesel)	LCA result (kg CO ₂ -eq.)	NZ-specific result (kg CO ₂ -eq.)	Variation of diesel emissions	Variation of total climate change impact
Incineration	49.5	193	153	-20.4%	-11%
Pyrolysis	8.11	32	25	-20.6%	-4%

Figure 25: Breakdown of the climate change impact category per FU for the incineration and pyrolysis EoL treatments comparing the LCA results to the MfE diesel use emissions



Note. *Organic composting and land spreading displacement. **Synthetic fertiliser production displaced from operations.

Transport fuel emissions

The datasets used in each EoL treatment depended on the size of truck used for transport. The ecoinvent transport datasets that were used in the modelling are listed as being valid from 2009 to 2013. These were compared with the average MfE emission factors as they were the only ones using the same units as the ecoinvent datasets ('t-km' as opposed to km travelled by the truck) (MfE, 2022, p.84; Appendix M, Table 33). The container ship MfE emission factor used was obtained from Table 69 in MfE (2022, p.93).

Table 15 shows the difference in climate change results between the LCA and MfE emission factors for freight transport. The largest variation in the total climate change impact was for the landfill EoL treatment when switching to the MfE values (-30%), and the smallest was for the anaerobic digestion EoL treatment (-5%).

The differences between results using the two sets of datasets were bigger or smaller depending on the size of the vehicle modelled in GaBi. For small truck transportation, the difference was -75% when the 'all-trucks' MfE value was used instead of the 'transport, freight, lorry 3.5-7.5-ton EURO6 truck' ecoinvent dataset. For medium truck transportation, the difference ranged

from -39.6% to -39.7% when the ‘all-trucks’ MfE value was used instead of the ‘transport, freight, lorry 7.5-12-ton EURO6 truck’ ecoinvent dataset. For large truck transportation, the difference ranged from -7% to +13% when the ‘long-haul heavy truck’ MfE value was used instead of the ‘transport, freight, lorry >32-ton EURO6 truck’ ecoinvent dataset. For shipping, the difference ranged from +38% to +41% when the ‘container ship, 8000+ TEU’ MfE value was used instead of the ‘transport, freight, container ship’ ecoinvent dataset.

The differences found in this analysis could be explained in several ways:

- The MfE values are likely to have not included the impacts associated with the extraction and processing of the fuel which are included in the ecoinvent datasets.
- According to MfE (2022, p.89), the primary source for any uncertainty in the MfE transport freight goods emission factors is that “net tonne-kilometres must be inferred from truck road user charge (RUC) returns and the NZTA’s truck weigh-in-motion statistics”.
- McLaren et al. (2021b) found that the weight and type of vehicle as well as the distance travelled can make a significant difference in the appropriate emission factor to use for the study, with a 298% difference between the smallest and largest emission factor available for trucks in one transport database alone.

It is recommended to collect more accurate data on the emissions of transport in future studies as well as complete comparisons on the emission factors available before inventory assessment occurs in LCAs.

Table 15: Sensitivity analysis on transport fuel emissions of LCA results to MfE emission factors per FU for the climate change impact category for all alternative EoL treatments

	Distance (t-km)	LCA Result (kg CO ₂ -eq.)	MfE Value	MfE Result (kg CO ₂ -eq)	Variation between results	Variation of total climate change impact with all MfE values used
LANDFILL						-33%
Transport of green waste for use on-site	100	54.17	0.135	13.5	-75%	
Transport of bleach for use on-site	2.53	1.37	0.135	0.34	-75%	
Transport of mixed material to the transfer station	237.5	53.10	0.135	32.06	-39.6%	
Transport of material from the transfer station to the landfill	282.63	25.40	0.105	29.68	+17%	
Organic composting transport	100	54.20	0.135	13.5	-75%	
Synthetic fertiliser production by truck freight	3.25	0.37	0.105	0.34	-8%	
Synthetic fertiliser production by sea freight	286.5	2.69	0.013	3.72	+38%	

COMPOSTING						-40%
Transport of green waste for use on-site	100	54.17	0.135	13.5	-75%	
Transport of mixed material off-site	200	44.80	0.135	27	-39.7%	
Synthetic fertiliser production by truck freight	10.64	1.21	0.105	1.12	-8%	
Synthetic fertiliser production by sea freight	938	8.81	0.013	12.19	+38%	
ANAEROBIC DIGESTION						-8%
Transport of digestate solids off-site	37.56	20.40	0.135	5.07	-75%	
Synthetic fertiliser production by truck freight	1.23	0.03	0.105	0.13	-8%	
Synthetic fertiliser production by sea freight	108.5	0.20	0.013	0.28	+41%	
INCINERATION						+7%
Transport of mobile unit for use on-site	1596	143.00	0.105	167.58	+17%	
Transport of ash to the transfer station	0.725	0.39	0.135	0.098	-75%	
Transport of ash from the transfer station to the landfill	0.86275	0.08	0.105	0.09	+13%	
PYROLYSIS						+15%
Transport of mobile unit for use on-site	1596	143.00	0.105	167.58	+17%	
Transport of biochar to land	10.15	5.50	0.135	1.37	-75%	
Synthetic fertiliser production by truck freight	1.16	0.13	0.105	0.12	-7%	
Synthetic fertiliser production by sea freight	107.24	1.00	0.013	1.39	+39%	

Landfill emissions

MfE (2022) provides emission factors for landfills with or without gas recovery systems in place as well as emission factors for each class of landfill. The landfill classes are either Class 1 (municipal landfill) or Classes 2 to 4 (non-municipal landfill). For this comparison, only Class 1 with gas recovery was used because a sanitary landfill with gas and leachate recovery was modelled in this study. The relevant MfE emission factor was 0.492 kg CO₂-eq./kg material for green waste (MfE, 2022, p.106). Table 16 lists the data and the difference between the original LCA-modelled climate change impact result and the result using the MfE (2022) Class 1 with gas recovery emission factor for green waste. A difference of +273% was found in the landfill EoL treatment total climate change impact result. The emission factors from MfE (2022, p.110) have an uncertainty of $\pm 40\%$. However, the difference between the datasets is

much larger; this could be explained by the fact that only methane emissions and no carbon dioxide or nitrous oxide emissions were considered in the MfE emission factor.

Table 16: Sensitivity analysis for landfill emissions comparing the LCA result to MfE emission factor results per FU in the climate change impact category for the landfill EoL treatment

EoL treatment	Item	Landfilled waste (kg)	LCA result (kg CO ₂ -eq.)	MfE result (kg CO ₂ -eq.)	Variation of LCA to MfE (2022)	Variation of total climate change
Landfill	Green waste	2000	179	984	+450%	+273%

Composting emissions

Only one emission factor is provided in MfE (2022, p.107) for composting biological treatment (0.172 kg CO₂-eq./kg material). Table 17 shows that in the landfill, composting, and anaerobic digestion EoL treatments, a difference of +160% was found between the climate change result calculated using the MfE emission factors for specific composting activities instead of the ecoinvent emission factors. This translated into a smaller difference in the total climate change impact result: landfill had a +36% difference, composting had a +154% difference, and anaerobic digestion had a +20% difference, when the MfE composting emission values were used. The same uncertainty was provided by MfE (2022, p.107) for the composting emissions as for the landfiling emissions of $\pm 40\%$. The reason for the difference in ecoinvent and MfE emission factors is unclear and requires further investigation; it may be due to different assumptions about the composition of materials being composted, and the composting activity itself.

Table 17: Sensitivity analysis of composting emissions comparing the LCA results to MfE emission factor results per FU in the climate change impact category for the landfill, composting, and anaerobic digestion EoL treatments

EoL treatment	Item	Landfilled waste (kg)	LCA result (kg CO ₂ -eq.)	MfE result (kg CO ₂ -eq.)	Variation of LCA to NZ-sp.	Variation of total climate change
Landfill	Displaced green waste composted	1000	66.21	172.00	+160%	+36%
Composting	Cannabis plant waste + green waste	2000	132	344.00	+161%	+154%
Anaerobic Digestion	Solid digestate	376	24.90	64.67	+160%	+20%

Anaerobic digestion emissions

For the anaerobic digestion (AD) treatment, MfE (2022, p.107) provides an emission factor of 0.020 kg CO₂-eq./kg material; this value takes methane into account but not carbon dioxide or

nitrous oxide. Although methane does dominate the anaerobic digestion treatment AD emissions, methane is not the only emission occurring. The ecoinvent emission factors used in the baseline study are much larger than the MfE value.

Table 18 shows that the use of the MfE emission factor leads to a decrease of -49% in anaerobic digestion EoL treatment total climate change impact result. The same uncertainty was provided by MfE (2022, p.107) for the composting emissions as for the landfilling emissions of $\pm 40\%$. Additionally, different assumptions about the compositions of the material being digested could explain the difference.

Table 18: Sensitivity analysis of anaerobic digestion emissions comparing the LCA result to the MfE emission factor result per FU in the climate change impact category for the anaerobic digestion EoL treatment

EoL treatment	Item	Landfilled waste (kg)	LCA result (kg CO ₂ -eq.)	NZ-specific (kg CO ₂ -eq.)	Variation of LCA to NZ-sp.	Variation of total climate change
Anaerobic Digestion	Cannabis waste + water	2000	135	40	-70%	-49%

5.3 Summary of the LCA and sensitivity analysis results for the alternative EoL treatments

This chapter presented the LCA results for each alternative treatment and included several sensitivity analyses for the climate change impact categories. The ReCiPe 2016 v1.1 method used in this study provides impact assessment factors for 19 impact categories, three of which were omitted from this study: land use, metal depletion, and stratospheric ozone depletion. Generally, the rankings of the alternative treatments across all the assessed impact categories is: **composting** (best), **anaerobic digestion**, **pyrolysis**, **incineration**, and **landfill** (worst).

The only EoL treatment that offered carbon sequestration potential was the **pyrolysis** EoL treatment, shown in the climate change impact category. However, when compost is land-spread it also has carbon sequestration potential which could decrease the results for the **landfill**, **composting**, and **anaerobic digestion** EoL treatments. For this study, an in-depth analysis of this aspect was not completed but this should be considered in future work.

The environmental hotspots found in this study for the **composting** and **pyrolysis** EoL treatments were compared to literature; it was found that emissions from the decomposition of composted organic matter and carbon sequestration of biochar, were hotspots for the respective EoL treatments in both the literature and this study. The emissions from burning diesel on-site were found to be the hotspot in the climate change impact for the **incineration** EoL treatment, in this study but not in the literature. **Landfill** and **anaerobic digestion** hotspots could not be compared to literature; the **landfill** EoL treatment contained bleach which is not commonly completed in literature studies on landfill. The **anaerobic digestion** EoL treatment had several

assumptions attached to it which meant that comparisons could not be made. Table 10 shows the hotspots for the alternative EoL treatments found in this study.

A sensitivity analysis was completed on the climate change impact category for several ranges of values for the **pyrolysis** EoL treatment. The biochar yield, biochar losses, moisture content of biochar, carbon content of biochar, BCSF, and suppression of N₂O from soil ranges were all assessed. The largest positive difference in the total climate change result was also the maximum difference found across all the sensitivity analyses. The difference of +415% was obtained when the BCSF was decreased from 68% to 14% which was the minimum found in literature (where the plus sign (+) indicates an increase in the climate change impact). The largest negative difference in the total climate change result was also the minimum (most negative) difference found across all the sensitivity analyses; this difference of -2468%, was found when the biochar yield increased from 102 kg biochar/FU to 590 kg biochar/FU; this was due to the biochar yield increasing the carbon sequestered (where the minus sign (-) indicates a reduction in the climate change impact). Further development and research is needed to identify what pyrolysis temperature profile is most effective for high BY and CC when using cannabis plant biomass.

A sensitivity analysis was also completed on the climate change impact category for: the distance to landfill, the potential heat captured from thermal EoL treatments to displace natural gas, and comparison to the MfE emission factors for diesel use, transport fuel, landfill, composting, and anaerobic digestion. The distance to landfill was changed from 219 km to 40 km which created a difference in the total climate change result for the **landfill** and **incineration** EoL treatments of -19.4% and -0.1%, respectively. When 100% of the excess heat not required for reactions within the **incineration** and **pyrolysis** EoL treatments is captured, a difference of -61% and -29% is found for the total climate change result, respectively. The MfE value of 2.67 kg CO₂-eq. per litre of diesel when used for diesel use in the thermal treatments created a difference of -11% and -4% in the total **incineration** and **pyrolysis** EoL climate change results.

The MfE provided two different values for transport emissions depending on the size of truck used for transport: all trucks (0.135 kg CO₂-eq./t-km) and long-haul heavy trucks (0.105 kg CO₂-eq./t-km). The largest difference was seen for small truck transportation, with a difference of -75% when the 'all-trucks' MfE value was used instead of the 'transport, freight, lorry 3.5-7.5-ton EURO6 truck' ecoinvent dataset. The results show that with the difference in climate change impact results when MfE value are used instead of ecoinvent datasets, there is a need for more accurate data on the emissions of transport to be collected in future studies.

For the landfill of green waste in the **landfill** EoL treatment, the total climate change impact result had a difference of +273% when the MfE value was used instead of the ecoinvent dataset. The emission factors from MfE (2022, p.110) have an uncertainty of $\pm 40\%$. However, the difference between the datasets is much larger; this could be explained by the fact that only methane emissions and no carbon dioxide or nitrous oxide emissions were considered in the MfE emission factor.

Composting occurs in the **landfill**, **composting**, and **anaerobic digestion** EoL treatments, the total climate change impact results had differences of +36%, +154%, and +20%, respectively, when the MfE value was used instead of the ecoinvent datasets. The reason for the difference in ecoinvent and MfE emission factors is unclear and requires further investigation; it may be due to different assumptions about the composition of materials being composted, and the composting activity itself.

Anaerobic digestion only occurs in the **anaerobic digestion** EoL treatment, using the only MfE value for anaerobic digestion available, a difference of -49% was found for the total climate change impact of the treatment. The likely explanation of the difference is the MfE values have different assumptions about the compositions of the material being digested compared to the ecoinvent datasets and this study's assumptions.

The sensitivity analyses allowed for the LCA climate change results to be compared against the results when more New Zealand specific factors were used. These sensitivity analyses showed that, for some activities, there were large differences in the results created by the use of different datasets. This may be due to different modelling assumptions or to New Zealand-specific conditions; therefore, future research should be conducted into what climate change values are most appropriate for New Zealand specific studies.

Chapter 6: Preliminary assessment of the economic, social, and cultural aspects, with analysis of the New Zealand medicinal cannabis licence regulations and carbon accounting frameworks

This chapter describes and assesses the preliminary economic (Section 6.1), social (Section 6.2), and cultural (Sections 6.3-6.5) analysis for each end-of-life (EoL) treatment. In addition, the current regulations within New Zealand for undertaking research on medicinal cannabis (Sections 6.6.1 and 6.6.2), and for carbon accounting (Section 6.6.3), are briefly reviewed given their relevance to the research topic. In Section 6.7, an integrated comparison of the alternative EoL treatments with regard to the environmental assessment results, and preliminary economic, social, and cultural analyses, is provided.

6.1 Preliminary analysis of economics

An economic assessment of each treatment was completed. Due to the size of this study, only a basic preliminary economic analysis was completed for each EoL treatment, which included the capital cost, operational cost, cash flow, revenue, and net present value (NPV). It should be noted that this preliminary analysis only incorporates the costs associated with the foreground activities i.e. when the landfill dump fee is paid, the costs to this project end.

Even though the potential profit has relevance, the interviewees at Zymbi acknowledged that a focus on the greatest profit could not come at the expense of other aspirations, such as environmental impact or cultural elements (Int-1-AM). According to Pizzirani (2016), a similar acknowledgement was expressed in her study interviews which were concerned with culturally focused life cycle sustainability assessment but also incorporated the economic analysis aspect; her iwi interviewees wanted economic viability but were not focussed on the size of the potential profit.

As stated in Section 3.1.3, processing is either stationary or mobile, where the stationary facilities are assumed for the landfill, composting and anaerobic digestion treatments, whereas the mobile facilities are incineration and pyrolysis. For this economic assessment, it was assumed that the stationary site EoL treatment costs are additional to the existing operations of the medicinal cannabis cultivation facility (where the on-site activities occur before the by-products are transported to either a landfill or composting facility). However, for the mobile facilities, which are transported to the cultivation site when needed, it was assumed that the cultivator could be charged a processing fee of up to 60% of the cost of disposing the cannabis plant residues in a landfill. In addition, revenue may be earned from the by-products of the processes, which may accrue to either the mobile operator or the cultivator as agreed. For this study, all revenue is added together.

Since Zymbl is the case study being used for this study, the location of the (future) processing facility is assumed to be Rotorua and is assumed to be on the same site as the cannabis plant cultivation to adhere to the licence requirements. It is important to have a flat site for whichever treatment is used, but the overall area of the site required depends on the processing route.

6.1.1 Accuracy

The costing accuracy is based on the capital cost estimation with the probable accuracy range. According to Bouman et al. (2005, p.2), there are five estimation types with different probable ranges of accuracy: order of magnitude (± 30 to $\pm 50\%$), study (± 20 to $\pm 30\%$), preliminary (± 10 to $\pm 25\%$), definitive (± 5 to $\pm 15\%$), and detailed (± 2 to $\pm 5\%$). For this study, the accuracy is assumed to be at the ‘study’ estimation type, with a probable accuracy of $\pm 25\%$ assumed. The ‘study’ estimate includes preliminary sizing of equipment, plant location, preliminary process flow diagrams, process plant materials of construction, approximate sizes and types of buildings and structures, initial estimates for quantities of utilities required, preliminary flow sheet for piping requirements, and a preliminary motor and pump list (Bouman et al., 2005). In the future, further research could undertake an in-depth analysis would reduce the uncertainty of cost estimations; therefore, increasing the accuracy of the economic analysis, due to time constraints this was not undertaken in this study.

6.1.2 Components of an economic assessment

There are five sections of this preliminary economic assessment: capital cost, operational cost, cash flow, revenue, and NPV. The total cost consists of the capital cost and operating costs multiplied by the sum of the Lang factors (Table 34), but the accuracy of these costs also needs to be considered. The capital cost is spent over the first year to set up the plant/business, with processing beginning in the second year. The capital cost is estimated from the capacity of the machinery required using the process capital cost estimate for New Zealand (NZ) from 2004 (Bouman et al., 2005). The capital goods price index from Statistics NZ is then used to adjust the prices from historical to current values.

The working capital is the money kept in the bank to pay bills and wages, assumed to be 15% of the total capital cost. The operational costs are the sum of raw materials, electricity, water, fuel, chemicals, etc. Maintenance is calculated based on the assumed percentage of the capital cost, usually 2-10%. Therefore, an average of 6% was used for this study. Transport is within the system boundary due to several raw materials and end products required to be transported. Labour consists of administration requirements as well as operational labour, this is often a major cost. For health and safety, labour is assumed to be at least two minimum workers per shift.

To cover these capital and operational costs it is assumed that this project is funded 50:50 by investors and borrowed capital. The borrowed capital interest rate for large projects is 5% (*Discount rates*, 2020). However, the average lending rate over the last 10 years in New Zealand was 6.79% (*New Zealand interest rate*, 2022). For this project, an interest rate of 5%

was chosen. The New Zealand company tax rate is 28%, and at the end of the project, the salvage value of the plant is assumed to be 40% of the initial capital cost of equipment before lang factors are included.

A cash flow table is the easiest method to summarise the economic assessment.

6.1.3 Landfill

The capital cost of equipment was estimated to be \$578,678 (Appendix N.1, Table 35), and the operating cost was estimated to be \$102,900 (Appendix N.2, Table 40). For the landfill EoL treatment, it is assumed that no revenue will be earned; thus, this treatment is a net cost to the business. Table 45 (Appendix O) shows the cash flow of the landfill EoL treatment.

As landfilling is avoided in the below treatment options, it is assumed that the cultivator can be charged 60% of the landfill fee by the alternative processors (Appendix N.3). However, this cannot be completed for the composting and anaerobic digestion EoL treatments because they occur as stationary treatments on-site at the cultivation facility. Therefore, the cultivator can only be charged 60% of the landfill fee by the thermal EoL treatments, incineration, and pyrolysis. Each of the alternative processing routes also has additional revenue streams.

6.1.4 Composting

The capital cost of equipment was estimated to be \$572,770 (Appendix N.1, Table 36), and the operating cost was estimated to be \$44,976 (Appendix N.2, Table 41). The product of the composting EoL treatment is compost which has the potential to sell at \$178.60/t of compost or \$89.30/FU (Appendix N.3). Table 46 (Appendix O) shows the cash flow of the composting EoL treatment.

6.1.5 Anaerobic digestion

The capital cost of equipment was estimated to be \$2,136,279 (Appendix N.1, Table 37), and the operating cost was estimated to be \$111,919 (Appendix N.2, Table 42). The biogas produced from anaerobic digestion has heat value, with potential revenue of \$25.20/FU. The remaining by-products are the solid and liquid phase streams which are sent to a composting facility and the wastewater treatment plant as trade waste, respectively. The solid phase of the digestate sent to the composting facility can then be sold as compost; assuming the same compost sale price and compost density as in Section 6.1.4, the anaerobic digestion EoL treatment has the potential to sell the compost at \$178.60/t of compost or \$67.08/FU. The operating cost above includes the cost of trade waste treatment at \$603.35/FU (Appendix N.3). Tables 47-49 (Appendix O) shows the cash flow of the anaerobic digestion EoL treatment.

6.1.6 Incineration

The capital cost of equipment was estimated to be \$3,081,528 (Appendix N.1, Table 38), and the operating cost was estimated to be \$120,559 (Appendix N.2, Table 43). The incineration

EoL treatment used industrial ovens to estimate the capital cost of the dryer, incinerator, and diesel burner. In future studies, this is an area that should be investigated, and more accurate costs should be found.

The first revenue of incineration is the landfill avoidance fee charged to the cultivator of \$127.56/FU. Incineration produces heat and ash. Heat has no revenue value here because the incinerator is a small mobile unit, unlike the stationary anaerobic digester.

The incineration ash can go two ways, to the landfill or land-spread to exploit its nutrient value. Sending ash to the landfill deducts \$3.17/FU from the landfill avoidance fee charged to the cultivator. Instead, ash can be put onto land and used as fertiliser despite its low quality (J. Jones, personal communication, 2022). Since ash has a much lower nutrient content than compost, an assumed lower price of \$30/tonne was used for an approximate revenue or 17% of the compost equivalent value. The black ash has a density of 540 kg/m³ (*Wood Density Chart*, 2012). Therefore, the ash would bring in revenue of \$138.96/FU inclusive of the 60% avoided landfill charge (Appendix N.3). Tables 50 and 51 (Appendix O) show the cash flow of the incineration EoL treatment showing the different revenue options.

6.1.7 Pyrolysis

The capital cost of equipment was estimated to be \$1,736,774 (Appendix N.1, Table 39), and the operating cost was estimated to be \$94,378 (Appendix N.2, Table 44). The pyrolysis EoL treatment used industrial ovens to estimate the capital cost of the dryer, pyrolyser, and diesel burner. In future studies, this is an area that should be investigated, and more accurate costs should be found.

The first revenue of pyrolysis is the landfill avoidance fee charged to the cultivator of \$127.56/FU. Similar to incineration, heat has no revenue value here because the pyrolyser is a small mobile unit. Due to the versatility of the charcoal or biochar produced by the EoL treatment pyrolysis, there are multiple revenue options. Biochar can be sold by itself and used as a fuel or as a soil modifier, or as a chemical adsorbent (not explored here).

When the biochar is sold as fuel, a revenue range was obtained by using a simple \$10/GJ of heat delivered and the price of wood pellets used in pellet burners (\$675/t biochar) (Jones et al., 2020); therefore, the revenue could either be \$128.02/FU or \$196.07, respectively (both revenues are exclusive of the fee that could be charged to the cultivation facility (Appendix N.3)).

When it is land spread as a soil modifier, it has two potential revenue streams, as a soil modifier and as a carbon sink, but only if the application is incorporated into the Voluntary Market scheme (Puro Earth, n.d.) or in future, if it is permitted as a sink within the NZ ETS. Using the same price as for grape marc in Jones et al. (2020) and considering inflation of the New Zealand Units for carbon sequestered if the biochar was land spread, the revenue could be \$8.83/FU or if the biochar was put into the voluntary market and the carbon was sequestered the revenue

could be \$12.77/FU (exclusive of avoided landfill fee). Tables 52-55 (Appendix O) show the cash flow of the pyrolysis EoL treatment showing the different revenue streams.

6.1.8 Summary

Table 19 shows that no profit can be made from any of the EoL treatments when only 30 tonnes of cannabis plant residues are processed per year. Only the pyrolysis and composting EoL treatments cost less than the landfill EoL treatment, with composting being the cheapest. The anaerobic digestion and incineration EoL treatments have the largest NPV after 15 years (above -\$4 million), with anaerobic digestion being the largest when solely the heat from biogas is sold. The new proposed EoL treatment of pyrolysis has many options, with the cheapest being if the biochar was sold as fuel at \$675/t of biochar. The landfill treatment did not have the lowest capital and operating costs; it was found to be composting, which also had the better NPV after 15 years across all alternative EoL treatments. Since no profit was found in the revenue options, the IRR was not calculated for this study.

Table 19: Summary of the alternative EoL treatments preliminary Net Present Value after 15 years

EoL Treatment (Revenue Stream)	Capital Cost (\$)**	Operating Cost (\$)**	NPV* after 15 years
Landfill	\$579,000	\$103,000	-\$2,650,000
Composting	\$573,000	\$45,000	-\$1,013,000
Anaerobic Digestion (Biogas heat)	\$2,136,000	\$112,000	-\$4,471,000
Anaerobic Digestion (Compost)	\$2,136,000	\$112,000	-\$4,457,000
Anaerobic Digestion (Biogas heat and compost)	\$2,136,000	\$112,000	-\$4,449,000
Incineration (Ash to landfill including the landfill avoidance fee)	\$3,082,000	\$121,000	-\$4,108,000
Incineration (Ash land-spread including the landfill avoidance fee)	\$3,082,000	\$121,000	-\$4,152,000
Pyrolysis (Biochar as fuel at \$10/GJ including the landfill avoidance fee)	\$1,737,000	\$94,000	-\$2,558,000
Pyrolysis (Biochar as fuel at \$675/t biochar including the landfill avoidance fee)	\$1,737,000	\$94,000	-\$2,545,000
Pyrolysis (Biochar land-spread including the landfill avoidance fee)	\$1,737,000	\$94,000	-\$2,565,000
Pyrolysis (Biochar land-spread and carbon sequestered including the landfill avoidance fee)	\$1,737,000	\$94,000	-\$2,560,000

Note. See Appendix N.3 for revenue calculations. Values were rounded to the nearest one thousand. *Net Present Value. **The capital and operating costs were assumed to be approximately the same for the different revenue streams and within the range of accuracy of 25% as described in Section 6.1.1.

6.2 Preliminary analysis of social indicators

The social impacts of research projects are difficult to specify because of the variety of interpretations and numerous measurement systems, indicators, and interactions available (Viana-Lora & Nel-lo-Andreu, 2021). One main social indicator affecting any community is employment (Bornmann, 2013; Pizzirani, 2016; Sykes et al., 2019). Other social indicators that

have been discussed in the literature are human health and household income (Bornmann, 2013; Pizzirani, 2016; Sykes et al., 2019), as well as the availability of Rongoā (Māori traditional medicine or health treatment) (Pizzirani, 2016). Due to the size of this study, only a basic preliminary analysis of one social indicator was completed but future research could include more social indicators when undertaking an in-depth analysis. For this study, the social indicator of employment was analysed using the amount of ‘hours’ required by all employees for each treatment. It should be noted that this preliminary analysis only incorporates the labour associated with the foreground activities i.e. those occurring on-site at the cultivation facility.

For each of these treatments, it was assumed that a 12-hour workday was completed; this includes one hour of set-up and one hour of pack-down. The landfill and composting EoL treatments each have the same processing times and will require the same number of employees. The anaerobic digestion EoL treatment requires the same number of employees, but a different processing time occurs.

Even though the incineration and pyrolysis EoL treatments have different amounts of technical work being completed, they are both conducted in a mobile site, and therefore are assumed to require the same number of employees. This is due to the technical nature of the work and the requirement for at least two employees to have a heavy truck licence to drive the mobile unit vehicle, for health and safety purposes. On the other hand, landfill, composting, and anaerobic digestion treatments are conducted on-site at the cultivation facility and require a different number of employees.

6.2.1 Landfilling and composting

The landfill and composting EoL treatments are similar, with the shredder and mixer being utilised before the mixed material is transferred into the back container on the two-container heavy vehicle rig to be transported to the landfill or composting facility.

The number of employees required for each of these two treatments is assumed to be:

- Three employees for technical service: one supervisor and two technical hands
- One additional administrator for the company.

It will take 5.33 days/cycle to process the required residues for both treatments, rounding this up to six days/cycle at five cycles/year, this means that 30 days of work are required. At 12 hours of work per day, for all four employees, 132 hours are available at the assumed processing requirement of 30 tons of cannabis plant residues per year.

6.2.2 Anaerobic digestion

Compared to the landfill and composting treatments, anaerobic digestion is more technical, requiring a shredder, digester, and belt filter press. In the anaerobic digestion route, there are also three tanks: the water tank for the digester, the solids collection tank, and the liquids

collection tank from the belt filter press. The water tank will be connected to the water line on-site, and the liquid collection tank will have an outlet dumped on-site as trade waste.

The number of employees required for this treatment is assumed to be:

- Three employees for technical service: one supervisor and two technical hands
- One additional administrator for the company.

There are several stages to this treatment; when the material is digested, it is not necessary for all employees to be on-site. However, for this social analysis, it will be assumed that the employees are on-site even during digestion because there may be other jobs for them to complete. Therefore, it will take approximately 2.67 days/cycle to complete the shredding and 0.2 days/cycle to complete pressing the digestate. Even though the retention time required for anaerobic digestion is assumed to be 30 days, J. Jones (personal communication, December 5, 2022) described that practically the retention time could be longer. However, no matter the retention time, labour is not required the entire time as the digester can bubble away by itself. J. Jones (personal communication, December 5, 2022) suggested assuming $\frac{1}{3}$ of the assumed retention time labour would be required. Therefore, 10 days/cycle of labour for the digester is required. Overall, labour will be required approximately 13 days/cycle at five cycles/year and 12 hours/day. There are therefore 780 hours of work available per year for all four employees.

6.2.3 Incineration and pyrolysis

The incineration and pyrolysis EoL treatments are similar, with a maximum of three burners running at any time. A diesel tank is required for both treatments, along with air pumps, gas flares, and collection pits/tanks for ash, char, oil, and water. This unit requires technical service, supervisory roles, heavy vehicle licensed drivers (also technical operators), and administration employees. Therefore, the following employees for these two treatments are assumed as the minimum required:

- Four employees for technical service (including two supervisors); two of these employees will require heavy vehicle licencing
- Two employees completing administration for the company (one office management, the other administration).

The thermal processes assume that it will take one full week on-site to complete the processing of the material each cycle. Therefore, there will be approximately 420 hours of work available per year for all six employees, considering the assumed processing rate of 30 tonnes of cannabis plant residues per year.

6.3 Method for preliminary analysis of cultural aspects in New Zealand

For cultural considerations, two qualitative interviews were undertaken: the first interview consisted of two participants, and the second interview consisted of one participant. This

section includes a description of the participants, the structure of the whole interviewing process, and how the interview data was analysed. The information collected in the interviews is presented alongside a brief review of literature on cultural aspects in Section 6.5. It should be noted that this cultural assessment is only preliminary due to the constricted time frame and size of this study.

6.3.1 Participants

The two participants were found through the Te Arawa case study. Due to this being a vital but small part of this study, the participants were happy to give a few hours of their time. Each participant was already involved with other projects involving Māori, and was able to provide extra and invaluable insights based on these other projects.

Walter (Wally) Tangohau is the general manager of Te Pumautanga o Te Arawa Trust (TPT), where he identified and develops economic opportunities for the trust. TPT is a Post-Settlement Governance Entity (PSGE) formed in 2006 to receive, hold and manage the assets negotiated on behalf of the eleven Te Arawa iwi and hapū that it represents. He is also the director at Zymbl Innovation Limited, where he is currently involved in several projects with universities across New Zealand. Zymbl is an innovation hub based in Rotorua that looks to commercialise products and provide support for innovators to take on the world.

Aaron McCallion works at Zymbl Innovation Ltd and Zymbl Pharma Ltd, a subsidiary of Zymbl Innovation Ltd. He works closely with Wally to support research projects that resonate with the values of TPT, the wider entity. He has been working in research and development (R&D) since 2008, working with Māori communities to understand what is going on with their Whenua (land), Whānau (family), and Wai (water). In 2015 he transitioned into production systems which sits well with this project.

6.3.2 Interview process

The purpose of the interviews was to obtain insights on the environmental impact results using a cultural lens. The two interviews took place with a six-month gap between them. The time difference was due to the need to collect and analyse data between the interviews while accommodating the participants' schedules. The first interview was a group interview which was beneficial as different opinions and thoughts were provoked for in-depth discussions. However, the second interview was one-on-one due to the participants' schedules and the time frame for this study.

A questionnaire and semi-structured interviews were utilised in this part of the research. At the beginning of each interview, the project problem, goal, and EoL treatments were presented and described. Visual aids such as PowerPoint were used to present the questions and background information on the project. Each interview was semi-structured, using open- and close-ended questions to encourage discussion. An effort was made not to lead the participants toward any answer or discussion point but simply offer guidance or clarification. The interviews were audited by a third party (research supervisor, Professor Sarah McLaren), who ensured that no

bias from the researcher (myself) occurred. Interview questions are provided in Appendix P. All interviews were conducted via Zoom due to the diversity of locations of the participants. Each interview and participant was given a reference for simplified identification throughout the data analysis (Table 20).

Table 20: Summary of interview discussions and participants involved

	Reference	Participant(s)	Subjects discussed
Interview 1	Int-1-WT Int-1-AM	Wally (via Zoom) Aaron (via Zoom)	Life cycle scenarios, cultural considerations, Māori values, views, and principles
Interview 2	Int-2-WT	Wally (via Zoom)	Cultural compliance and cultural indicator matrix

6.3.3 Analysis of interview data

The participants consented to the interviews being recorded, which were then transcribed by the researcher (myself) which ensured confidentiality and met the ethical considerations of a low-risk study. The ethical considerations are outlined in Section 6.4. Analysis of the interviews was done by organising the material into chunks and reviewing each segment to develop the general answer or meaning for each question, also known as “coding” (Pizzirani, 2016). According to Pizzirani (2016), identifying the dominant themes using codes of dominant or reoccurring subjects is a practical way to check that the qualitative data addresses the research and interview questions. Therefore, for this study, reoccurring subjects were identified and given a suitable code during the review of the transcripts. The codes were then used as cultural indicators. This study used “sets of values” to describe the codes.

6.4 Ethical principles and conduct

This study engaged with the participants from Te Arawa and sought their opinions on cultural considerations for this project concerning the selected EoL treatments. A respectful approach was taken through this interview process:

- Before the presentations, the outline of the interview structure was sent to participants.
- Each presentation was developed and tested with a moderator, Professor Sarah McLaren, prior to the interviews to ensure no leading of answers or bias.
- At the start of each presentation, a brief overview of the problem, the research aims and EoL treatments were described.
- The researcher completed the transcription of all audio recordings to ensure the confidentiality of the discussions.
- Before publication, comments and feedback on the reporting of the interviews were obtained from the participants.

The study was evaluated as low risk by peer review, approval was given on 24/05/2022. Therefore, the Massey University Human Ethics Committee (MUHEC) did not review it. This means that it is up to the researcher and supervisors to responsibly carry out the research

ethically. The ethics notification number is 4000026038, it can be used to identify the ethics application in the Massey University system.

6.5 Preliminary analysis of cultural indicators

This section describes the cultural aspects of this study, including the importance of cultural competency in research and the Māori cultural views and principles from both literature and the qualitative interviews conducted. This section also describes how the criteria was chosen for analysing each EoL treatment with respect to the cultural values in New Zealand.

6.5.1 Cultural competency

What is culture? Culture shapes our approach to our world by affecting our interactions with it (Cain & Lawless, n.d.). When completing research, cultural considerations, whether in New Zealand or worldwide, are important in order to understand and involve communities (Cain & Lawless, n.d.). The benefits of cultural competence in research are collaboration (*mahi tahi*), self-determination (*tino rangatiratanga*), capacity building, and intergenerational knowledge (*Mātauranga Māori*). Research such as this completed between *Mātauranga Māori* and Western science can increase the range of the research and improve relations and collaboration between the two (Int-1-AM). *Mātauranga Māori* is the traditional knowledge, but when looking at it from a research cultural view, it is critical to note that traditional knowledge does not only mean knowledge of the past but also knowledge of the future (Int-1-WT).

According to Salmons (2022), when researchers work in – or with – a culture they do not fully understand, they may lack the mental ability required to interpret and understand information signals. Therefore, it is crucial to understand the New Zealand culture and what the communities within it view as most important. There is surface culture and deep culture, known as the Iceberg Concept in Cain and Lawless (n.d.). Surface culture is the tip of the iceberg, with a relatively low emotional load of the culture being seen. However, deep culture under the surface describes: unspoken rules (just below the surface), unconscious rules (the deepest below the surface), and an intense emotional load (Cain & Lawless, n.d.). The emotional load describes the impact that the culture has: a low emotional load is interpreted as the cuisine, games, language, celebrations, literature, and dance, whereas an intense emotional load can impact concepts of food, tone of voice, attitudes toward elders, and the concept of “self” to name a few. For this study, the interviews focused “just below the surface” for gathering Māori cultural views, principles, and values.

6.5.2 Māori cultural views and principles

The Māori worldview (*te ao Māori*) states that everything living and non-living is interconnected with the ecosystem defining an individual’s quality of life (*Māori and biodiversity*, 2018). In the first interview on cultural considerations, this topic of interconnectedness was brought up several times, establishing the importance of this view. Therefore, the cultural consideration of interconnectedness needs to be considered. It is about *whakapapa* (ancestry) and the knowledge that what you do with something affects something

else and so on, it never stops (Int-1-WT; *Māori and biodiversity*, 2018). The interconnectedness could also be described as wairua (the soul). Wairua is the spiritual dimension where spiritual connections bind the living and non-living (*Key Māori principles*., n.d.).

When asked what Māori values, principles, or views are relevant to this project in the first interview, the following were stated: Whanaungatanga, Manaakitanga, Kaitiakitanga, and Māramatanga (Int-1-AM). Whanaungatanga and Mahi tahi (relationships and collaboration) were touched on in Section 6.5.1. However, the key is having iwi and land trusts working with CRIs (Crown Research Institutes) and universities to combine those two worlds (te ao Māori and Western science), which is what is occurring in this project. Similar to Whanaungatanga and Mahi Tahi, Māramatanga is the principle of understanding, working between the two world views of Māori and Western science through knowledge sharing to reach a collective understanding. Whanaungatanga, Mahi Tahi, and Māramatanga bring together the further importance of understanding each other, kanohi ki te kanohi (eye to eye) (Int-1-AM). Manaakitanga (care/homage) and Kaitiakitanga (guardianship) of the environment, which is what land trusts such as TPT think about, and working with the land to look after it, especially for the next generations, which links back to the circular approach of thinking in wairua (Int-1-AM).

The values and principles discussed here naturally resonate with one another while relating to te ao Māori. Māori organisations have values at the forefront of everything they do. The key values that were at the forefront of TPT and the key principles that have emerged from studies into soil health from a Māori perspective by Landcare Research New Zealand were looked at for similarities in values to the interview participants' answers. Landcare Research New Zealand provided insight into the values concerning the soil, which is very appropriate for this study (*Key Māori principles*, n.d.). As expected, there were many crossovers, and Table 21 provides a summary of the identified Māori values from all these resources. For this study, values identified through the interviews that were similar or related to the same ideal were combined. In the second interview, the participants then checked the combination of values to ensure against cultural insensitivity.

Table 21: Māori values collated from interview one and literature

Ideal, value, principle (Sets of values)	Summarised definition	Reference
<u>Mana</u> , mana whakahaere, rangatiratanga, mana Motuhake	Authority and rights to manage land, soil, and resources, to exercise control, power (mana), guardianship (kaitiakitanga), and protection over resources. Recognition of the Treaty of Waitangi; Leading with integrity, courage, and honour	(1) (2) (3)
Mauri	Life force or energy, vitality, and continuous capacity of the soil to support/sustain life and wellbeing (well-functioning vital living soil ecosystems, full of soil biota, which maintain interconnections between physical, chemical, biological components, and people); Ecosystem defines the quality of life	(1) (2)
<u>Mahinga kai</u> / <u>Maara kai</u>	The ability of soil to produce and sustain healthy food for harvest and collection	(1)

<u>Oranga ora</u> , whenua ora, oneone ora, tikanga	The ability of soil to provide and ensure the health and well-being of people, following Tikanga and kawa (no human waste) and supply healthy food (no harmful contaminants, pathogens, pesticides, and free of toxicity); peoples influence requires more attention than the ecosystems themselves; Doing the right thing	(1) (4) (3)
<u>Whakapapa</u> , whanaungatanga, manaakitanga, kotahitanga	Respect for ancestral links or lineage of the soil; Working together respectfully and acknowledging our Whakapapa; Embracing all people with oneness and respect; Moving together as one (he waka eke noa).	(1) (3) Int-1-WT Int-1-AM
Wairua	Spiritual domain or dimension. Elements of soils to spiritual connections which bind the living and non-living; What you do with something affects something else which affects something else	(1) (2) Int-1-WT
Taonga Tuku Iho, <u>kaitiakitanga</u>	Ability to sustain the soil resource for future generations, in as good or if not better condition for future generations. Intergenerational equity of the soil resource and its ability to provide for future generations.; Caring for and protecting our taonga for future generations	(1) (3) Int-1-AM

Note. The underlined values from Table 21 were used as the headings/sets of values when assessing the EoL treatments. (1) From *Key Māori principles* (n.d.), (2) From *Māori and biodiversity* (2018), (3) From Te Pūmāutanga o Te Arawa Trust (2017), and (4) From Reid and Rout (2020).

6.5.3 Preliminary cultural analysis

After grouping the key values, a criterion was created from which the EoL treatments can be analysed to see if they would create a positive or negative cultural impact on the Rotorua community in New Zealand. Due to the study size and knowledge limitation, no weighting was given to the values themselves. However, a rating out of three was given to each treatment. The rating matrix depicts the extent to which the EoL treatment follows the value or principle set out. In the rating matrix, a score of 0 means that the treatment follows the principle to “no extent”, 1 means a “slight extent”, 2 means to “some extent”, and 3 to a “great extent”. The scores from each treatment (rows) were summed to consolidate the cultural indicators. The highest score represented the treatment that most closely aligned with the cultural values. Table 22 indicates the approximate extent to which each EoL treatment aligns with the specified cultural value. The second interview which went over the extent of alignment of each EoL treatment, only had one participant as stated in Table 20.

The landfill EoL treatment was given a total rating of 12 (Int-2-WT). Mauri, Maara Kai, and Kaitiakitanga were given a ‘slight extent’ rating because the EoL treatment only makes a limited contribution to the values for sustainable soil life. Overall, the residues being dumped into the landfill do not leave the soil in better condition and contribute to poor outcomes for food grown in the soil. Unfortunately, landfill is an EoL treatment with minimal improvement opportunities in this area other than improving the management of the landfill operation.

The composting EoL treatment was given a total rating of 16 (Int-2-WT). Compared to the landfill EoL treatment, composting better contributes to the mauri value of sustaining and supporting wellbeing, which in turn contributes to better growing conditions in the value of maara kai. On average, this EoL treatment provides the values to ‘some extent.’ However, no matter what EoL treatment is used, there is always a consequence to something else.

The anaerobic digestion EoL treatment was given a total rating of 17 (Int-2-WT); this EoL treatment steps even closer to following the values with the ability to reduce the waste residue size naturally without adding harmful chemicals as well as the ability to return nutrients into the soil. Therefore, this EoL treatment goes to some extent to meet the Māori values (Int-2-WT).

The incineration EoL treatment was given a total rating of 11 (Int-2-WT). Overall, the incineration EoL treatment only contributes a 'slight extent' to most of the values with large amounts of diesel required and the final product landfilled. Even though a smaller amount of waste is landfilled, the overall treatment is not sustainable or environmentally conscious (Int-2-WT). Therefore, the lowest total rating was obtained. Although it was not assessed in this study, there is an option in the **incineration** EoL treatment to land-spread the ash as well as reducing the diesel used in the system. These changes would improve the extent to which the incineration treatment aligns with the Māori values and its ranking for cultural considerations.

The pyrolysis EoL treatment was given a total rating of 19 (Int-2-WT). While there is diesel required to provide some heat for pyrolysis to occur, like in the incineration EoL treatment, the by-product of biochar can be applied to soil or used in many environmentally beneficial ways. Therefore, it meets the mauri value with its ability to support and sustain life and well-being, and it has good outcomes (biochar), following the value of maara kai and doing the right thing (Int-2-WT).

Table 22: Preliminary cultural considerations for alternative EoL treatments assessed through interviews

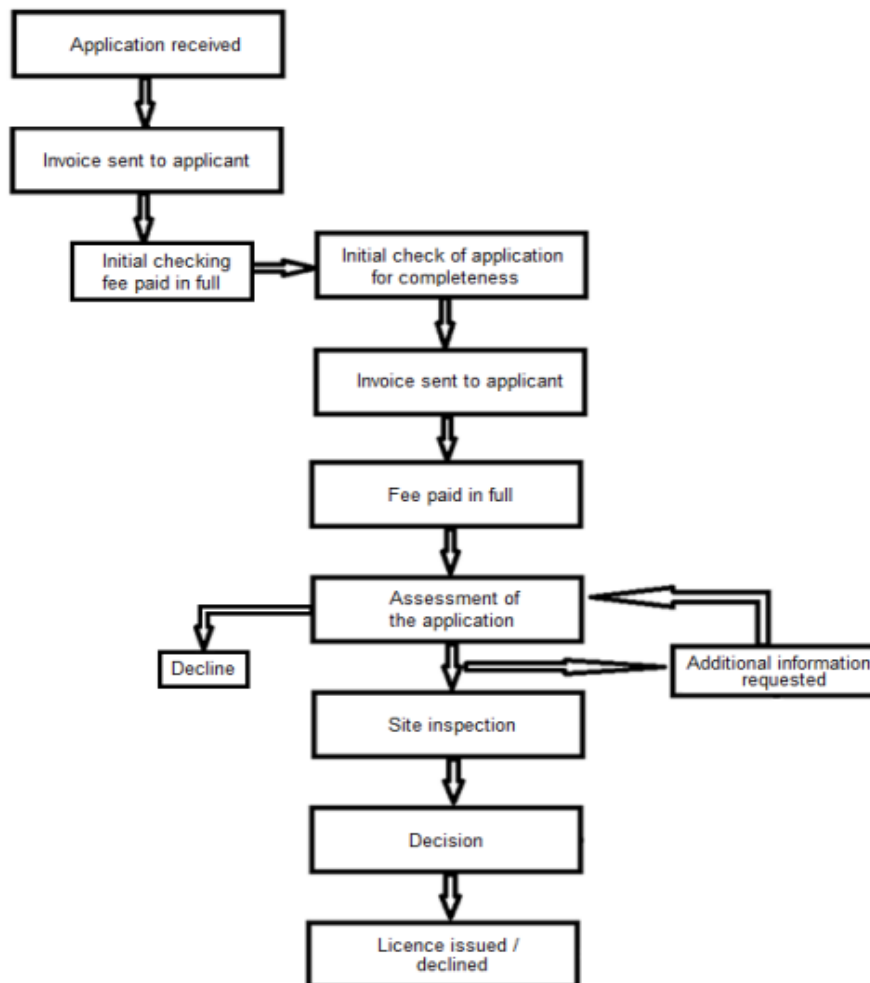
	Mana Authority and rights to manage land, soil, and resources. Power and protection over resources.	Mauri The continuous capacity of the soil to support/sustain life and wellbeing. The ecosystem defines the quality of life.	Maara kai The ability of soil to produce and sustain healthy food for harvest and collection	Oranga ora Adding no human waste, harmful chemicals, pathogens, pesticides, or toxicity to the ecosystem Doing the right thing.	Whakapapa Working together respectfully and acknowledging our Whakapapa Embracing all people and moving together as one.	Wairua The spiritual connections which bind the living and non-living What you do with something affects something else, which affects something else.	Kaitiakitanga Leaving resources in as good or if not better condition for future generations.	Total
Landfill	2	1	1	2	2	3	1	12
Composting	3	2	2	2	2	3	2	16
Anaerobic Digestion	3	2	2	3	2	3	2	17
Incineration	3	1	1	1	1	3	1	11
Pyrolysis	2	3	3	3	3	3	2	19

6.6 New Zealand regulations

6.6.1 Medicinal cannabis regulation regime

In New Zealand, the Medicinal Cannabis Agency (MCA) was formed under the Ministry of Health (MoH) when the medicinal cannabis scheme came into effect in 2020. The MCA regulated the commercial cultivation, manufacture, and supply of cannabis for medicinal purposes, including cannabis-based ingredients, starting material, and products. The MCA handles licensing for the scheme for specific activities relating to medicinal cannabis. The Guideline on the Regulation of Medicinal Cannabis in New Zealand is set out in Part 4 - Guidance for Applicants for a Medicinal Cannabis Licence under the MCA and the MoH. The licensing framework states that a single Medicinal Cannabis Licence authorises the licence holder to conduct one or more of the following types of licensed activity: cultivation activity, nursery activity, research activity, possession for manufacture activity, and supply activity. However, the application requires which activity or combination of activities the licence will be for to be stated. An amendment to the licence can be arranged to add on further activities at any time. A single licence can cover one of the following: one activity at one location only, one or more activities at the same location and one or more activities at separate locations. During the application process, management of activities and security at the location where activities will be completed are assessed. When applying for a licence, the destruction method of waste material and products must be outlined. Under the guidelines, “You must outline your procedures for disposing of all unwanted or excess material (particularly seed heads, seeds, and flowers) in a way that renders the material unusable, unrecognisable, and irretrievable.” This vague statement makes understanding a suitable and acceptable disposal method complex. The applicant is also checked for eligibility. A summary of the licensing process is displayed in Figure 26.

Figure 26: New Zealand medicinal cannabis licensing process summary (from MoH, 2020b, p.5)



The MoH (2020b) sets out a description of each activity under the medicinal cannabis licences:

- A cultivation activity includes physical processes such as harvesting, collection, trimming or discarding, and drying. It does not allow the applicant to extract, grind or mill constituents from cannabis.
- A nursery activity includes importing, purchasing, and supplying seeds to another licence holder for cultivation. It does not allow the licence holder to deal in cannabis plants or cultivate plants for supply. This licence acts more as a seed merchant.
- A research activity solely includes the supply of medicinal cannabis products (that are not CBD products) to participants in a clinical trial. The applicant should only apply for this activity if the Director-General of Health has approved the clinical trial.
- A possession for manufacture activity includes the manufacture of medicinal cannabis products. It allows the following activities: extracting constituents from cannabis material, grinding or milling dried cannabis product, manufacturing starting material, manufacturing a cannabis-based ingredient, manufacturing a dried product, manufacturing a dosage product, packing, labelling, and testing cannabis material, ingredients, and products for a therapeutic purpose. You can no longer conduct these

activities under the previous licence, a licence to deal in controlled drugs. However, with this activity, if the intention is to manufacture a finished product for patients to use, the medicinal cannabis minimum quality standard must be met and comply with the Good Manufacturing Practice (GMP) requirements. Another licence, the licence to manufacture medicines under the Medicines Act 1981, must also be held by the applicant.

- A supply activity includes supplying medicinal cannabis products (as stated on the licence) to others who hold an appropriate licence and importing medicinal cannabis products to distribute them from a holding warehouse. However, it does not cover the wholesale supply of CBD products, as they are no longer controlled drugs and are classed as prescription medicines, which requires a Licence to Sell Medicines by Wholesale under the Medicines Act 1981.

6.6.2 Roadblocks in activity licensing

One major gap seen in the specified activities under medicinal cannabis licensing was research for the industry rather than for clinical research; this is where this project is located. The researchers asked the MCA for advice regarding licensing related to this project, and specifically for testing on medicinal cannabis at Massey University (12th April 2021). The MCA was sympathetic to the issue, but this project did not fit into any existing licensing of activities (15th April 2021). Subsequently a private company suggested obtaining a licence to deal in controlled drugs (19th April 2021). On the 13th May 2021, the MCA advised the researchers to apply for the licence to deal in controlled drugs through the MoH as they continued investigating how the licensing regime could be updated to include projects like this one. The MoH was contacted regarding applying for the licence to deal in controlled drugs (17th May 2021). MoH requested a project proposal for more information which was sent the same day (26th May 2021). MoH requested further details on the project, including the suppliers' details, which were sent on 27th May 2021. On 11th June 2021, the MoH was emailed asking for any news regarding the licence for this project, to which they replied that it was still being assessed as it was not a straightforward fit (17th June 2021). On 2nd July 2021, the MoH stated that the employee looking after this project's licence had left and the supplier of medicinal cannabis residues that the researchers had arranged did not have the correct licence to supply this material. The MoH sent through contact details of another department within MoH, medicines control (which is the department that the licence should be applied through). The MoH also sent through the application for the licence to deal in controlled drugs. The supplier would also be required to hold this licence in order to cultivate a prohibited plant specifically in order to supply to this project (14th July 2021). An application form for the suppliers' licence was also sent directly to the supplier. Due to Covid lockdowns and the pandemic inhibiting communications, it was unknown if the supplier had applied for their licence. Therefore, the licence to deal in controlled drugs application was sent in for this project (8th September 2021). On the 14th September 2021, the project's licence application was halted until a supplier with the required licence could be obtained. On the 11th November 2021, after months of trying to find a supplier willing to get this licence and going back and forth with more information, it was identified that the licence to cultivate a prohibited plant required the

set-up of a new cultivation area solely to supply this project, as it must be kept separate from the normal day-to-day operations. This was not feasible for any company within New Zealand. Therefore, a new approach to testing was required. The only option was to complete the testing on-site at medicinal cannabis companies since destroying material on-site is allowed under the licenses currently held by medicinal cannabis facilities. The final on-site testing was completed in October 2022.

Meanwhile, S. King (personal communication, October 4, 2022) informed the researchers that the MCA had advised that regulatory non-compliance was approved so that research in the industry for non-clinical purposes was allowed but this was not a long-term solution. This provides a legal solution to the licencing issue for companies to provide cannabis plant materials for research purposes legally but not long-term; the MCA communicated to the researchers that a long-term solution is said to be in the works for the coming years (S. King, personal communication, October 4, 2022).

Sustainability is a big part of New Zealand and any growing industry. Although the regulations are moving in the right direction, with projects slowly being allowed within the industry, the description above shows that more effort is needed to facilitate licensing to enable sustainability-orientated work in this industry.

6.6.3 Regulation of carbon accounting and management

Carbon accounting

Carbon accounting is essentially when an organisation quantifies its contribution to climate change. Methodologies and frameworks enable robust demonstration of greenhouse gas (GHG) emission reductions when changes are made to activities (Slade et al., 2018). For this study, the methods used in LCA were analysed as well as the methods and frameworks currently used within New Zealand.

As described earlier in the study, an LCA has five phases: the goal and scope, inventory analysis, impact assessment, and interpretation. The most important are inventory analysis and impact assessment. Bessou et al. (2020) compiled a review of methods developed to account for climate change, and particularly related to accounting for soil carbon emission and sequestration based on the impact of land use and land use change (LULUC) on various soil properties and functions. Matušík et al. (2020) describe the variables that most affect carbon accounting, including the LCA software and analysis methods used. According to Bessou et al. (2020), 19-24% of anthropogenic global emissions are due to agriculture, forestry, and LULUC. The majority of the impacts from LULUC are from the release of soil organic carbon (SOC) (Bessou et al., 2020; Lal, 2016).

In Section 3.6.5, the labile and stable fractions of the biochar carbon were calculated. SOC is made up of several fractions, including both labile and stable. Therefore, when accounting for biochar carbon, this article is relevant. Bessou et al. (2020) use 22 scenarios of land use changes

(LUC) and agricultural land management changes (LMC) to compare three methods for accounting for LUC and LMC: IPCC, Muller-Wenk and Brandao (2010) (MW&B), and Levasseur et al. (2012). The IPCC method assesses all carbon stocks/pools (vegetation biomass and SOC), with vegetation biomass including the above-ground and below-ground carbon stocks (Bessou et al., 2020). Therefore, IPCC calculates GHG emissions as the difference between two carbon stocks (vegetation biomass and SOC) when they are at equilibrium in two different land-use systems, this is then divided by a defined time period so that the impact is allocated over a specified time. The typical time period for GHG emissions is 100 years. SOC loss and emissions are calculated using the carbon-to-nitrogen (C:N) ratio in the IPCC method; also, the nitrous dioxide direct and indirect emissions are calculated.

The variables assessed by Bessou et al. (2020) are the carbon stocks, regeneration times, and C:N ratios. Matušík et al. (2020), on the other hand, use the variables: feedstock, conditions and technique of pyrolysis, the rate at which the biochar is applied to the soil, stability of the biochar in soil, and the effect that the biochar has on the soil. It is important to look at the carbon when the biochar enters the soil and identify how long it will last in the soil. Therefore, all the above variables are relevant yet highly context-specific (Sykes et al., 2019).

The two other methods used by Bessou et al. (2020) are MW&B and Levasseur et al. (2012) (dynamic LCA), methods. MW&B use characterisation factors (CF) that integrate the reversibility of biogenic carbon using residence times shorter than fossil carbon. They use the land use framework, which refers to LUC and LMC as “transformation impacts” and adds the “occupation impact” to represent the land occupation LCI elementary flows. The dynamic LCA accounts for the role of timing of GHG emissions in accounting for climate change, using dynamic global warming potentials. In contrast, IPCC takes location into account but uses static characterisation factors.

While Bessou et al. (2020) discuss the methods, they do not specify the modelling software used in the different reviewed studies. However, Matušík et al. (2020) identify that two articles they reviewed used GaBi, and the others used OpenLCA (one article), SimaPro (nine articles) whilst four articles reviewed did not state what software was used.

Overall, the best course of action for future carbon accounting practices would be to include more methods in LCA software programmes so that the influence of different methods on the climate change results can be investigated.

For carbon accounting, then, there are many aspects to be considered. For this study, it was decided to set a range for the variables based on literature or actual data collected and do an in-depth sensitivity analysis based on a specific location with a specific soil type. The LU and LMC of the soil were not defined for this study, therefore, no methods described in Bessou et al. (2020) were used for carbon accounting in this study; the use of variables such as feedstock, and biochar carbon stability from Matušík et al. (2020) and equations from Anaya de la Rosa (2013) were used. The environmental impacts associated with the EoL treatments in this study show that when biogenic carbon, in the form of carbon sequestration in biochar, is included in

the climate change impact assessment, it can dramatically change the environmental impact results (Section 5.1.1). Therefore, accounting for the carbon, it is important to analyse different methods, and the results can then be compared. Due to the size of this study, an in-depth analysis of the carbon accounting comparison for the alternative EoL treatments could not be conducted. In future, further research should also be undertaken on the effect biochar produced from cannabis plant material has on various soils and crops grown in those soils.

Regulation of greenhouse gas emissions in New Zealand

In New Zealand, the Ministry for the Environment (MfE) is the official ministry managing the national carbon accounting. The MfE has produced guidelines on greenhouse gas (GHG) emissions (see Section 5.2). While these guidelines allow for GHG emission estimates to be made, they don't account for carbon accounting comprehensively (see discussion regarding the landfill, composting, and anaerobic digestion emission factors in Section 5.2.1). Also, the New Zealand emissions trading scheme (ETS) was set up through the Climate Change Response Act 2002 (EPA, n.d.). It should be noted that the ETS scheme was created to involve all sectors of the economy so that all GHG emissions can be accounted for; however, economic, social, and political pressures on the economy have led to delays in some economic sectors entering the ETS (Anaya de la Rosa, 2013).

A gap in the carbon accounting framework is that the agriculture sector is not being completely accounted for in the ETS, with the current obligations being mandatory at the processor-level reporting only to date (no obligations at the farmer-level). Therefore, within New Zealand, the framework would not allow for the carbon in biochar to be accounted for when applied to land.

For this study, since pyrolysis is the potential new EoL treatment for cannabis plant residues, its future inclusion (or not) in the ETS will dramatically affect the potential profits available. The difference between the land-spread revenue option in the land-spread including carbon sequestration option shows that a potential loss of approximately \$4/FU, or \$5,000 after 15 years, would occur if there was no credit for biochar carbon sequestration. An investigation is currently underway into claims for carbon sequestration and carbon emissions in the agricultural sector, using over 500 sites around the country (NZAGRC, n.d.); this is important in order to develop a better understanding of the carbon sequestration benefits of using biochar.

The next step for New Zealand would therefore be to:

- Add agriculture at a farmer level to the ETS
- Require measurement of carbon in soils (or use of proxy indicators) and include options for carbon credits for farmers that can demonstrate they are increasing soil carbon by incorporation of biochar.

6.7 Summary of the environmental impacts and preliminary economic, social, and cultural aspects

There is a fuzzy boundary between economic, social, cultural, and even environmental aspects because activities may provide benefits across several aspects (Bornmann, 2013). For example, Salter and Martin (2001, p.510) provide a good example of this blurred line, stating that “If a new medical treatment improves health and reduces the days of work lost to a particular illness, are the benefits economic or social?”³ In this study, quantitative indicators were chosen to measure the environmental, economic, social, and cultural aspects of each EoL treatment evaluated in this study but recognising there may be some overlap between them. Table 23 shows a summary of the overall results from the study.

On an environmental scale, it was found that across the assessed impact categories, the alternative EoL treatments rankings are: composting (best), anaerobic digestion, pyrolysis, incineration, and landfill (worst). The rankings are presented in Table 23; it should be noted that the results shown in Table 23 are only for the baseline EoL treatments and do not include any changes made in the sensitivity analysis or varying revenue streams.

On an economic scale, the preliminary results show that the composting EoL treatment has the smallest capital and operating costs and the better NPV after 15 years. Based on the preliminary economic assessment, the ranking of the alternative treatments are: composting (best), pyrolysis, landfill, incineration, and anaerobic digestion (worst). The comparison of the NPV after 15 years is also included in Table 23.

There are many social indicators could have been considered for this study; however, due to time constraints, a single indicator was used: the number of hours available for employment per year. The hours available for employment for each EoL treatment were dependent on the processing times of the treatments i.e. how long the employees would be required for each EoL treatment. The preliminary results rankings are: anaerobic digestion (best), pyrolysis and incineration, and landfill and composting (worst).

For the cultural assessment, seven major headings (sets of values) were used to show the values important to the Māori. The preliminary rankings of the EoL treatments are: pyrolysis (best), anaerobic digestion, composting, landfill, and incineration (worst). The total extent to which each EoL treatment aligns with the values is shown in Table 23. Due to the limited available of participants in this cultural assessment, future research could involve more participants from the same iwi which would allow for more in-depth discussion and reasoning behind the extent that the EoL treatments align with the Māori values. Future research could also incorporate

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participants from a range of iwi, which would create a wider awareness about the acceptability of the various disposal options.

The results in Table 23 show that if the environmental impacts, and preliminary economic, social, and cultural aspects are all considered, the rankings of the alternative EoL treatments are: pyrolysis (best), anaerobic digestion and composting equal second, incineration and landfill (worst). However, it should also be noted that the additional options in the table using different profit streams for the anaerobic digestion, incineration, and pyrolysis EoL treatments, have assumed the same environmental and cultural results, and capital and operating costs. This may not, in fact, be the case and further investigation should be completed into these options.

Given the insights provided by this study, landfill and incineration should not be EoL treatments used for cannabis plant residues as they generally rank the lowest of all the aspects discussed in this study

Table 23: Environmental, economic, social, and cultural matrix for alternative EoL treatments showing a summary of all aspects

EoL Treatment (Revenue Stream)	Environmental - across all assessed impact categories (Ranking)	Economic - NPV* after 15 years (\$***)	Social - working hours available (hours/year)	Cultural - total extent following the Māori values (Sum of extent)
Landfill (Nil)	5th (worst)	-\$2,650,000	132 (worst)	12
Composting (Compost)	1st (best)	-\$1,013,000 (best)	132 (worst)	16
Anaerobic Digestion (Heat from biogas)	2nd**	-\$4,471,000 (worst)	780 (best)	17**
Anaerobic Digestion (Compost)	2nd**	-\$4,457,000	780 (best)	17**
Anaerobic Digestion (Heat from biogas + Compost)	2nd	-\$4,449,000	780 (best)	17
Incineration (Ash to landfill including the landfill avoidance fee)	4th	-\$4,108,000	420	11 (worst)
Incineration (Ash land-spread including the landfill avoidance fee)	4th**	-\$4,152,000	420	11** (worst)
Pyrolysis (Biochar as fuel at \$10/GJ including the landfill avoidance fee)	3rd**	-\$2,558,000	420	19** (best)
Pyrolysis (Biochar as fuel at \$675/t of biochar including the landfill avoidance fee)	3rd**	-\$2,545,000	420	19** (best)
Pyrolysis (Biochar land-spread including the landfill avoidance fee)	3rd**	-\$2,565,000	420	19** (best)
Pyrolysis (Biochar land-spread and carbon sequestered including the landfill avoidance fee)	3rd	-\$2,560,000	420	19 (best)

Note. *Net Present Value. **The same environmental and cultural results were assumed for the alternative revenue streams as the EoL treatment base results. ***Rounded to the nearest one thousand.

Chapter 7: Conclusions and recommendations

This study investigated the environmental, economic, social, and cultural impacts of current EoL treatments used for cannabis plant residues in comparison to a proposed new EoL treatment, pyrolysis, using a life cycle-based approach. The current common EoL treatments for cannabis plant residues are landfilling, composting, anaerobic digestion, and incineration. Additional pyrolysis experiments showed that the pyrolysis EoL treatment can be used to treat cannabis plant residues safely. The pyrolysis by-product of interest, biochar, contains no cannabinoids, the key compounds of concern in the cannabis plant.

When the environmental, social, economic, and cultural aspects of the alternative EoL treatments were evaluated, the rankings were pyrolysis (best), composting, anaerobic digestion, landfill, and incineration (worst).

7.1 Implications

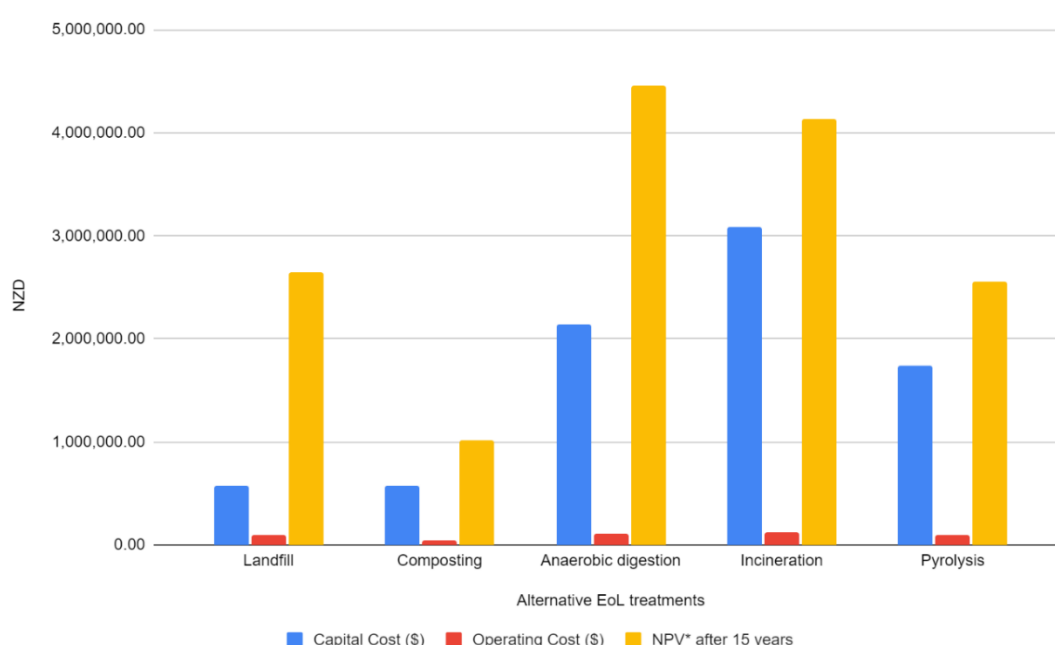
The environmental, economic, social, and cultural assessments identified hotspots that can be used to support decision making about improving the systems, and the areas where future research should be conducted.

The environmental hotspots in each EoL treatment were addressed in Section 5.1.3. For the **landfill** EoL, no existing studies were found in the literature. The process involved adding bleach and other organic waste, and sending the mixed material to landfill. The major hotspot was found to be bleach production, specifically NaOCl production, which contributed 20% or more of the impact in 7 out of 15 of the impact categories. The bleach was only incorporated as the worst-case scenario; if bleach was not added, the environmental impact of this treatment would improve dramatically. For the **composting** EoL treatment, the decomposition emissions during composting were the hotspot in the literature and also in this study. The management of the composting facility plays a big part in the amount of emissions emitted. Therefore, improving the management of the composting facility so that a greater percentage of methane emissions produced are oxidised in the heap would reduce the overall environmental impact of this treatment. For the **anaerobic digestion** EoL treatment, many assumptions had to be made – but it was found that the anaerobic digestion emissions produced on-site contributed 20% or more of the impact in 9 out of 15 impact categories. However, more research is needed to verify the various assumptions. For the **incineration** EoL treatment, a hotspot found in this study was diesel burning in the incineration process; this was not identified in literature. The use of diesel could be reduced by optimising the system and increasing the amount of dried cannabis plant residues being burnt to fuel the incineration process. Another hotspot found in the **incineration** EoL treatment was transportation which was identified in this study and in the literature. For the **pyrolysis** EoL treatment, it was found that transportation contributed the largest impact due to assuming use of a mobile unit; however, literature studies assumed a stationary unit. A hotspot that was found in both literature and this study was the displaced climate change impact from carbon sequestration (Sections 3.6.5 and 5.2.1). In the sensitivity analysis, it was found that when the biochar yield from the pyrolysis unit was increase from 10.15% to the most

favourable scenario (59%), a difference of -2468% was found in the climate change impact category. Therefore the variables should be further assessed in future research. In general, the rankings across all the assessed impact categories were: **composting** (best), **anaerobic digestion**, **pyrolysis**, **incineration**, and **landfill** (worst).

The preliminary economic hotspots can be determined based on the rankings of each section of the economic assessment: capital cost, operating cost, and net present value (NPV) after 15 years (Figure 27). The accuracy of the economic assessment was $\pm 25\%$ (Section 6.1.1). Reducing this uncertainty would increase the accuracy of the results.

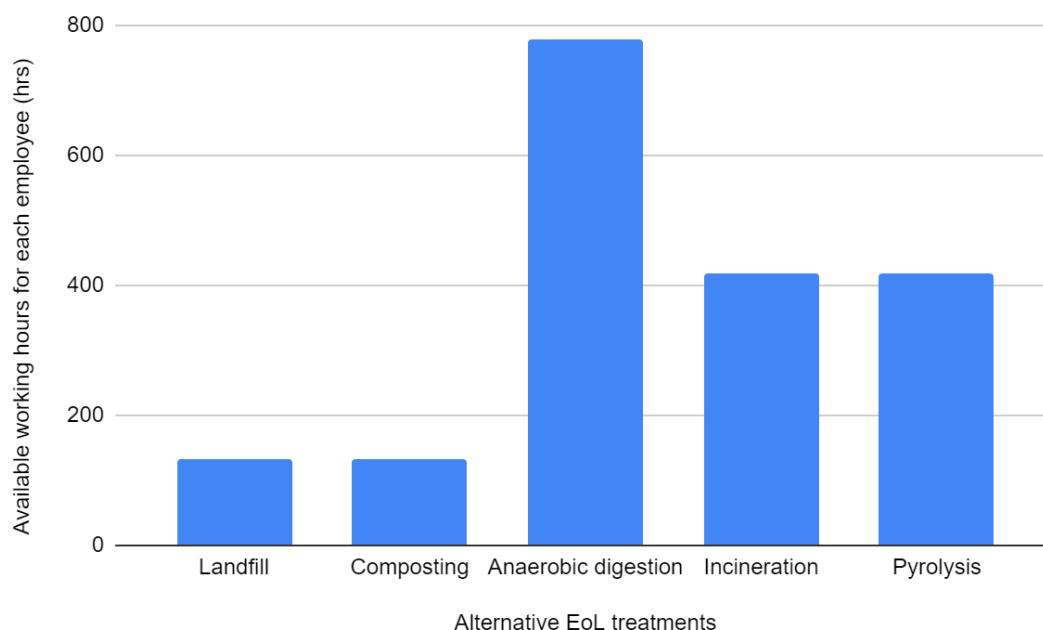
Figure 27: General economic hotspots from preliminary economic analysis of alternative EoL treatments for cannabis plant residues



Note. The average NPV values from all possible revenue streams in the EoL treatment was taken. This data is graphed from Table 19. *Net present value.

The preliminary social analysis in this study assessed the total working hours available for an estimated number of employees required (Section 6.2). Figure 28 shows that the **anaerobic digestion** EoL treatment provided more working hours than the other alternative EoL treatments, with the **composting** and **landfill** EoL treatments providing the least number of hours. It should be noted that the social indicators only incorporate the total working hours available on-site at the cultivation facility. In future studies, the social assessment should incorporate more social indicators such as health and safety and household income, creating a more in-depth analysis.

Figure 28: Preliminary social analysis - total working hours available on-site at the cultivation facility for alternative EoL treatments of cannabis plant residues



The preliminary cultural assessment investigated the extent to which the EoL treatments align with the Māori values laid out in Section 6.5.3. Overall it was found that the **incineration** EoL treatment aligned with majority of the values to a “slight extent”, the **landfill** EoL treatment aligned with majority of the values to either a “slight extent” or to “some extent”. The **composting** EoL treatment aligned with majority of the values to “some extent”, and the **anaerobic digestion** EoL treatment aligned with majority of the values to either “some extent” or a “great extent”. Finally, the **pyrolysis** EoL treatment aligned with majority of the values to a “great extent”. The similarities for the **incineration** and **landfill** EoL treatments only aligned with the Mauri, Maara kai, and Kaitiakitanga values to a “slight extent”. The “slight extent” rating was given for the **landfill** EoL treatment because the treatment only makes a limited contribution to the values for sustainable soil life. Unfortunately, **landfill** is an EoL treatment with minimal improvement opportunities in this area other than improving the management of the landfill operation. The **incineration** EoL treatment was given this rating because a large amount of diesel is required for incineration, and the final product is landfilled. Although it was not assessed in this study, there is an option in the **incineration** EoL treatment to land-spread the ash as well as reducing the diesel used in the system. These changes would improve the extent to which the incineration treatment aligns with the Māori values and its ranking for cultural considerations.

Given the insights provided by this study, **landfill** and **incineration** should not be EoL treatments used for cannabis plant residues as they generally rank the lowest of all the aspects discussed in this study (Section 6.7). The **pyrolysis** EoL treatment is a promising new method with many possibilities for future development and implementation. The environmental impact of this treatment varies by a large amount due to the variables associated with carbon sequestration; future research should critically review the variables used in this study and those

in the literature to obtain more accurate variables for biochar produced from organic materials. While the social and cultural aspects of the **pyrolysis** EoL treatment were ranked in the middle of the EoL treatments, more research could alter this ranking; further social indicators should be assessed and more participants should be involved in the cultural interviews. The economic assessment of this treatment was basic, a possible improvement option for the pyrolysis EoL treatment could be the mobile unit obtaining more business, increasing the revenue stream of this treatment (Section 3.1.3). For example, a pyrolysis mobile unit could be used to manage cannabis plant residue disposal for both the hemp and medicinal cannabis industries, or even other types of organic waste as well (Anaya de la Rosa, 2013).

7.2 Limitations

The environmental impact results of this study had several limitations including the LCA software dataset specificity, and the mass and energy balance assumptions used to create the models. While several **LCA software** options are available, GaBi Sphera (GaBi) was chosen because Massey University already held a licence for the software (Section 3.1.4). The variability in results found in this study was partly due to differences between the **datasets and impact assessment methods** provided within the software, relative to other datasets and impact assessment methods. The variability was also partly due to the number of **assumptions made in the mass and energy balances** which helped to create the models for the alternative EoL treatments (Sections 3.2-3.6).

The preliminary economic analysis was completed for the **activities on-site** at the cultivation facility (Section 6.1). An assumption that was made during this preliminary economic analysis was that **industrial ovens were used to cost** the dryers, a pyrolyser, diesel burners, and an incinerator (Sections 6.1.6 and 6.1.7) While this may be feasible in a preliminary analysis, further costing analysis of the incineration and pyrolysis EoL treatments would allow for more accurate results.

The preliminary social analysis was constrained by the timeframe of this study and therefore only **one social indicator** was analysed: the total working hours available per employee (Section 6.2), with an estimated number of employees that could be required which helped with labour costs in the economic analysis.

The preliminary cultural analysis was limited by the **availability of participants** limited the cultural assessment of the EoL treatments (Section 6.3). In future research, obtaining more participants from the same iwi would allow for more in-depth discussion and reasoning behind the extent that the EoL treatments align with the Māori values. Future research could also incorporate participants from a range of iwi, which would create a wider awareness about the acceptability of the various disposal options.

There were several factors that limited the experimental tests these including sampling issues, licencing and regulation requirements, the mulching consistency of the cannabis plant residues, and the NETZSCH thermal analyser used for proximate analysis. **Licencing** was required to

process fresh cannabis plant residues at Massey University, and so the pyrolysis experiments were completed at the cultivation facilities (Sections 4.7, 6.6.1 and 6.6.2) conducting the experiments at the cultivation facilities necessarily limited the **selection of plant material**, and so cannabis plant residues were obtained from just two locations (Sections 4.2 and 4.7). Hemp was harvested from Massey University's experimental plots, and medicinal cannabis was harvested from Puro's cultivation site. In future, harvesting and testing of more plants would increase the accuracy of these datasets. The cannabis plant residues were not **mulched** as they would be on a commercial scale. Instead, secateurs or the machine used in Puro's harvest process were used to chop the material to fit into the pyrolysis unit (Sections 4.2 and 4.7). The surface area and size of the material entering the pyrolysis unit can impact how fast or slow pyrolysis occurs. Therefore, in future research, a specific size (length and thickness) and an uncertainty level should be defined; this would enable more accurate pyrolysis temperature profiles, specifically for the stalks and roots, which have the most variation in sizes. The **NETZSCH thermal analyser used for proximate analysis** of the char ran up to approximately 900°C, and so the ash that remained in the crucible was less than the actual ash of the sample because heavy metals and alkali would be vapourised at this temperature (Section 4.7). To reduce this limitation, the researcher used a standard error.

The degree **time constraint** of three years restricted this study as there was insufficient time to undertake in-depth analysis (Section 1.4). However, the major time limitation occurred due to the pandemic Covid lockdowns and slow communication with respect to resolving licensing requirements for the experimental work in this project (Section 6.6.2).

7.3 Recommendations for future research

This study is a first step towards future research into how this industry can improve the management of its EoL plant residues. Future research that would apply to all EoL treatments includes:

- **LCA dataset/database selectivity**: this study used the GaBi LCA software and ecoinvent database (Section 3.1.5). However, with a range of datasets available across several LCA software options, further research should be undertaken to investigate differences between the datasets and to compare them for quality assurance purposes, as well as applicability to the New Zealand situation.
- **Synthetic fertiliser production climate change impact**: this study found that synthetic fertiliser production was modelled as a displaced activity in the alternative EoL treatments. A comparison of the modelled climate change impacts to those found in other literature showed that there was a difference (Section 5.1.5). Therefore, future research should investigate the appropriateness of using different datasets for fertiliser production to ensure the results accurately represent the New Zealand industry.
- **Economic assessment**: a basic economic assessment was undertaken in this study (Section 6.1). Future research should be undertaken to provide a more in-depth economic assessment of each EoL treatment. The in-depth assessment should include more accurate costing of the dryers, incinerator, pyrolyser, and diesel burners required in the incineration and pyrolysis EoL treatments (Sections 6.1.6 and 6.1.7).

- Social assessment: in future studies, the social assessment should incorporate more social indicators such as health and safety and household income, creating a more in-depth analysis (Section 6.2).
- Cultural assessment: as noted in Section 6.7, further interviews involving more participants (from the same iwi or multiple iwi) would allow for greater detail and discussion into the extent that each EoL treatment aligns with the Māori values.

The anaerobic digestion EoL treatment should be scaled in future research. The anaerobic digestion system used in this study would have a large amount of downtime due to it not being utilised all year round (Section 6.2.2). Therefore, future research should focus on the scaling of the anaerobic digestion EoL treatment to include reduced downtime and increased biogas production – which could benefit the cultivation facility (heat available) and increase the potential revenue of this treatment.

Since pyrolysis was the new potential EoL treatment for cannabis plant residues that was investigated thoroughly in this study, there are several recommendations as discussed in Chapter 4:

- Replication of pyrolysis trials: this study tested one harvest of hemp and one harvest of medicinal cannabis, with no replicates. Future research should conduct additional pyrolysis experiments for the hemp and medicinal cannabis industries to replicate results and reduce the uncertainty associated with the biochar yields. This would give the industry more accuracy about the feasibility of pyrolysis as an EoL treatment and using biochar to create a circular economy.
- Alternative uses of biochar: this study estimated data for modelling end uses of biochar; however, while the composition of the biochar was obtained, no experiments into biochar use were completed. Future research should focus on hands-on experiments to collect and compare quantitative data on the potential use of biochar for drinking water filtration, sanitation of human and kitchen wastes, and as an amendment to soils.
- Flaring the pyrolysis by-product, condensate: this study assumed that the condensate was burnt to ensure the condensates do not enter the human food cycle. The cultivation facility can utilise the heat if it is collected from flaring the condensate. This requires further innovation in the pyrolysis mobile unit equipment.
- Cannabinoids found in the pyrolysis condensate: this study found that the condensate collected from pyrolysis contained cannabinoids, the key compounds of interest in the cannabis plants. Future research should look into the methods for extracting them and how the industry could utilise them (provided there is enabling legislation in place).

7.4 Conclusions

The research objectives and questions set for this project were to: identify the common global EoL treatments for cannabis plant residues in the hemp and medicinal cannabis industries; determine and evaluate the environmental impacts of the common and potential EoL treatments; collect missing data on the potential EoL treatment, pyrolysis; identify the

economic, social, and cultural aspects of the alternative EoL treatments; and compare and contrast the environmental, economic, social, and cultural aspects (Section 1.2).

The first research question was addressed by a literature review which found that the common EoL treatments for cannabis plant residues used globally were landfilling, composting, anaerobic digestion, and incineration (Chapter 2). The second research question was addressed by calculating mass and energy balances which led to LCA models of the alternative EoL treatments being created. Through the use of the ReCiPe 2016 v1.1 method, the environmental impacts were determined for these treatments as well as the potential new EoL treatment, pyrolysis (Section 5.1.2) and then analysed to identify the environmental hotspots with each EoL treatment (Section 5.1.3).

The literature on the pyrolysis EoL treatment for cannabis plant residues was scarce, and so missing data was collected by undertaking experiments using one harvest of hemp and one harvest of medicinal cannabis (Section 4.2). The by-products of pyrolysis, biochar and condensate were analysed through a proximate analysis (Section 4.5) and a Py-GCMS analysis (Section 4.6), and this showed that pyrolysis could be a suitable EoL treatment for cannabis plant residues, completing the third objective of this study.

The fourth research question was addressed by a preliminary analysis of the life cycle-based economic (Section 6.1), social (Section 6.2), and cultural (Sections 6.3-6.5) aspects of the alternative EoL treatments was undertaken. The final research objective was then addressed in Chapter 6 when the environmental, economic, social, and cultural results were ranked across the different EoL treatments and compared to obtain a general ranking of: pyrolysis (best treatment), composting, anaerobic digestion, landfill, and incineration (worst treatment).

Even though the economic, social, and cultural analyses provide only preliminary results, overall this study provided new insights and a platform for future research within the hemp and medicinal cannabis industries.

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Appendix A: Calculations of process times

Appendix A.1: Landfill EoL treatment

Shredder

A shredder was found for this treatment to be 15hp, but no processing capacity was provided (Monster Industrial, n.d.). A similar shredder was found to be 10hp with a processing capacity of 500-1000 kg/hour (Indiamart, n.d.). Therefore, a 15hp shredder was assumed to have a processing capacity of approximately 750-1500 kg/hour.

However, the material to be shredded contains leafy material as well as stalks and roots, this leafy material would decrease the rate at which the material is processed. Therefore, one-fifth of the standard processing capacity was used, 150-300 kg/hour.

$$750 \frac{kg}{hour} * \frac{1}{5} = 150 \frac{kg}{hour}$$

$$1500 \frac{kg}{hour} * \frac{1}{5} = 300 \frac{kg}{hour}$$

Taking an average of 225 kg/hour it would take 4.44 hours to process one tonne of solely cannabis material.

$$\frac{300 - 150}{2} = 225 \frac{kg}{hour}$$

$$\frac{1000 \frac{kg}{cycle}}{225 \frac{kg}{hour}} = 4.44 \text{ hours}$$

The process rate required is six tonnes of cannabis waste per cycle, but six tonnes of green waste is also added for this EoL treatment, so 12 tonnes of material is required to be shredded per cycle. At the above rate of 225 kg/hour, it would take 53.33 hours per cycle to process 12 tonnes of material. Running at 10 hours per day, it would take 5.33 days to process all the required material.

$$\frac{12000 \frac{kg \text{ material}}{cycle}}{225 \frac{kg}{hour}} = 53.33 \frac{hours}{cycle}$$

$$53.33 \frac{hours}{cycle} * \frac{1 \text{ day}}{10 \text{ hours}} = 5.33 \frac{days}{cycle}$$

Mixer

A rotary continuous mixer was found to be 3hp with a two-minute product residence time running at 13.5 m³/hour (Munson, n.d.). For this study, the cannabis material was assumed to have a density of 125 kg/m³ (Shojaeiarani et al., 2019), giving a processing capacity of 1687.5 kg/hour.

$$13.5 \frac{m^3}{hour} * 125 \frac{kg}{m^3} = 1687.5 \frac{kg}{hour}$$

However, the same assumption of using a fifth of the processing capacity for leafy material was used to obtain a processing capacity of 337.5 kg/hour.

$$1687.5 \frac{kg}{hour} * \frac{1}{5} = 337.5 \frac{kg}{hour}$$

The same processing requirement of six tonnes of cannabis material and six tonnes of green waste was used and the requirement for 2.25 tonnes of bleach per cycle gives a total processing requirement of 14.25 tonnes per cycle.

$$6 \frac{t \text{ plant material}}{cycle} + 6 \frac{t \text{ green waste}}{cycle} + 2.25 \frac{t \text{ bleach}}{cycle} = 14.25 \frac{tonnes}{cycle}$$

Using the above rate of 337.5 kg/hour it would take 42.22 hours per cycle to process the material, at 10 hours per day, it would take 4.22 days to process the material.

$$\frac{14.25 \frac{tonnes}{cycle} * 1000 \frac{kg}{tonnes}}{337.5 \frac{kg}{hour}} = 42.22 \frac{hours}{cycle}$$

$$42.22 \frac{hours}{cycle} * \frac{1 \text{ day}}{10 \text{ hours}} = 4.22 \frac{days}{cycle}$$

Conveyor

The conveyor provided a range that it can run at of 1.975-3.21 tonne/hour (Asli-Arden & Mohsenimanesh, 2012). Using the same processing requirement of 14.25 tonne/cycle running 10 hours per day. It would only take 0.55 days to convey the material.

$$\frac{3.21 - 1.975}{2} = 2.59 \frac{tonnes}{hour}$$

$$\frac{14.25 \frac{\text{tonnes}}{\text{cycle}}}{2.59 \frac{\text{tonnes}}{\text{hour}}} = 5.50 \frac{\text{hours}}{\text{cycle}}$$

$$5.50 \frac{\text{hours}}{\text{cycle}} * \frac{1 \text{ day}}{10 \text{ hours}} = 0.55 \frac{\text{days}}{\text{cycle}}$$

Overall, the shredder is the slowest part of the EoL treatment. Therefore, it would take approximately 5.33 days for the landfill treatment method to process the waste.

Appendix A.2: Composting EoL treatment

Shredder

A shredder was found for this treatment to be 15hp, but no processing capacity was provided (Monster Industrial, n.d.). A similar shredder was found to be 10hp with a processing capacity of 500-1000 kg/hour (Indiamart, n.d.). Therefore, a 15hp shredder was assumed to have a processing capacity of approximately 750-1500 kg/hour.

However, the material to be shredded contains leafy material as well as stalks and roots, this leafy material would decrease the rate at which the material is processed. Therefore, one-fifth of the standard processing capacity was used, 150-300 kg/hour.

$$750 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 150 \frac{\text{kg}}{\text{hour}}$$

$$1500 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 300 \frac{\text{kg}}{\text{hour}}$$

Taking an average of 225 kg/hour would take 4.44 hours to process one tonne of solely cannabis material.

$$\frac{300 - 150}{2} = 225 \frac{\text{kg}}{\text{hour}}$$

$$\frac{1000 \text{ kg}}{225 \frac{\text{kg}}{\text{hour}}} = 4.44 \text{ hours}$$

The process rate required is six tonnes of cannabis waste per cycle, but six tonnes of green waste is also added for this EoL treatment, so 12 tonnes of material is required to be shredded per cycle. At the above rate of 225 kg/hour, it would take 53.33 hours per cycle to process 12 tonnes of material. Running 10 hours per day, it would take 5.33 days to process all the required material.

$$\frac{12000 \frac{kg \text{ material}}{cycle}}{225 \frac{kg}{hour}} = 53.33 \frac{hours}{cycle}$$

$$53.33 \frac{hours}{cycle} * \frac{1 \text{ day}}{10 \text{ hours}} = 5.33 \frac{days}{cycle}$$

Mixer

A rotary continuous mixer was found to be 3hp with a two-minute product residence time running at 13.5 m³/hour (Munson, n.d.). For this study, the cannabis material was assumed to have a density of 125 kg/m³ (Shojaeiarani et al., 2019), giving a processing capacity of 1687.5 kg/hour.

$$13.5 \frac{m^3}{hour} * 125 \frac{kg}{m^3} = 1687.5 \frac{kg}{hour}$$

However, the same assumption of using a fifth of the processing capacity for leafy material was used to obtain a processing capacity of 337.5 kg/hour.

$$1687.5 \frac{kg}{hour} * \frac{1}{5} = 337.5 \frac{kg}{hour}$$

The same processing requirement of six tonnes of cannabis material and six tonnes of green waste per cycle gives a total processing requirement of 12 tonnes per cycle.

$$6 \frac{t \text{ plant material}}{cycle} + 6 \frac{t \text{ green waste}}{cycle} = 12 \frac{tonnes}{cycle}$$

Using the above rate of 337.5 kg/hour it would take 35.56 hours per cycle to process the material, at 10 hours per day, it would take 3.56 days to process the material.

$$\frac{12 \frac{tonnes}{cycle} * 1000 \frac{kg}{tonnes}}{337.5 \frac{kg}{hour}} = 35.56 \frac{hours}{cycle}$$

$$35.56 \frac{hours}{cycle} * \frac{1 \text{ day}}{10 \text{ hours}} = 3.56 \frac{days}{cycle}$$

Conveyor

The conveyor provided a range that it can run at of 1.975-3.21 tonne/hour (Asli-Arden & Mohsenimanesh, 2012). Using the same processing requirement of 12 tonnes per cycle running at 10 hours per day. It would only take 0.46 days to convey the material.

$$\frac{3.21 - 1.975}{2} = 2.59 \frac{\text{tonnes}}{\text{hour}}$$

$$\frac{12 \frac{\text{tonnes}}{\text{cycle}}}{2.59 \frac{\text{tonnes}}{\text{hour}}} = 4.63 \frac{\text{hours}}{\text{cycle}}$$

$$4.63 \frac{\text{hours}}{\text{cycle}} * \frac{1 \text{ day}}{10 \text{ hours}} = 0.46 \frac{\text{days}}{\text{cycle}}$$

Overall, the shredder is the slowest part of the EoL treatment. Therefore, it would take approximately 5.33 days for the composting treatment method to process the waste.

Appendix A.3: Anaerobic digestion EoL treatment

Shredder

A shredder was found for this treatment to be 15hp, but no processing capacity was provided (Monster Industrial, n.d.). A similar shredder was found to be 10hp with a processing capacity of 500-1000 kg/hour (Indiamart, n.d.). Therefore, a 15hp shredder was assumed to have a processing capacity of approximately 750-1500 kg/hour.

However, the material to be shredded contains leafy material as well as stalks and roots, this leafy material would decrease the rate at which the material is processed. Therefore, one-fifth of the standard processing capacity was used, 150-300 kg/hour.

$$750 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 150 \frac{\text{kg}}{\text{hour}}$$

$$1500 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 300 \frac{\text{kg}}{\text{hour}}$$

Taking an average of 225 kg/hour would take 4.44 hours to process one tonne of solely cannabis material.

$$\frac{300 - 150}{2} = 225 \frac{\text{kg}}{\text{hour}}$$

$$\frac{1000 \text{ kg}}{225 \frac{\text{kg}}{\text{hour}}} = 4.44 \text{ hours}$$

The process rate required is six tonnes of cannabis waste per cycle. At the above rate of 225 kg/hour, it would take 26.67 hours per cycle to process six tonnes of material. Running 10 hours per day, it would take 2.67 days to process all the required material.

$$\frac{6000 \frac{\text{kg material}}{\text{cycle}}}{225 \frac{\text{kg}}{\text{hour}}} = 26.67 \frac{\text{hours}}{\text{cycle}}$$

$$26.67 \frac{\text{hours}}{\text{cycle}} * \frac{1 \text{ day}}{10 \text{ hours}} = 2.67 \frac{\text{days}}{\text{cycle}}$$

Digester

The digester is required to process six tonnes of wet cannabis plant material, and six tonnes of water. Therefore, 12 tonnes are to be processed by the digester per cycle. The retention time of digestion is dependent on the amount of material inside as well as the size of the digester itself. Assuming the residue entering has a density of 125 kg/m³ and the water entering has a density of 997 kg/m³, then the total mass entering volume would be 54 m³.

$$V_{total} = V_{cannabis} + V_{water} = \left(\frac{6000 \text{ kg}}{125 \frac{\text{kg}}{\text{m}^3}} \right) + \left(\frac{6000 \text{ kg}}{997 \frac{\text{kg}}{\text{m}^3}} \right) = 48 + 6 = 54 \text{ m}^3$$

A good retention time is said to be 30 days (Meegoda et al., 2018), this would line up with the cultivation cycles well with no overlapping of EoL treatment cycles. J. Jones (personal communication, December 7, 2022) states that retention time could be 70 days. Due to the many variables encompassing this EoL treatment, 30 days will be assumed.

Belt filter press

A belt filter press with a belt width of 0.5 m was found to have a capacity of 500 dry pounds per hour (EPA, 2000), which converted to approximately 226.76 dry kg/hour.

$$\frac{500 \frac{\text{dry pounds}}{\text{hour}}}{2.205 \frac{\text{pounds}}{\text{kg}}} = 226.76 \frac{\text{kg dry matter}}{\text{hour}}$$

Based on the mass and energy balances in Appendix D.3, 1858.3 kg of digestate sludge is produced per functional unit. Per cycle, there are six tonnes of cannabis that is required to be

processed, this means that 11150 kg digestate sludge is produced per cycle from the anaerobic digestion EoL treatment.

$$1858.3 \frac{\text{kg digestate solids}}{\text{tonne of plant material}} * 6 \frac{\text{tonnes}}{\text{cycle}} = 11150 \frac{\text{kg digestate solids}}{\text{cycle}}$$

Based on the mass and energy balances in Appendix D.3, there is 4% dry matter present in the digestate sludge, this means that 96% of the digestate is considered wet. Based on the moisture content of the digestate sludge, 450.74 kg of dry solids in the digestate sludge per cycle.

$$11150 \frac{\text{kg digestate solids}}{\text{cycle}} * 4\% \text{ dry} = 450.74 \frac{\text{kg dry solids in digestate sludge}}{\text{cycle}}$$

Based on the capacity found above, the time taken to process the total digestate sludge in the belt filter press was found to be 1.99 hours per cycle.

$$\frac{450.74 \frac{\text{kg dry solids in digestate sludge}}{\text{cycle}}}{226.76 \frac{\text{kg dry matter}}{\text{hour}}} = 1.99 \frac{\text{hours}}{\text{cycle}}$$

Appendix A.4: Incineration EoL treatment

Shredder

A shredder was found for this treatment to be 15hp, but no processing capacity was provided (Monster Industrial, n.d.). A similar shredder was found to be 10hp with a processing capacity of 500-1000 kg/hour (Indiamart, n.d.). Therefore, a 15hp shredder was assumed to have a processing capacity of approximately 750-1500 kg/hour.

However, the material to be shredded contains leafy material as well as stalks and roots, this leafy material would decrease the rate at which the material is processed. Therefore, one-fifth of the standard processing capacity was used, 150-300 kg/hour.

$$750 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 150 \frac{\text{kg}}{\text{hour}}$$

$$1500 \frac{\text{kg}}{\text{hour}} * \frac{1}{5} = 300 \frac{\text{kg}}{\text{hour}}$$

Taking an average of 225 kg/hour would take 4.44 hours to process one tonne of solely cannabis material.

$$\frac{300 - 150}{2} = 225 \frac{kg}{hour}$$

$$\frac{1000 \frac{kg}{kg}}{225 \frac{kg}{hour}} = 4.44 \text{ hours}$$

The process rate required is six tonnes of cannabis waste per cycle. At the above rate of 225 kg/hour, it would take 26.67 hours per cycle to process six tonnes of material. Running ten hours per day, it would take 2.67 days to process all the required material.

$$\frac{6000 \frac{kg \text{ material}}{cycle}}{225 \frac{kg}{hour}} = 26.67 \frac{hours}{cycle}$$

$$26.67 \frac{hours}{cycle} * \frac{1 \text{ day}}{10 \text{ hours}} = 2.67 \frac{days}{cycle}$$

Mobile unit (Thermal processes)

For the incineration EoL treatment using a mobile unit on-site a time frame was set out using the assumption that the unit will only be on-site for one week. The one week would consist of the following, one day set up, one day pack down, one-day contingency, and one day for the equipment to cool down; this left three days for the processing of the six tonnes of plant material per cycle. Therefore, each day two tonnes of plant material are required to be processed. If the unit runs at 10 hours per day, 200 kg/hour must be processed.

$$\frac{6000 \frac{kg \text{ plant material}}{cycle}}{3 \frac{days}{cycle}} = 2000 \frac{kg \text{ plant material}}{day}$$

$$\frac{2000 \frac{kg \text{ plant material}}{day}}{10 \frac{hours}{day}} = 200 \frac{kg}{hour}$$

The plant material has a moisture content of 71%, this meant that 58 kg of dry plant material needs to be processed per hour. Assuming the plant material has a lower heating value of 15 MJ/kg (dry basis), a heating requirement of 0.24 MW of heating energy is required for the incineration, dryer, and burner.

$$200 \frac{kg}{hour} * (1 - 71\%) = 58 \frac{kg}{hour} (\text{dry basis})$$

$$58 \frac{kg}{hour} (dry basis) * 15 \frac{MJ}{kg} (dry basis) = 870 \frac{MJ}{hour} (dry basis)$$

$$870 \frac{MJ}{hour} (dry basis) * \frac{1}{3600} \frac{hour}{sec} = 0.24 \frac{MJ}{s} = 0.24 MW \text{ of heating}$$

Appendix A.5: Pyrolysis EoL treatment

Shredder

A shredder was found for this treatment to be 15hp, but no processing capacity was provided (Monster Industrial, n.d.). A similar shredder was found to be 10hp with a processing capacity of 500-1000 kg/hour (Indiamart, n.d.). Therefore, a 15hp shredder was assumed to have a processing capacity of approximately 750-1500 kg/hour.

However, the material to be shredded contains leafy material as well as stalks and roots, this leafy material would decrease the rate at which the material is processed. Therefore, one-fifth of the standard processing capacity was used, 150-300 kg/hour.

$$750 \frac{kg}{hour} * \frac{1}{5} = 150 \frac{kg}{hour}$$

$$1500 \frac{kg}{hour} * \frac{1}{5} = 300 \frac{kg}{hour}$$

Taking an average of 225 kg/hour would take 4.44 hours to process one tonne of solely cannabis material.

$$\frac{300 - 150}{2} = 225 \frac{kg}{hour}$$

$$\frac{1000 \frac{kg}{hour}}{225 \frac{kg}{hour}} = 4.44 \text{ hours}$$

The process rate required is six tonnes of cannabis waste per cycle. At the above rate of 225 kg/hour, it would take 26.67 hours per cycle to process six tonnes of material. Running ten hours per day, it would take 2.67 days to process all the required material.

$$\frac{6000 \frac{kg \text{ material}}{cycle}}{225 \frac{kg}{hour}} = 26.67 \frac{hours}{cycle}$$

$$26.67 \frac{\text{hours}}{\text{cycle}} * \frac{1 \text{ day}}{10 \text{ hours}} = 2.67 \frac{\text{days}}{\text{cycle}}$$

Mobile unit (Thermal processes)

For the incineration EoL treatment using a mobile unit on-site a time frame was set out using the assumption that the unit will only be on-site for one week. The one week would consist of the following, one day set up, one day pack down, one-day contingency, and one day for the equipment to cool down; this left three days for the processing of the six tonnes of plant material per cycle. Therefore, each day two tonnes of plant material are required to be processed. If the unit runs at 10 hours per day, 200 kg/hour must be processed.

$$\frac{6000 \frac{\text{kg plant material}}{\text{cycle}}}{3 \frac{\text{days}}{\text{cycle}}} = 2000 \frac{\text{kg plant material}}{\text{day}}$$

$$\frac{2000 \frac{\text{kg plant material}}{\text{day}}}{10 \frac{\text{hours}}{\text{day}}} = 200 \frac{\text{kg}}{\text{hour}}$$

The plant material has a moisture content of 71%, this means that 58 kg of dry plant material needs to be processed per hour. Assuming the plant material has a lower heating value of 15 MJ/kg (dry basis), a heating requirement of 0.24 MW of heating energy is required for the incineration, dryer, and burner.

$$200 \frac{\text{kg}}{\text{hour}} * (1 - 71\%) = 58 \frac{\text{kg}}{\text{hour}} (\text{dry basis})$$

$$58 \frac{\text{kg}}{\text{hour}} (\text{dry basis}) * 15 \frac{\text{MJ}}{\text{kg}} (\text{dry basis}) = 870 \frac{\text{MJ}}{\text{hour}} (\text{dry basis})$$

$$870 \frac{\text{MJ}}{\text{hour}} (\text{dry basis}) * \frac{1 \text{ hour}}{3600 \text{ sec}} = 0.24 \frac{\text{MJ}}{\text{s}} = 0.24 \text{ MW of heating}$$

Appendix B: EURO6 emission class standard

According to Dow (2022), the following are the emission standard limits for a vehicle to be in the EURO6 class for a diesel engine. Even though there are emission standards for petrol and diesel engines, only diesel engines were used in this study.

- (1) Carbon monoxide: 0.50 g/km
- (2) Hydrocarbons and Nitrogen oxides: 0.17 g/km
- (3) Nitrogen oxides: 0.08 g/km
- (4) Particulate matter: 0.005 g/km

Appendix C: Bleach concentration for disinfection in the landfill EoL treatment

A final concentration in the mixture of 1.25% NaOCl is required for disinfection. Therefore, at 2 tonnes of cannabis and green waste going into the landfill per tonne of cannabis material processed, 25.32 kg NaOCl per functional unit is required.

$$2000\text{kg plant material} * 1.25\% = 25\text{kg NaOCl required per functional unit}$$

Bleach is purchased at an average NaOCl concentration of 6.75%. Therefore, approximately 375 kg of bleach is required per functional unit.

$$\frac{25}{6.75\%} = 375\text{kg of bleach required per functional unit}$$

To create the NaOCl bleach dilution for modelling this EoL treatment, 25 kg of NaOCl was produced and 350 kg of tap water was added.

$$375\text{kg of bleach} - 25\text{kg of NaOCl} = 350\text{kg of water added}$$

Appendix D: Mass and energy balances

Appendix D.1: Landfill EoL treatment

The following assumptions were made to complete the mass and energy balance.

- One tonne of cannabis waste material at 71% wet moisture content enters the system.
- The entire system operates at 20°C.
- The ‘wet’ cannabis entering the system has a specific heat capacity of 1.6 kJ/kg.°C while the green waste has a specific heat capacity of 1.63 kJ/kg.°C.
- Bleach has a specific heat capacity of 0.908 kJ/kg.°C.

The amount of bleach was calculated based on disinfection requirements (Appendix C). The mass balance was completed using the following equations.

$$(1) + (2) = (3) \quad 1 \text{ tonne} + 1 \text{ tonne} = 2 \text{ tonne} = 2000 \text{ kg}$$

$$(3) + (4) = (5) \quad 2 \text{ tonne} + 0.375 \text{ tonne} = 2.375 \text{ tonne} = 2375 \text{ kg}$$

The energy balance used the assumed specific heat capacities and temperature along with the calculated masses, as shown below.

$$(1) + (2) = (3)$$

$$\left(1000 \text{ kg} * 20^{\circ}\text{C} * 0.0016 \frac{\text{MJ}}{\text{kg}^{\circ}\text{C}}\right) + \left(1000 \text{ kg} * 20^{\circ}\text{C} * 0.00163 \frac{\text{MJ}}{\text{kg}^{\circ}\text{C}}\right) = 64.6 \text{ MJ}$$

$$(3) + (4) = (5)$$

$$64.6 \text{ MJ} + \left(375 \text{ kg} * 20^{\circ}\text{C} * 0.000908 \frac{\text{MJ}}{\text{kg}^{\circ}\text{C}}\right) = 71.4 \text{ MJ}$$

Appendix D.2: Composting EoL treatment

The following assumptions were made to complete the mass and energy balance.

- One tonne of cannabis waste material at 71% wet moisture content enters the system.
- The entire system operates at 20°C.
- The ‘wet’ cannabis entering the system has a specific heat capacity of 1.6 kJ/kg°C while the green waste has a specific heat capacity of 1.63 kJ/kg°C.

The mass and energy balance was completed using the following equations.

$$(1) + (2) = (3) = (4)$$

$$1 \text{ tonne} + 1 \text{ tonne} = 2 \text{ tonne} = 2 \text{ tonne}$$

The energy balance used the assumed specific heat capacities and temperature along with the calculated masses, as shown below.

$$(1) + (2) = (3) = (4)$$

$$\left(1 \text{ tonne} * 20^{\circ}\text{C} * 0.0016 \frac{\text{MJ}}{\text{kg}^{\circ}\text{C}}\right) + \left(1 \text{ tonne} * 20^{\circ}\text{C} * 0.00163 \frac{\text{MJ}}{\text{kg}^{\circ}\text{C}}\right) = 64.6 \text{ MJ}$$

Appendix D.3: Anaerobic digestion EoL treatment

Table 24 shows the in-depth mass balance with a look into the composition of the dry mass, wet mass, and gas phases. It should be noted that the balances were created without the use of stoichiometry calculations. The following assumptions were made to complete the mass and energy balance.

1. One tonne of cannabis waste material at 71% wet moisture content enters the system.
2. The ‘wet’ cannabis entering the system has a specific heat capacity of 1.6 kJ/kg°C.
3. The system runs at 20°C before digestion and 35°C after digestion.
4. The baseline temperature for enthalpy calculations is 20°C.
5. The digester is inoculated before the cannabis material is added.
6. The solids from pressing are sent to composting.
7. The liquid from pressing is sent through the drain to a wastewater treatment plant as trade waste.
8. The cannabis fresh material contains 3% nitrogen, 48% carbon, 9% hydrogen and 40% oxygen.
9. The density of fresh cannabis material is 125 kg/m³.
10. Approximately 68.25 MJ/FU of heat is produced from microbial activity during anaerobic digestion.
11. 50% of total solids (TS) is lost during digestion.
12. The fraction of dry mass in the resulting sludge/digestate is 7.35% averaged by Möller and Müller (2012) as they conducted an in-depth review of values.
13. The portion of dry mass from digestate to solid phase is 55%, averaged (Bioenergy Association, 2021).
14. The methane conversion of cannabis is assumed to be 70 L CH₄/kg volatile solids (VS), compared to Maize at 300 L/kg VS (Muhlack et al., 2018).
15. A conversion ratio of 22.4 L/mole.
16. The methane molar volume fraction of biogas is 60%.
17. The remainder of biogas is CO₂.
18. Fraction of H and O from dry mass to water in digestate sludge is 0.1483684.
19. The specific heat capacities in MJ/kg°C of components at 35°C are as follows c_N, nitrogen (0.00104); c_C, carbon (0.000702); c_H, hydrogen (0.01431); c_O, oxygen (0.00092); c_{CO2}, carbon dioxide (0.000566864); c_w, water (0.0738); c_{CH4}, methane (0.001558875).

20. All nitrogen remains in the biomass and does not leave in the biogas.
21. The solid phase of digestate from the belt filter press has an 80% moisture content.

Table 24: Mass balance of anaerobic digestion EoL treatment

Stream name	Unit	Fresh cannabis	Shredder out	Water tank	Digester	Biogas	Sludge	Solid phase	Liquid phase
Stream number		1	2	7		3	4	5	6
Mass	kg	1000	1000	1000	2000	141.7* ²	1858.3* ³	375.6* ⁵	1482.7* ⁷
Moisture Content	%	71%	71%					80%	
Dry mass	kg	290	290		290		136.59* ³	75.1* ⁵	
nitrogen	kg	8.7	8.7		8.7		8.7* ³	4.8* ⁵	
carbon	kg	139.2	139.2		139.2		76.7* ³	42.2* ⁵	
hydrogen	kg	26.1	26.1		26.1		11.7* ³	6.5* ⁵	
oxygen	kg	116.0	116.0		116.0		39.4* ³	21.7* ⁵	
							-0.148		
Dissolved solids (origin biomass)	kg	0.0	0.0		0.0		0.0	10.4* ⁵	51.1* ⁷
nitrogen	kg	0.0	0.0		0.0		0.0	0.7* ⁵	3.3* ⁷
carbon	kg	0.0	0.0		0.0		0.0	5.8* ⁵	28.7* ⁷
hydrogen	kg	0.0	0.0		0.0		0.0	0.9* ⁵	4.4* ⁷
oxygen	kg	0.0	0.0		0.0		0.0	3.0* ⁵	14.8* ⁷
Water	kg	710	710	1000	1710		1721.7	290.1* ⁵	1431.6* ⁷
hydrogen	kg	78.9* ¹	78.9	111.1* ¹	190* ¹		191.9* ⁴	32.2* ⁶	159.6* ⁷
oxygen	kg	631.1* ¹	631.1	888.9* ¹	1520* ¹		1529.9* ⁴	257.9* ⁶	1272* ⁷
Gas phase						141.7			
gas phase carbon	kg					62.5* ²			
gas phase hydrogen	kg					12.5* ²			
gas phase oxygen	kg					66.7* ²			
gas CO ₂	kg					91.7* ²			
gas H ₂ O	kg								
gas CH ₄	kg					50.0* ²			
Balance	kg	1000	1000	1000		141.7	1858.3	375.6	1482.7

Note. Assumed values are in blue, and the balance in peach is the sum of the phases in each stream. *Calculations are numbered on the following pages.

Calculation *1

The water phase in Stream 1 is related to the moisture content of the fresh cannabis material. Since it was assumed that 71% of the cannabis is water there is 710 kg of water per tonne of fresh cannabis. To calculate the hydrogen and oxygen masses for streams 1, 2, and 7, the atomic masses were used. Hydrogen has an atomic mass of 1, and oxygen has an atomic mass of 16. Therefore, water has an atomic mass of 18.

$$m_{H_{in\ water(1)}} = 710kg * \left(\frac{2}{18}\right) = 78.9kg \quad m_{O_{in\ water(1)}} = 710kg * \left(\frac{16}{18}\right) = 631.1kg$$

The water that is present in the digester was calculated by the summation of the components in streams 2 and 7.

$$m_{H_{in\ water(1)}} + m_{H_{in\ water(7)}} = 78.9 + 111.1 = 190$$

$$m_{O_{in\ water(1)}} + m_{O_{in\ water(7)}} = 631.1 + 888.9 = 1520$$

Calculation *2

The gas phase of stream 3 was calculated using the methane conversion for cannabis (Assumption 14); it was assumed that 70 L methane/kg VS, with 60% of the molar volume of biogas being methane and the remainder being CO₂ (Assumption 16 and 17). A conversion of 22.4 litres to moles was used for this calculation (Assumption 15). Carbon has an atomic mass of 12, and hydrogen has an atomic mass of 1, giving methane an atomic mass of 16. Meanwhile, oxygen has an atomic mass of 16, giving carbon dioxide an atomic mass of 44.

Methane in stream 3 calculation

$$\begin{aligned} \frac{\frac{70\ L}{kg\ VS}}{\frac{22.4\ L}{moles}} &= 3.125 \frac{mole\ CH_4}{kg\ VS} \\ 3.125 \frac{mole\ CH_4}{kg\ VS} * \frac{16}{1000} \left(\frac{kg}{mole}\right) &= 0.05 \frac{kg\ CH_4}{kg\ VS} \\ 0.05 \frac{kg\ CH_4}{kg\ VS} * 1000\ kg_{fresh\ cannabis} &= 50.0\ kg\ CH_{4gas} \end{aligned}$$

Carbon dioxide in stream 3 calculation

$$\frac{3.125 \frac{\text{mole } CH_4}{\text{kg VS}}}{60\%} * (1 - 60\%) = 2.0833 \frac{\text{moles } CO_2}{\text{kg VS}}$$

$$2.08333 \frac{\text{moles } CO_2}{\text{kg VS}} * \frac{44}{1000} \left(\frac{\text{kg}}{\text{mole}} \right) = 0.0917 \frac{\text{kg } CO_2}{\text{kg VS}}$$

$$0.0917 \frac{\text{kg } CO_2}{\text{kg VS}} * 1000 \text{ kg}_{\text{fresh cannabis}} = 91.7 \text{ kg } CO_{2\text{gas}}$$

The total gas phase of stream 3

$$\text{Total (3)} = 50.0 \text{ kg } CH_{4\text{gas}} + 91.7 \text{ kg } CO_{2\text{gas}} = 141.7 \text{ kg}$$

The gas phase of carbon (c), hydrogen (H) and oxygen (O) for stream 3 was calculated to, using the atomic masses of elements: carbon (12), hydrogen (1), and oxygen (16), to ensure mass balance within the stream.

$$\text{Gas phase}_{c3} = 50 \text{ kg}_{CH_4} * \frac{12}{16} + 91.7 \text{ kg}_{CO_2} * \frac{12}{44} = 62.5 \text{ kg}_{c3}$$

$$\text{Gas phase}_{H3} = 50 \text{ kg}_{CH_4} * \frac{4}{16} = 12.5 \text{ kg}_{H3}$$

$$\text{Gas phase}_{O3} = 91.7 \text{ kg}_{CO_2} * \frac{32}{44} = 66.7 \text{ kg}_{O3}$$

$$\text{Total gas phase}_3 = 62.5 \text{ kg}_{c3} + 12.5 \text{ kg}_{H3} + 66.7 \text{ kg}_{O3} = 141.7 \text{ kg}$$

Calculation *3

The sludge (stream 4) mass was calculated from the difference between the mass going into the digester and the mass lost in the biogas (stream 3).

$$\text{kg}_{\text{sludge}} = 2000\text{kg} - 141.7\text{kg} = 1858.3\text{kg}$$

According to Möller and Müller (2012), the range of dry mass percentage in the digestate from literature was 1.5 – 13.2%, this is a large range and therefore, an average was taken. The mass fraction in the resulting sludge (stream 4) on a dry basis is assumed to be 7.35% (Assumption 12).

$$\text{kg}_{\text{dry mass}} = 1858.3\text{kg} * 7.35\% = 136.6\text{kg}$$

The composition of the dry mass phase in stream 4 was calculated from the assumption that all nitrogen remains in the biomass (Assumption 20), and 50% of the carbon is lost during digestion (Assumption 11). From using SOLVER on EXCEL, the assumed fraction of hydrogen to oxygen from dry matter to water was able to be calculated as 0.1483684; this value was then used to find the composition of hydrogen and oxygen in both the dry mass and water phases inside stream 4. The atomic masses were also used of hydrogen (1) and oxygen (16), in methane and carbon dioxide proportions.

$$Dry\ mass_{nitrogen} = 8.7kg_{nitrogen_{digester}} = 8.7kg_{nitrogen_{stream\ 4}}$$

$$Dry\ mass_{carbon} = 139.2kg_{carbon_{digester}} - 62.5\ kg_{gas\ phase_{c3}} = 76.7kg_{carbon_{stream\ 4}}$$

$$\begin{aligned} Dry\ mass_{hydrogen} &= Dry\ mass_{hydrogen_{digester}} - \left(1 - \left(-\frac{H}{O}\right)\right) * \left(\left(\frac{4}{16}\right) * kg\ CH_{4_{gas}}\right) \\ &= 26.1kg - (1 - (-0.1483684)) * \left(\left(\frac{4}{16}\right) * 50\right) = 11.7kg \end{aligned}$$

$$\begin{aligned} Dry\ mass_{oxygen} &= Dry\ mass_{oxygen_{digester}} - \left(1 - \left(-\frac{H}{O}\right)\right) * \left(\left(\frac{32}{44}\right) * kg\ CO_{2_{gas}}\right) \\ &= 116kg - (1 - (-0.1483684)) * \left(\left(\frac{32}{44}\right) * 91.7\right) = 39.4kg \end{aligned}$$

Calculation *4

A similar equation to calculate the dry mass of hydrogen and oxygen in stream 4 was also used to calculate the hydrogen and oxygen content in the water of stream 4. A simple balance was first used to calculate the total amount of water present in stream 4.

$$Water_{stream\ 4} = m_{stream\ 4} - Dry\ mass_{stream\ 4} = 1858.3 - 136.6 = 1721.7kg$$

$$\begin{aligned} Water_{hydrogen_{stream\ 4}} &= Water_{hydrogen_{digester}} - \left(-\frac{H}{O}\right) * \left(\left(\frac{4}{16}\right) * kg\ CH_{4_{gas}}\right) \\ &= 190kg - (-0.1483684) * \left(\left(\frac{4}{16}\right) * 50\ kg\ CH_{4_{gas}}\right) = 191.9kg \end{aligned}$$

$$\begin{aligned}
Water_{oxygen_{stream\ 4}} &= Water_{oxygen_{digester}} - \left(-\frac{H}{O}\right) * \left(\left(\frac{32}{44}\right) * kg\ CO_{2_{gas}}\right) \\
&= 1520kg - (-0.1483684) * \left(\left(\frac{32}{44}\right) * 91.7\ kg\ CO_{2_{gas}}\right) = 1529.9kg
\end{aligned}$$

Calculation *5

The dry mass of the solid phase coming out of the belt filter press (stream 5) was next to be calculated using the assumption that 55% of the dry mass from the sludge would be present in the solid stream (Bioenergy Association, 2021) (Assumption 13). The result was then used to calculate the total mass of stream 5 with the assumption that the solids stream has a moisture content of 80% (Assumption 21).

$$Dry\ mass_{total_{stream\ 4}} * 55\% = Dry\ mass_{total_{stream\ 5}}$$

$$136.6kg * 55\% = 75.1kg$$

$$Total\ mass_{stream\ 5} = \frac{Dry\ mass_{total_{stream\ 5}}}{1 - 80\%} = \frac{75.1}{1 - 80\%} = 375.6kg$$

The dry mass components of nitrogen, carbon, hydrogen, and oxygen were calculated based on the same fraction as above, that 55% of the mass from the sludge would be present in the solids stream. An example calculation for nitrogen was given.

$$Dry\ mass_{nitrogen_{stream\ 5}} = Dry\ mass_{nitrogen_{stream\ 4}} * 55\% = 8.7kg * 55\% = 4.8kg$$

The dissolved solids (DS), total (T) and components for stream 5 were calculated using a mass fraction ratio from the total mass (TM) and dry mass (DM) in streams 4 and 5.

$$DS_{T_{stream\ 5}} = (DM_{T_{stream\ 4}} - DM_{T_{stream\ 5}}) * \left(\frac{(TM_{stream\ 5} - DM_{T_{stream\ 5}})}{TM_{stream\ 4} - DM_{T_{stream\ 5}}}\right)$$

$$= (136.6 - 75.1) * \frac{375.6 - 75.1}{1858.3 - 75.1} = 10.4kg$$

$$DS_{nitrogen_{stream\ 5}} = (DM_{N_{stream\ 4}} - DM_{N_{stream\ 5}}) * \left(\frac{(TM_{stream\ 5} - DM_{T_{stream\ 5}})}{TM_{stream\ 4} - DM_{T_{stream\ 5}}}\right)$$

$$= (8.7 - 4.8) * \frac{375.6 - 75.1}{1858.3 - 75.1} = 0.7kg$$

$$\begin{aligned}
DS_{carbon_{stream\ 5}} &= (DM_{c_{stream\ 4}} - DM_{c_{stream\ 5}}) * \left(\frac{(TM_{stream\ 5} - DM_{T_{stream\ 5}})}{TM_{stream\ 4} - DM_{T_{stream\ 5}}} \right) \\
&= (76.7 - 42.2) * \frac{375.6 - 75.1}{1858.3 - 75.1} = 5.8kg
\end{aligned}$$

$$\begin{aligned}
DS_{hydrogen_{stream\ 5}} &= (DM_{H_{stream\ 4}} - DM_{H_{stream\ 5}}) * \left(\frac{(TM_{stream\ 5} - DM_{T_{stream\ 5}})}{TM_{stream\ 4} - DM_{T_{stream\ 5}}} \right) \\
&= (11.7 - 6.5) * \frac{375.6 - 75.1}{1858.3 - 75.1} = 0.9kg
\end{aligned}$$

$$\begin{aligned}
DS_{oxygen_{stream\ 5}} &= (DM_{O_{stream\ 4}} - DM_{O_{stream\ 5}}) * \left(\frac{(TM_{stream\ 5} - DM_{T_{stream\ 5}})}{TM_{stream\ 4} - DM_{T_{stream\ 5}}} \right) \\
&= (39.4 - 21.7) * \frac{375.6 - 75.1}{1858.3 - 75.1} = 3.0kg
\end{aligned}$$

Calculation *6

The water phase in stream 5 was calculated using a simple balance over the stream and then using the atomic masses of hydrogen (1) and oxygen (16) to complete the component masses. The same equations were used to calculate the total water phase and water components for stream 6.

$$\begin{aligned}
Water_{hydrogen_{stream\ 5}} &= (TM_{stream\ 5} - DM_{T_{stream\ 5}} - DS_{T_{stream\ 5}}) * \left(\frac{2}{18} \right) \\
&= (375.6 - 75.1 - 10.4) * \left(\frac{2}{18} \right) = 32.2kg
\end{aligned}$$

$$\begin{aligned}
Water_{oxygen_{stream\ 5}} &= (TM_{stream\ 5} - DM_{T_{stream\ 5}} - DS_{T_{stream\ 5}}) * \left(\frac{16}{18} \right) \\
&= (375.6 - 75.1 - 10.4) * \left(\frac{16}{18} \right) = 257.9kg
\end{aligned}$$

Calculation *7

The total of stream 6 was calculated using a simple balance over the belt filter press, which allowed for the total and components in the dissolved solids phase of the stream to also be calculated similarly to stream 5 calculations.

$$TM_{stream\ 6} = TM_{stream\ 4} - TM_{stream\ 5} = 1858.3 - 375.6 = 1482.7kg$$

$$\begin{aligned} DS_{T_{stream\ 6}} &= (DM_{T_{stream\ 4}} - DM_{T_{stream\ 5}}) * \left(\frac{(TM_{stream\ 6})}{(TM_{stream\ 4} - DM_{T_{stream\ 5}})} \right) \\ &= (136.6 - 75.1) * \frac{1482.7}{1858.3 - 75.1} = 51.1kg \end{aligned}$$

$$\begin{aligned} DS_{nitrogen_{stream\ 6}} &= (DM_{N_{stream\ 4}} - DM_{N_{stream\ 5}}) * \left(\frac{(TM_{stream\ 6})}{(TM_{stream\ 4} - DM_{T_{stream\ 5}})} \right) \\ &= (8.7 - 4.8) * \frac{1482.7}{1858.3 - 75.1} = 3.3kg \end{aligned}$$

$$\begin{aligned} DS_{carbon_{stream\ 6}} &= (DM_{c_{stream\ 4}} - DM_{c_{stream\ 5}}) * \left(\frac{(TM_{stream\ 6})}{(TM_{stream\ 4} - DM_{T_{stream\ 5}})} \right) \\ &= (76.7 - 42.2) * \frac{1482.7}{1858.3 - 75.1} = 28.7kg \end{aligned}$$

$$\begin{aligned} DS_{hydrogen_{stream\ 6}} &= (DM_{H_{stream\ 4}} - DM_{H_{stream\ 5}}) * \left(\frac{(TM_{stream\ 6})}{(TM_{stream\ 4} - DM_{T_{stream\ 5}})} \right) \\ &= (11.7 - 6.5) * \frac{1482.7}{1858.3 - 75.1} = 4.4kg \end{aligned}$$

$$\begin{aligned} DS_{oxygen_{stream\ 6}} &= (DM_{O_{stream\ 4}} - DM_{O_{stream\ 5}}) * \left(\frac{(TM_{stream\ 6})}{(TM_{stream\ 4} - DM_{T_{stream\ 5}})} \right) \\ &= (39.4 - 21.7) * \frac{1482.7}{1858.3 - 75.1} = 14.8kg \end{aligned}$$

Energy Balance

Table 25 describes the energy balance occurring over the anaerobic digestion EoL treatment.

Table 25: Energy balance of anaerobic digestion EoL treatment

Stream Number	Stream Name	Mass	Moisture content	Temperature	Specific Heat Capacity	Sensible Heat
		kg	% Wet	°C	MJ/kg°C	MJ
1	Fresh cannabis	1000	71	20	0.0016	0
	Conveyors	1000		20		
	Shredder	1000		20		
2	Shredded mix	1000		20	0.0016	0
7	Water added	1000		20	0.0042	0
	Anaerobic Digestion	2000		35		
3	Biogas	141.7		35	0.00092*	4.547**
4	Sludge	1858.3		35	0.00238*	66.303**
	Belt filter Press	1858.3				
5	Solids	375.6	80	35	0.002305*	12.988
6	Liquids	1482.7		35	0.002397*	53.315

Note. Enthalpy calculations were completed using a baseline temperature of 20°C (Assumption 4). *Calculations are below. **The production of 68.25 MJ/kg°C of heat was assumed to be from microbial activity in the digester (Assumption 10).

The specific heat capacity of each stream was calculated using the assumed specific heat capacities of components (Assumption 19) and the ratio of those components in the stream.

$$c_{stream\ 3} = \frac{kg_{CO_2stream3}}{kg_{CO_2stream3} + kg_{CH_4stream3}} * c_{CO_2} + \frac{kg_{CH_4stream3}}{kg_{CO_2stream3} + kg_{CH_4stream3}} * c_{CH_4}$$

$$= \frac{91.7}{91.7 + 50} * 0.000566864 + \frac{50}{91.7 + 50} * 0.001558875$$

$$c_{stream\ 3} = 0.00092 \frac{MJ}{kg.C}$$

$$c_{stream\ 4} = \frac{kg_{N_2stream4}}{kg_{stream4}} * c_N + \frac{kg_{cstream4}}{kg_{stream4}} * c_c + \frac{kg_{Hstream4}}{kg_{stream4}} * c_H + \frac{kg_{Ostream4}}{kg_{stream4}} * c_O$$

$$= \frac{8.7}{1858.3} * 0.00104 + \frac{76.7}{1858.3} * 0.000702 + \frac{11.7 + 191.9}{1858.3} * 0.01431 + \frac{39.4 + 1529.9}{1858.3} * 0.00092$$

$$c_{stream\ 4} = 0.0238 \frac{MJ}{kg.C}$$

$$c_{stream\ 5} = \frac{kg_{N_2stream5}}{kg_{stream5}} * c_N + \frac{kg_{cstream5}}{kg_{stream5}} * c_c + \frac{kg_{Hstream5}}{kg_{stream5}} * c_H + \frac{kg_{Ostream5}}{kg_{stream5}} * c_o$$

$$= \frac{4.8 + 0.7}{375.6} * 0.00104 + \frac{42.2 + 5.8}{375.6} * 0.000702 + \frac{6.5 + 0.9 + 32.2}{375.6} * 0.01431$$

$$+ \frac{21.7 + 3 + 257.9}{375.6} * 0.00092$$

$$c_{stream\ 5} = 0.002305 \frac{MJ}{kg.C}$$

$$c_{stream\ 6} = \frac{kg_{N_2stream6}}{kg_{stream6}} * c_N + \frac{kg_{cstream6}}{kg_{stream6}} * c_c + \frac{kg_{Hstream6}}{kg_{stream6}} * c_H + \frac{kg_{Ostream6}}{kg_{stream6}} * c_o$$

$$= \frac{3.3}{1482.7} * 0.00104 + \frac{28.7}{1482.7} * 0.000702 + \frac{4.4 + 159.6}{1482.7} * 0.01431 + \frac{14.8 + 1272.0}{1482.7}$$

$$* 0.00092$$

$$c_{stream\ 6} = 0.002397 \frac{MJ}{kg.C}$$

Appendix D.4: Incineration EoL treatment

To better explain this balance, the stream numbers will be added to the equations in subscript brackets. Five parts were considered to complete the mass and energy balance of the incineration EoL treatment.

- The dryer: How much hot gas is needed to dry the biomass before incineration?
- The incinerator: How much air is needed to burn the biomass?
- The incinerator: What is the temperature of the flue gas?
- Inlet air to the dryer: What proportion of the flue gas diverts to the dryer, and how much cooling air is needed to achieve the 260°C inlet temperature?
- Start-up burner: How much diesel and air (streams 6 & 13) is required to achieve the required heat energy of 3805 MJ to dry and incinerate the material?

A. The dryer: How much hot gas is needed to dry 1 tonne of 'as received' wet biomass?

Assumptions:

1. Basis: one tonne of 'as received' cannabis residue (called biomass). Therefore, the units below are kg/t or MJ/t.
2. The feed is 71% water and 29% dry matter.
3. The dryer reduces biomass moisture from 71% to 20%.
4. The dryer is 'indirect'; that is, the hot-side gas does not directly contact the biomass. Rather, heat passes through walls/pipes separating the flows. This avoids a fire in the dryer.
5. The dryer is counter-current; that is, the feed side of the hot gas first contacts the exit side of the biomass.
6. The feed-side hot gas has a maximum temperature of 260°C to avoid any hot and dry spots causing pyrolysis in the dryer.
7. The exit side of the biomass is at 100°C. This is because the indirect dryer heats the biomass to 100°C, so internal water turns to vapour, creating pressure. This is the fastest drying method.
8. The feed-side hot gas is a mixture of flue gas from the incinerator and air used to cool it to the required inlet temperature.
9. The feed-side hot gas is assumed to have the properties of air.
10. The radiant and convective heat loss from the surface of the dryer is assumed to be 10% of the heat supplied to the dryer.
11. The hot gas cools from 260°C to a control value of 140°C.
12. The moisture ratio in hot gas is 0.0075 kg water/kg dry gas (set as 50% relative humidity for 20°C).

One tonne of fresh cannabis at 71% moisture content consists of 290 kg dry biomass and 710 kg free moisture.

$$M_{C_{dry}(2)} = M_{C_{total}(1)} + M_{C_{water}(1)}$$

$$M_{C_{dry\ portion}(2)} = 1000kg - (1000kg * 71\%) = 290kg$$

The free moisture out of the dryer was determined along with the resulting water vapour (3) and dried cannabis out of the dryer (2).

$$\begin{aligned} M_{C_{wet\ portion}(2)} &= \text{free moisture out} = \frac{M_{C_{dry\ portion}(2)}}{0.8} - M_{C_{dry\ portion}(2)} = \frac{290}{0.8} - 290 \\ &= 72.5kg \end{aligned}$$

$$M_{water\ vapour(3)} = M_{C_{water}(1)} - M_{C_{wet\ portion}(2)} = 710kg - 72.5kg = 637.5kg$$

$$M_{C_{dry}(2)} = M_{C_{dry\ portion}(2)} + M_{C_{wet\ portion}(2)} = 290 + 72.5 = 362.5\text{kg}$$

Determination of enthalpy values

The enthalpy change of water from 20°C to 100°C was calculated to be 336 kJ/kg based on the enthalpy values of water at 20°C and 100°C.

$$\Delta_{H_{water}(20^{\circ}\text{C}-100^{\circ}\text{C})} = 419 - 83 = 336 \frac{\text{kJ}}{\text{kg}}$$

The enthalpy change of water from 20°C to water vapour at 100°C was calculated to be 2569 kJ/kg based on the enthalpy values of water at 20°C and water vapour at 100°C.

$$\Delta_{H_{(3)}(20^{\circ}\text{C}_{water}-100^{\circ}\text{C}_{water\ vapour})} = 2679 - 83 = 2569 \frac{\text{kJ}}{\text{kg}}$$

The heat capacity of biomass when it is heated from 20°C to 100°C is 1.884 kJ/kg/°C, this was calculated based on the change in specific heat capacity over the temperatures (Perry et al., 1997). The specific heat capacity value is converted and then required to be converted from cal./g/°C to J/kg/°C.

$$\begin{aligned} 0.45 \frac{\text{cal}}{\text{g} \cdot ^{\circ}\text{C}} * 4186.8 &= 1884 \frac{\text{J}}{\text{kg} \cdot ^{\circ}\text{C}} \\ \frac{1884 \frac{\text{J}}{\text{kg} \cdot ^{\circ}\text{C}}}{1000} &= 1.884 \frac{\text{kJ}}{\text{kg} \cdot ^{\circ}\text{C}} \end{aligned}$$

The enthalpy change of hot gas (Δ_{Hg}) when cooled from 260°C to 140°C is then calculated. For dry air going from 260°C to 140°C, the change is 538 – 414 = 124 kJ/kg. For water vapour (in the hot gas) from 260°C to 140°C, the change is 2994.5 – 2756.7 = 237.8 kJ/kg. Therefore, the overall enthalpy change of hot gas is calculated to be 125 kJ/kg/°C.

$$124 * \left(\frac{1}{1.0075} \right) * 124 + \frac{0.0075}{1.0075} * 237.8 = 124.8 = 125 \frac{\text{kJ}}{\text{kg} \cdot ^{\circ}\text{C}}$$

The heat balance for the dryer is calculated using the following three equations, and the enthalpy and heat capacities are calculated above.

$$\text{Heat supplied}(9) = \text{heat required} + 10\% (\text{heat losses})$$

$$\text{Heat required} = \text{heat acquired by the steam} + \text{heat acquired by the dried biomass}$$

Heat supplied = heat lost by the hot gases

The heat acquired by the steam, Q_s (3):

$$Q_{steam(3)} = M_{steam(3)} * \Delta H_{(3)} = 637.5 \frac{kg}{t} * 2596 \frac{kJ}{kg} = 1654.95 \frac{MJ}{t}$$

The heat acquired by the dried biomass, $Q_{C,dry}$ (2):

$$Q_{Cdry(2)} = M_{Cdry(1)} * Cp_{Cdry(1)} * (T_{Cdry(2)} - T_{Ctotal(1)}) + M_{Cwet(2)} * \Delta H_{water(20^\circ C - 100^\circ C)}$$

$$Q_{Cdry(2)} = 290 \frac{kg}{t} * 1.884 \frac{kJ}{kg \cdot C} * (100C - 20C) + 72.5 \frac{kg}{t} * 336 \frac{kJ}{kg}$$

$$Q_{Cdry(2)} = \frac{68068.8 \frac{kJ}{t}}{1000} = 68.0688 \frac{MJ}{t}$$

Therefore, the total heat required by the dryer would be 1723 MJ/t.

$$Q_{dryer_{total\ heat\ required}} = Q_{steam(3)} + Q_{Cdry(2)} = 1654.95 + 68.0688 = 1723.0188$$

$$Q_{dryer_{total\ heat\ required}} = 1723 \frac{MJ}{t}$$

Therefore, the heat loss of the dryer would be 172 MJ/t.

$$Q_{dryer_{loss}} = (Q_{dryer_{total\ heat\ required}}) * 10\% = 1723 \frac{MJ}{t} * 10\% = 172.3 \frac{MJ}{t}$$

The heat supplied by the dryer is then calculated.

$$Q_{dryer_{supplied}} = Q_{dryer_{total\ heat\ required}} + Q_{dryer_{loss}} = 1723 + 172.3 = 1895.3 \frac{MJ}{t}$$

The hot gas required to dry the biomass before incineration, is calculated using the heat supplied by the dryer and the enthalpy change of hot gas when cooled from 260°C to 140°C.

$$M_{hot\ gases(260^\circ C - 140^\circ C)} = \frac{Q_{dryer_{supplied}}}{\Delta H_{gas}} = \frac{1895.3 \frac{MJ}{t\ fresh\ cannabis}}{125 \frac{MJ}{t\ hot\ gas}}$$

$$M_{hot\ gases(260^\circ C - 140^\circ C)} = 15.16 \frac{tonne\ of\ hot\ gas}{tonne\ of\ fresh\ cannabis}$$

B. The incinerator: How much air is needed to burn the biomass?

Assumptions:

1. Basis: one tonne of 'as received' cannabis residue (called the biomass) to the dryer. This carries through to the incinerator.
2. Air supply to the combustor ensures that the outlet flue gas contains 12 vol% O₂.
3. Air supply is at 20degC and contains 21 vol% O₂.
4. The generalised N:C:H:O mass fractions are 2:55:8:35.
5. The ash content % of the dry weight is 2.50%.
6. The oxygen and nitrogen content of air is 21% and 78%, respectively.
7. The oxygen content in the flue gas is assumed to be 12%.
8. The molar mass of each component is 0.014 kg/moles for nitrogen, 0.012 kg/moles for carbon, 0.001 kg/moles for hydrogen, and 0.016 kg/moles for oxygen.
9. Nitrogen is assumed to be inert.
10. The molecular weight of air is assumed to be 29 g/mol.

The ash content of the dry biomass in steam (2):

$$M_{ash(4)} = M_{C_{dry}(2)} * \%ash = 290 \frac{kg}{t} * 2.50\% = 7.25 \frac{kg}{t}$$

The combustion of biomass is calculated to find the oxygen required:

The mass of each component in the dry biomass is calculated using the same method as stated below for nitrogen (N).

$$M_{N,C_{dry}(2)} = M_{C_{dry}(2)} * (1 - \%ash) * M_N\%$$

$$M_{N,C_{dry}(2)} = 290 \frac{kg}{t} * (1 - 2.5\%) * 2\% = 5.655 \frac{kg}{t}$$

Therefore, the following are the masses for each component inside the dry biomass in stream 2; nitrogen (5.655 kg/t), carbon (155.5 kg/t), hydrogen (22.62 kg/t), and oxygen (99 kg/t).

The moles of each component in the dry biomass are calculated using the previously calculated masses and molar masses of each compound. The same method is used for each. Nitrogen is calculated below using the molar mass, 14 g/mole.

$$Moles_{N,C_{dry}(2)} = \frac{M_{N,C_{dry}(2)}}{\text{molar mass of nitrogen}}$$

$$Moles_{N,C,dry(2)} = \frac{5.655 \frac{kg}{t}}{0.014 \frac{kg}{moles}} = 403.9 \frac{moles}{t}$$

Therefore, the following are the moles for each component in the dry biomass in steam 2; nitrogen (403.9 moles/t), carbon (12959 moles/t), hydrogen (22620 moles/t), and oxygen (6185.2 moles/t).

The oxygen required to combust biomass in the incinerator

Moles of oxygen to combust carbon

$$Moles_{O_2 to combust carbon} = Moles_{C,dry(2)} = 12959.4 \frac{moles}{t}$$

Moles of oxygen to combust hydrogen

$$Moles_{O_2 to combust hydrogen} = \frac{Moles_{H,C,dry(2)}}{4} = 5655 \frac{moles}{t}$$

Therefore, the amount of oxygen required is 15521.8 moles/t. Using the oxygen required for combustion, the amount of air required can be calculated (Table 26).

$$Moles_{O_{2sum}} = Moles_{O_2 to combust carbon} + Moles_{O_2 to combust hydrogen} - \frac{M_{O_2 already in material}}{2}$$

$$Moles_{O_{2sum}} = 12959.4 \frac{moles}{t} + 5655 \frac{moles}{t} - \frac{6185.16 \frac{moles}{t}}{2}$$

$$Moles_{O_{2sum}} = 15521.8 \frac{moles}{t}$$

Table 26: Calculation of fresh air required for incineration in the incineration EoL treatment

	Air in (moles/t)	After combustion			vol %
		Gases consumed (moles/t)	Gas created (moles/t)	Flue gas (moles/t)	
1 st guess air supply	172464.41*				
iterated air supply (N2, O2, Ar only)	182600**				
N2	142428*			142428*	74.86%*
O2	38346*	15521.8*		22824.2*	12%***
Ar	1826*			1826*	0.96%*

CO2	146.1*		12959.4*	13105.5*	6.89%*
H2O	4412.8*		5655*	10067.8*	5.29%*
Amount of air needed to combust the biomass	187158.9*				
Mw,air = molecular weight of air	29				
Mair	5373.95*				
Total flue gas				190251.4915*	

Note. *Calculations are laid out below. **The iterated air supply is completed using the Goal Seek function in EXCEL by setting the oxygen in the volume % to 12%, as indicated in the table above by ***.

The first guess of the air supply is calculated using the net oxygen required (calculated earlier), the oxygen content in flue gas and the oxygen content in the air.

$$1^{st} \text{ guess air supply} = \frac{\text{Net oxygen required to combust}}{(\text{Air oxygen content} - \text{Flue gas oxygen content})}$$

$$1^{st} \text{ guess air supply} = \frac{15521.8 \frac{\text{moles}}{t}}{21\% - 12\%} = 172464.4 \frac{\text{moles}}{t}$$

The nitrogen, oxygen and argon content of the air required is calculated by using the nitrogen and oxygen content % in air and the iterated air supply in the following equations.

$$\begin{aligned} N_{2\text{air}(12)} &= \text{iterated air supply} * N_2\% \text{ in biomass} = 182600 \frac{\text{moles}}{t} * 78\% \\ &= 142428 \frac{\text{moles}}{t} \end{aligned}$$

$$\begin{aligned} O_{2\text{air}(12)} &= \text{iterated air supply} * O_2\% \text{ in biomass} = 182600 \frac{\text{moles}}{t} * 21\% \\ &= 38346 \frac{\text{moles}}{t} \end{aligned}$$

The argon content is calculated from the difference to make up the air content composition to 100%.

$$Ar_{\text{air}(12)} = \text{iterated air supply} * (1 - N_2\% \text{ in biomass} - O_2\% \text{ in biomass})$$

$$Ar_{\text{air}(12)} = 182600 \frac{\text{moles}}{t} * (1 - 78\% - 21\%) =$$

$$Ar_{\text{air}(12)} = 1826 \frac{\text{moles}}{t}$$

The carbon dioxide component of fresh air required

$$CO_{2air(12)} = 0.0004 * \text{sum of air content and iterated air supply}$$

$$CO_{2air(12)} = 0.0004 * (182600 + 142428 + 38346 + 1826)$$

$$CO_{2air(12)} = 146.08 \frac{\text{moles}}{t}$$

The water component of the air required is calculated using the moisture ratio in a hot gas (X_g), 0.0075 kg water/kg dry gas.

$$H_2O_{air(12)} = \frac{\frac{X_g}{0.018}}{\frac{1}{0.029}} * \text{sum of air content and iterated air supply}$$

$$H_2O_{air(12)} = \frac{\frac{0.0075}{0.018}}{\frac{1}{0.029}} * (182600 + 142428 + 38346 + 1826)$$

$$H_2O_{air(12)} = 4412.8 \frac{\text{moles}}{t}$$

The gases consumed oxygen and created carbon dioxide and water after combustion. The flue gas column in Table 26 is the calculation from the 'air in' column, as follows:

$$\text{Nitrogen, } N_2 = \text{air in} \left(142428 \frac{\text{moles}}{t} \right) = \text{flue gas} \left(142428 \frac{\text{moles}}{t} \right)$$

$$\text{Oxygen, } O_2 = \text{air in} \left(38346 \frac{\text{moles}}{t} \right) - \text{gases consumed} \left(15521.8 \frac{\text{moles}}{t} \right)$$

$$\text{Oxygen, } O_2 = \text{flue gas} \left(22824.2 \frac{\text{moles}}{t} \right)$$

$$\text{Argon, } Ar = \text{air in} \left(1826 \frac{\text{moles}}{t} \right) = \text{flue gas} \left(1826 \frac{\text{moles}}{t} \right)$$

$$\text{Carbon dioxide, } CO_2 = \text{air in} \left(146.08 \frac{\text{moles}}{t} \right) + \text{gas created} \left(12959 \frac{\text{moles}}{t} \right)$$

$$\text{Carbon dioxide, } CO_2 = \text{flue gas} \left(13105 \frac{\text{moles}}{t} \right)$$

$$Water, H_2O = air\ in\ \left(4412.8 \frac{moles}{t}\right) + gas\ created\ \left(5655 \frac{moles}{t}\right)$$

$$Water, H_2O = flue\ gas\ \left(10067.8 \frac{moles}{t}\right)$$

The volume % is the fraction of each component in the flue gas, and the total flue gas is the sum of the moles in the flue gas.

The amount of air needed to combust the biomass in moles is calculated as the air supply, including CO₂ and H₂O:

$$Air\ supply\ incl.\ CO_2\ and\ H_2O = sum\ of\ N_2, O_2, Ar, CO_2, and\ H_2O$$

$$Air\ supply\ incl.\ CO_2\ and\ H_2O = 142428 + 38346 + 1826 + 146.08 + 4412.8$$

$$Air\ supply\ incl.\ CO_2\ and\ H_2O = 187158.9 \frac{moles}{t}$$

The molecular weight of air is assumed to be 29 grams/mol as M_{w,air}. Finally, the mass of air supply needed to combust the biomass, M_{air}, is calculated based on the moles/t of the air in and the molecular weight of the components.

$$\begin{aligned} M_{air(12)} &= \frac{N_{2(12)} * 28 + O_{2(12)} * 32 + Ar_{(12)} * 40 + CO_{2(12)} * 44 + H_2O_{(12)} * 18}{1000} \\ &= 5373.95 \frac{kg}{t} \end{aligned}$$

C. The incinerator: What is the temperature of the flue gas?

Assumption:

1. The air supply is heated to the flue gas exit temperature.
2. The additional moles of gases produced during combustion are assumed part of the reaction and do not require heating.
3. The ash quantity is small and is only removed after shutdown, so is assumed not to have a heat loss.
4. The higher heating value, dry basis (HHV, dry basis) is assumed to be 18 MJ/kg.
5. The latent heat of water (ΔH_{vap}) at 100°C turning to vapor at 100°C is assumed to be 2236 kJ/kg.
6. The specific heat of dry air (CP_{air}) over a range of heating, estimated from 100°C – 1000°C, is assumed to be 1.09 kJ/kg/K.
7. The specific heat of water vapour (CP_{vap}) over a range of heating, estimate from 100°C – 1000°C, is assumed to be 2.1 kJ/kg/K.

8. The moisture ratio in a hot gas (X_g) is assumed to be 0.0075 kg water/kg dry gas, set the same as in A. as 50% relative humidity for 20°C.
9. Heat loss of the incinerator is assumed to be 5%.

An estimate of the specific heat of air (Cp_{net}) with 50% relative humidity at 20°C, over the range of heating is calculated:

$$Cp_{net} = \text{dry air} + \text{water vapour} = \frac{1}{1 + X_g} * CP_{air} + \frac{X_g}{1 + X_g} * CP_{vap}$$

$$Cp_{net} = \frac{1}{1 + 0.0075} * 1.09 \frac{kJ}{kg \cdot ^\circ C} + \frac{0.0075}{1 + 0.0075} * 2.1 \frac{kJ}{kg \cdot ^\circ C} = 1.098 \frac{kJ}{kg \cdot K}$$

The heat carried in by the dry biomass ($Q_{C_{dry}(2)}$) is calculated in Part A but the heat created by combustion ($Q_{combustion}$) is calculated from the higher heating value ($HHV_{dry basis}$) and the mass of dry biomass going into the incinerator ($M_{C_{dry}(2)}$):

$$Q_{combustion} = HHV_{dry basis} * M_{C_{dry}(2)} = 18 \frac{MJ}{kg} * 290 \frac{kg}{t} = 5220 \frac{MJ}{t}$$

The heat loss is assumed to be 5% and is then calculated:

$$Q_{loss, incinerator} = 5220 * 5\% = 261 MJ$$

The heat to evaporate moisture at 100°C:

$$Q_{evap, incinerator} = M_{incinerator_{moisture}} * \frac{\Delta H_{vap}}{1000} = 72.5 \frac{kg}{t} * \frac{2236 \frac{kJ}{kg}}{1000} = 162.11 MJ$$

The heat available to heat the air and evaporated water vapour is calculated to be 4864.96 MJ and this heat equates to

$$M_{air(12)} * Cp_{air(12)} * (T_f - 20) + M_{C_{wet}(2)} * Cp_{vap} * (T_f - 100)$$

$$Q_{C_{dry}(2)} + Q_{combustion} - Q_{loss, incinerator} - Q_{evap, incinerator}$$

$$= 68.07 + 5220 - 261 - 162.11$$

$$Q_{C_{dry}(2)} + Q_{combustion} - Q_{loss, incinerator} - Q_{evap, incinerator} = 4864.96 MJ$$

The heat calculated above is then used in conjunction with the heat equivalent equation to find the actual glue gas temperature (T_f), using Goal Seek in EXCEL.

$$Q_{C_{dry}(2)} + Q_{combustion} - Q_{loss,incinerator} - Q_{evap,incinerator} \\ = M_{air} * CP_{air} * (T_f - 20) + M_{w,in} * CP_{vap} * (T_f - 100)$$

$$M_{air(12)} * CP_{air(12)} * (T_f - 20) + M_{C_{wet}(2)} * CP_{vap} * (T_f - 100) \\ = 5373.95 * 1.09 * (T_f - 20) + 72.5 * 2.1 * (T_f - 100)$$

Goal Seek in EXCEL calculated the actual flue gas temperature to be:

$$T_f = 831.5^{\circ}\text{C}$$

This led to the correct amount of heat available to heat the air and evaporated water vapour being calculated:

$$M_{air(12)} * CP_{air(12)} * (T_f - 20) + M_{C_{wet}(2)} * CP_{vap} * (T_f - 100) \\ = 5373.95 * 1.09 * (831.5^{\circ}\text{C} - 20) + 72.5 * 2.1 * (831.5^{\circ}\text{C} - 100)$$

$$M_{air(12)} * CP_{air(12)} * (T_f - 20) + M_{C_{wet}(2)} * CP_{vap} * (T_f - 100) = 4864.96 \text{ MJ}$$

Then the heat of the flue leaving the combustor is calculated:

$$Q_{incinerator_{flue}(11)} = Q_{C_{dry}(2)} + Q_{loss,incinerator} - Q_{loss,incinerator} = 68.07 + 5220 - 261$$

$$Q_{incinerator_{flue}(11)} = 5027 \text{ MJ}$$

D. Inlet air to the dryer: What is the proportion of the flue gas to divert to the dryer and the amount of cooling air needed to achieve the 260°C inlet temperature?

Assumption:

1. The flue gas has the same molecular weight as air.
2. The specific heat of flue gas cooling in the range of 900°C to 260°C was assumed to be 1.08 kJ/kg/K.
3. The specific heat of flue gas heating in the range of 20°C to 260°C was assumed to be 1.03 kJ/kg/K.

The mass of the flue gas is calculated:

$$M_{flue(11)} = M_{air(12)} + M_{C_{dry}(2)} + M_{C_{wet}(2)} - M_{ash(4)}$$

$$M_{flue(11)} = 5373.9545 \frac{kg}{t} + 290 \frac{kg}{t} + 72.5 \frac{kg}{t} - 7.25 \frac{kg}{t}$$

$$M_{flue(11)} = 5729.2 \frac{kg}{t}$$

The mass required of hot gases was calculated in Part A to be 15.16 tonne/tonne which is the target of the total dryer air feed. The following equation was used to calculate the total dryer air feed by determining the fraction of flue gas required to be diverted to the dryer using Goal Seek in EXCEL.

$$M_{flue(9)} = \frac{M_{flue(11)}}{1000} * \text{Fraction of flue diverted to dryer} + M_{flue(8)}$$

It was determined that 75.68% of the flue is required to be diverted to the dryer to obtain the required amount of heat. This allowed for the flue gas to be diverted to the dryer to be calculated:

$$M_{flue(11a)} = M_{flue(11)} * \text{Fraction of flue diverted to dryer}$$

$$M_{flue(11a)} = 5729.2 * 75.68\% = 4335.96 \frac{kg}{t}$$

The quantity of cooling air is also calculated:

$$M_{flue(8)} = \frac{M_{flue(11)} * \text{fraction of flue diverted to dryer} * Cp_{net,cooling} * (T_f - 260)}{\frac{Cp_{net,heating} * (T_f - 20)}{1000}}$$

$$M_{flue(8)} = 10.83 \frac{\text{tonne of cooling air}}{\text{tonne of flue gas}}$$

The heat of each stream can now be calculated:

$$Q_{flue(11)} = 5027 \text{ MJ}$$

$$Q_{flue(11b)} = Q_{flue(11)} * (1 - \text{fraction of flue diverted to dryer})$$

$$Q_{flue(11b)} = 5027 \text{ MJ} * (1 - 75.68\%) = 1222.5 \text{ MJ}$$

$$Q_{flue(11a)} = Q_{flue(11)} * \text{fraction of flue diverted to dryer}$$

$$Q_{flue(11a)} = 5027 \text{ MJ} * 75.68\% = 3804.5 \text{ MJ}$$

$$Q_{dryer_{transferred}} = 1895.32 \text{ MJ}$$

$$Q_{flue(10)} = Q_{flue(11a)} * \text{fraction of flue diverted to dryer} - Q_{dryer_{transferred}}$$

$$Q_{flue(10)} = 3804.5 - 1895.32 = 1909.2 \text{ MJ}$$

$$Q_{stack(14)} = Q_{flue(10)} + Q_{flue(11b)} = 1222.5 + 1909.2 = 3131.7 \text{ MJ}$$

$$Q_{incinerator_{to\ evaporate\ water\ from\ biomass\ at\ 100^\circ C}} = 162.11 \text{ MJ}$$

$$Q_{stack(14)} - Q_{incinerator_{to\ evaporate\ water\ from\ biomass\ at\ 100^\circ C}} = 3131.7 - 162.11 = 2969.6 \text{ MJ}$$

The heat calculated above was also used to calculate the temperature of the stack, similar to the temperature of the flue gas calculation in Part C.

$$Q_{stack} - Q_{evap,incinerator} = \frac{(1 - 75.68\%) * M_{flue(11)} * Cp_{net,cooling} * (T_{stack} - T_{f(11)}) + 75.68\% * (M_{hot\ gases(260^\circ C - 140^\circ C)} * 1000) * Cp_{net,heating} * (T_{stack} - 140^\circ C)}{1000}$$

$$Q_{stack} - Q_{evap,incinerator} = \frac{(1 - 75.68\%) * 5729.2 \frac{kg}{t} * 1.08 \frac{kJ}{kg.K} * (T_{stack} - 831.5^\circ C) + 75.68\% * (15.163 \frac{tonne}{tonne} * 1000) * 1.03 * (T_{stack} - 140^\circ C)}{1000}$$

$$Q_{stack} - Q_{evap,incinerator} = 2969.6 \text{ MJ}$$

E. How much diesel (5) and air (6 & 13) is needed to achieve the required heat energy of 3805 MJ to dry and incinerate the material?

Assumptions:

1. The air-to-fuel ratio for diesel is 2.3 kg/kg.
2. The mass fraction of oxygen in the air is 23%.
3. 7.31 g H₂O/kg Air.
4. The lower heating value of diesel is 42.6 MJ/kg (dry basis) (LHV_{diesel}).
5. The diesel has a moisture content of 0.05%.
6. The amount of heat required to supply is 3804.6 MJ/tonne of 'as received' cannabis material ($Q_{burner\ to\ supply}$).
7. The heat loss in the diesel burner is 10% ($\%_{heat\ loss\ in\ burner}$).
8. The target air and flue mass is 15.16 tonne/tonne (M_{target}).
9. The target air and flue temperature in the dryer (T_{target}) is 260°C.
10. The air-to-fuel ratio for complete combustion is assumed to be 14.5 kg air/kg fuel.
11. The specific heat capacity of air (Cp_{air}) is 0.001047 MJ/kg°C.

12. The composition of diesel is assumed to be 86.2% carbon, 13.8% hydrogen, and 0.05% water.
13. The mass fraction of oxygen in the air is assumed to be 23%.

The net heat to generate

$$Q_{net\,diesel} = \frac{Q_{burner\,to\,supply}}{1 - \%_{heat\,loss\,in\,burner}} = \frac{3804.6 \frac{MJ}{tonne}}{1 - 10\%} = 4227.3 \frac{MJ}{tonne}$$

The heat produced by diesel:

$$Q_{diesel} = LHV_{diesel} * (1 - \%_{water\,in\,diesel}) = 42.6 \frac{MJ}{kg} * (1 - 0.05\%) = 42.58 \frac{MJ}{kg\,diesel}$$

The mass of diesel required:

$$M_{diesel(5)} = \frac{Q_{net\,diesel}}{Q_{diesel}} = \frac{4227.3 \frac{MJ}{t}}{42.58 \frac{MJ}{kg}} = 99.3 \frac{kg}{t}$$

The diesel burner temperature before heat loss is accounted for:

$$T_{burner(before\,heat\,loss)} = T_{diesel(5)} + \frac{Q_{net\,diesel}}{M_{target} * 1000 * Cp_{air}}$$

$$T_{burner(before\,heat\,loss)} = 20 + \frac{4227.3 \frac{MJ}{t}}{15.16 \frac{t}{t} * 1000 * 0.001047 \frac{MJ}{kg \cdot ^\circ C}}$$

$$T_{burner(before\,heat\,loss)} = 286^\circ C$$

The dryer supply temperature from the burner after heat loss:

$$T_{burner(after\,heat\,loss)} = T_{in} + \frac{Q_{burner\,to\,supply}}{M_{target} * 1000 * Cp_{air}}$$

$$T_{burner(after\,heat\,loss)} = 20 + \frac{3804.6 \frac{MJ}{t}}{15.16 \frac{t}{t} * 1000 * 0.001047 \frac{MJ}{kg \cdot ^\circ C}}$$

$$T_{burner(after\,heat\,loss)} = 259.7^\circ C$$

Using the air to fuel ratio assumption for complete combustion, the amount of air required is 1439.6 kg/t.

$$M_{air(6)} = M_{diesel(5)} * \text{fuel to air ratio} = 99.3 \text{ kg} * 14.5 \frac{\text{kg air}}{\text{kg fuel}} = 1440 \frac{\text{kg air}}{\text{t}}$$

Therefore, the mass out of the diesel burner is calculated:

$$M_{flue(7)} = M_{air(6)} + M_{diesel(5)} = 1440 + 99.3 = 1539.3 \frac{\text{kg}}{\text{t}}$$

To obtain the required mass flow of stream 9 into the dryer from the burner for start-up, an additional 13624 kg of air is required to be input in stream 13.

$$M_{air(13)} = M_{flue(9)} - M_{flue(7)} = 15163.3 - 1539.3 = 13624 \frac{\text{kg}}{\text{t}}$$

To ensure that the mass and energy over the entire system is balanced:

$$\text{Mass into dryer} = \text{Mass out of dryer}$$

$$1000 + 15163.3 = 362.5 + 637.5 + 15163.3$$

$$16163.3 = 16163.3$$

$$\text{Energy into dryer} = \text{Energy out of dryer}$$

$$0 + 3804.5 = 68 + 172.3 + 1655 + 1909.2$$

$$3804.5 = 3804.5$$

$$\text{Mass into incinerator} = \text{Mass out of incinerator}$$

$$362.5 + 5373.95 = 7.25 + 5729.2$$

$$5736.45 = 5736.45$$

$$\text{Energy into incinerator} = \text{Energy out of incinerator}$$

$$68 + 0 + 5220 = 261 + 0 + 5027$$

$$5288 = 5288$$

$$\text{Mass into burner} = \text{Mass out of burner}$$

$$1440 + 99.3 = 1539.3$$

$$1539.3 = 1539.3$$

$$\text{Energy into burner} = \text{Energy out of burner}$$

$$0 + 0 + 4227 = 422 + 3805$$

$$4227 = 4227$$

Appendix D.5: Pyrolysis EoL treatment

There are eight parts to this treatment's calculations:

- A. The biomass side of the dryer: How much hot gas is needed to dry the biomass before pyrolysis?
- B. The biomass side of the pyrolyser: How much heat is needed to pyrolyse the biomass?
- C. The diesel burner: How much heat is generated when the tar and gases are burnt?
- D. The flue gas side of the pyrolyser: What are the outlet conditions of the flue gas?
- E. The flue gas side of the dryer: Do the inlet conditions from the pyrolyser flue gas transfer the heat required for the drying of the biomass?
- F. The makeup diesel combustion heat: If there is not enough heat entering the dryer, then how much diesel is needed to produce the required heat?
- G. Recalculation of flows affected by the addition of diesel into the system.
- H. Dilution of air to the flue side inlet of the dryer: How much air is required to cool the inlet flue gas to the maximum temperature of 260°C before it enters the dryer?

A. The biomass side of the dryer: How much hot gas is needed to dry the biomass before pyrolysis?

Assumptions:

1. Basis: one tonne of 'as received' cannabis residue (called biomass). Therefore, the units below are kg/t or MJ/t.
2. The feed biomass is 71% water and 29% dry matter.
3. The dryer reduces biomass moisture from 71% to 20%.
4. The dryer is 'indirect'; that is, the hot-side gas does not directly contact the biomass. Rather, heat passes through walls/pipes separating the flows. This avoids a fire in the dryer.
5. The dryer is counter-current; that is, the feed side of the hot gas first contacts the exit side of the biomass.
6. The feed-side hot gas has a maximum temperature of 260°C to avoid any hot and dry spots causing pyrolysis in the dryer.

7. The exit-side of the biomass is at 100°C due to the indirect dryer heating the biomass to 100°C, and so internal water turns to vapour, creating pressure, and creating the fastest drying.
8. The feed-side hot gas is a mixture of flue gas from the incinerator and air used to cool it to the required inlet temperature.
9. The feed-side hot gas can be assumed to have the properties of air in the first iteration.
10. The radiant and convective losses from the surface of the dryer are assumed to be 10% of the heat supplied to the dryer.
11. The hot gas out of the dryer cools from 260°C to a control value, assumed to be 140°C.
12. Latent heat of evaporation = 2.257 MJ/kg.
13. Resulting pyrolysis products include 35% char, 30% condensable volatiles, and 35% non-condensable (permanent) gases.
14. The moisture ratio in hot gas is 0.0075 kg water/kg dry gas (set as 50% relative humidity for 20°C).
15. The zero-enthalpy line is set at 20°C, the lowest temperature in the system.

One tonne of fresh cannabis at 71% moisture content consists of 290 kg dry biomass and 710 kg free moisture.

$$M_{C_{dry}(2)} = M_{C_{total}(1)} + M_{C_{water}(1)}$$

$$M_{C_{dry\ portion}(2)} = 1000kg - (1000kg * 71\%) = 1000kg - 710kg = 290kg$$

The free moisture out of the dryer was determined along with the resulting water vapour (3) and dried cannabis out of the dryer (2).

$$M_{C_{wet\ portion}(2)} = \text{free moisture out} = \frac{M_{C_{dry\ portion}(2)}}{0.8} - M_{C_{dry\ portion}(2)} = \frac{290}{0.8} - 290 = 72.5kg$$

$$M_{water\ vapour(3)} = M_{C_{water}(1)} - M_{C_{wet\ portion}(2)} = 710kg - 72.5kg = 637.5kg$$

$$M_{C_{dry}(2)} = M_{C_{dry\ portion}(2)} + M_{C_{wet\ portion}(2)} = 290 + 72.5 = 362.5kg$$

Determination of enthalpy values

The enthalpy change of water from 20°C to 100°C was calculated to be 336 kJ/kg based on the enthalpy values of water at 20°C and 100°C.

$$\Delta H_{water(20^{\circ}C-100^{\circ}C)} = 419 - 83 = 336 \frac{kJ}{kg}$$

The enthalpy change of water from 20°C to water vapour at 100°C was calculated to be 2569 kJ/kg based on the enthalpy values of water at 20°C and water vapour at 100°C.

$$\Delta_{H(3)}(20^{\circ}\text{C}_{\text{water}}-100^{\circ}\text{C}_{\text{water vapour}}) = 2679 - 83 = 2596 \frac{\text{kJ}}{\text{kg}}$$

The heat capacity of biomass when it is heated from 20°C to 100°C is 1.884 kJ/kg/°C, this was calculated based on the change in specific heat capacity over the temperatures (Perry et al., 1997). The specific heat capacity value is converted and then required to be converted from cal./g/°C to J/kg/°C.

$$0.45 \frac{\text{cal}}{\text{g} \cdot ^{\circ}\text{C}} * 4186.8 = 1884 \frac{\text{J}}{\text{kg} \cdot ^{\circ}\text{C}}$$

$$\frac{1884 \frac{\text{J}}{\text{kg} \cdot ^{\circ}\text{C}}}{1000} = 1.884 \frac{\text{kJ}}{\text{kg} \cdot ^{\circ}\text{C}}$$

The enthalpy change of hot gas (Δ_{Hg}) when cooled from 260°C to 140°C is then calculated. For dry air going from 260°C to 140°C, the change is 538 – 414 = 124 kJ/kg. For water vapour (in the hot gas) from 260°C to 140°C, the change is 2994.5 – 2756.7 = 237.8 kJ/kg. Therefore, the overall enthalpy change of hot gas is calculated to be 125 kJ/kg/°C. The enthalpy change of hot gas will be recalculated when the incoming temperature of the hot gas is found.

$$124 * \left(\frac{1}{1.0075} \right) * 124 + \frac{0.0075}{1.0075} * 237.8 = 124.8 = 125 \frac{\text{kJ}}{\text{kg} \cdot ^{\circ}\text{C}}$$

The heat balance for the dryer is calculated using the following three equations, and the enthalpy and heat capacities are calculated above.

$$\text{Heat supplied}(7) = \text{heat required} + 10\% (\text{heat losses})$$

$$\text{Heat required} = \text{heat acquired by the steam} + \text{heat acquired by the dried biomass}$$

$$\text{Heat supplied} = \text{heat lost by the hot gases}$$

The heat acquired by the steam, $Q_{\text{steam}(3)}$:

$$Q_{\text{steam}(3)} = M_{\text{steam}(3)} * \Delta_{H(3)} = 637.5 \frac{\text{kg}}{\text{t}} * 2596 \frac{\text{kJ}}{\text{kg}} = 1654.95 \frac{\text{MJ}}{\text{t}}$$

The heat acquired by the dried biomass, $Q_{C_{\text{dry}}(2)}$:

$$Q_{C_{\text{dry}}(2)} = M_{C_{\text{dry}}(1)} * C_{p_{C_{\text{dry}}(1)}} * (T_{C_{\text{dry}}(2)} - T_{C_{\text{total}}(1)}) + M_{C_{\text{wet}}(2)} * \Delta_{H_{\text{water}}(20^{\circ}\text{C}-100^{\circ}\text{C})}$$

$$Q_{C_{dry}(2)} = 290 \frac{kg}{t} * 1.884 \frac{kJ}{kg.C} * (100C - 20C) + 72.5 \frac{kg}{t} * 336 \frac{kJ}{kg}$$

$$Q_{C_{dry}(2)} = \frac{68068.8 \frac{kJ}{t}}{1000} = 68.0688 \frac{MJ}{t}$$

Therefore, the total heat required by the dryer would be 1723 MJ/t.

$$Q_{dryer_{total\ heat\ required}} = Q_{steam(3)} + Q_{C_{dry}(2)} = 1654.95 + 68.0688 = 1723.0188$$

$$Q_{dryer_{total\ heat\ required}} = 1723 \frac{MJ}{t}$$

Therefore, the heat loss of the dryer would be 172 MJ/t.

$$Q_{dryer_{loss}} = (Q_{dryer_{total\ heat\ required}}) * 10\% = 1723 \frac{MJ}{t} * 10\% = 172.3 \frac{MJ}{t}$$

The heat supplied by the dryer is then calculated.

$$Q_{dryer_{supplied}} = Q_{dryer_{total\ heat\ required}} + Q_{dryer_{loss}} = 1723 + 172.3 = 1895.3 \frac{MJ}{t}$$

The hot gas required to dry the biomass before pyrolysis is calculated using the heat supplied by the dryer and the enthalpy change of hot gas when cooled from 260°C to 140°C. The hot gas required to dry the biomass before pyrolysis will be recalculated once the temperature and enthalpy change of the hot gas over the dryer is found.

$$\begin{aligned} M_{hot\ gases(260^{\circ}C-140^{\circ}C)} &= \frac{Q_{dryer_{supplied}}}{\Delta H_{gas}} = \frac{1895.3 \frac{MJ}{t\ fresh\ cannabis}}{125 \frac{MJ}{t\ hot\ gas}} \\ &= 15.16 \frac{tonne\ of\ hot\ gas}{tonne\ of\ fresh\ cannabis} \end{aligned}$$

The enthalpy of the hot gas exiting the dryer at 140°C is calculated by accounting for the enthalpy of flue gas and the enthalpy of water vapour arising from the evaporation of the water portion within the biomass. The enthalpy of hot gas exiting the dryer will be recalculated once the temperature of the hot gas going into the dryer is found.

$$\begin{aligned} Q_{flue_{140^{\circ}C}(10)} &= (M_{hot\ gases(260^{\circ}C-140^{\circ}C)} * 1000 - M_{C_{wet\ portion}(2)}) * \frac{\Delta H_g}{1000} + M_{C_{wet\ portion}(2)} \\ &* \frac{(\Delta H_{water(20^{\circ}C-100^{\circ}C)} + \Delta H_{(3)(20^{\circ}C_{water}-100^{\circ}C_{water\ vapour})} + Cp_{water\ vapour(100^{\circ}C-140^{\circ}C)} * (T_{flue(10)} - T_{steam(3)}))}{1000} \end{aligned}$$

$$Q_{flue_{140^{\circ}\text{C}}(10)} = (15.16 \frac{t}{t} * 1000 - 72.5 \frac{kg}{t}) * \frac{125 \frac{kJ}{kg}}{1000} + 72.5 \frac{kg}{t} * \frac{336 \frac{kJ}{kg} + 2596 \frac{kJ}{kg} + 2.08 \frac{kJ}{kg \cdot ^{\circ}\text{C}} * (140^{\circ}\text{C} - 100^{\circ}\text{C})}{1000}$$

$$Q_{flue_{140^{\circ}\text{C}}(10)} = 15087.5 * 0.125 + 72.5 * 3.0152 = 1886 + 219 = 2105 \frac{MJ}{t}$$

B. The biomass side of the pyrolyser: How much hot gas is needed to pyrolyse the biomass?

Assumptions:

1. Basis: one tonne of 'as received' cannabis residue (called biomass). Therefore, the units below are kg/t or MJ/t.
2. The feed is 20% water and 80% dry matter.
3. The pyrolysis heat of reaction (Hr_{pyro}) is 420 kJ/kg feed dry basis; this is a conservative value because it is for the primary reactions only (Fantozzi et al., 2007).
4. The biomass needs sensible heating to the pyrolysis temperature.
5. The yield of the pyrolysis reaction is 35% char, 30% volatiles, and 35% gases.
6. The ash content stays with the char.
7. The volatiles and non-condensable gases are combusted. The char is not because it is a product.
8. The heating value of the char is MJ/kg. Note: $HV(\text{dry biomass}) = (\%char * HV \text{ char}) + (\%volatiles * HV \text{ volatiles}) + (\%Ncgases * HV \text{ Ncgases})$.
9. The heating value of the volatiles is MJ/kg.
10. The heating value of the non-condensable gases is MJ/kg.
11. The radiant heat and convective losses from the surface of the pyrolyser are assumed to be 10% of the heat supplied to the pyrolyser.
12. The char product has no moisture.
13. The pyrolysis temperature ($T_{pyrolyser}$) is assumed to be conservative at 300°C.
14. The temperature of the char ($T_{(4)}$), volatiles and non-condensable gases ($T_{(12)}$) out of the pyrolyser are assumed to be 600°C.
15. The enthalpy of latent heat at 100°C for water ($\Delta Hw_{(100^{\circ}\text{C})}$) is 2256 kJ/kg.
16. The enthalpy change for sensible heat gain of steam from 100°C to 600°C at atmospheric pressure ($\Delta Hw_{vap(100^{\circ}\text{C}-600^{\circ}\text{C})}$) is 1030 kJ/kg.
17. The specific heat capacity of biomass when heated from 20°C to 100°C was calculated to be 1.884 kJ/kg/K above in Section A. It is assumed for this section that the specific heat capacity of biomass when heated from 100°C to 300°C ($Cp_{(100^{\circ}\text{C}-300^{\circ}\text{C})}$) is the same.
18. The specific heat capacity of char (Cp_{char}) is assumed to be 1.1 kJ/kg/K (Chen).

19. The specific heat capacity of pyrolysis volatiles ($Cp_{volatiles}$) is assumed to be 2.5 kJ/kg/K (Fantomzzi et al., 2007).
20. The specific heat capacity of pyrolysis gases (Cp_{gases}) is assumed to be 1.1 kJ/kg/K (Fantomzzi et al., 2007).
21. The zero-enthalpy line is set at 20°C, the lowest temperature in the system.

Firstly, the heat required to heat the moisture from liquid at 100°C to vapour at 600°C must be calculated to remove the water remaining in the dry biomass entering the pyrolyser.

$$Q_w = M_{C_{wet\ portion(2)}} * \frac{\Delta H_{w(100^\circ C)} + \Delta H_{w_{vap}(100^\circ C-600^\circ C)}}{1000} = 72.5 \frac{kg}{t} * \frac{2256 \frac{kJ}{kg} + 1030 \frac{kJ}{kg}}{1000}$$

$$= 238.235 \frac{MJ}{t}$$

The heat required for the sensible heating of biomass at 300°C is then calculated using assumption 17.

$$Q_{C,dry(300^\circ C)} = M_{C_{dry\ portion(2)}} * Cp_{(100^\circ C-300^\circ C)} * \frac{(T_{pyrolyser} - T_{(2)})}{1000}$$

$$= 290 \frac{kg}{t} * 1.884 \frac{kJ}{kg \cdot ^\circ C} * \frac{300^\circ C - 100^\circ C}{1000}$$

$$Q_{C,dry(300^\circ C)} = 109.272 \frac{MJ}{t}$$

Using assumption 3, the heat required to pyrolyse to dry biomass (the heat consumed in the pyrolyser) is calculated:

$$Q_{pyro} = M_{C_{dry\ portion(2)}} * \frac{Hr_{pyro}}{1000} = 290 \frac{kg}{t} * \frac{420 \frac{kJ}{kg}}{1000} = 121.8 \frac{MJ}{t}$$

The heat required to heat the pyrolysis products of char, volatiles, and non-condensable gases to 600°C is then calculated using assumptions 5, 13, 14, 18, 19, and 20.

$$Q_{sensible_{pyro}} = M_{C_{dry\ portion(2)}} * (\%_{char} * Cp_{char} + \%_{volatiles} * Cp_{volatiles} + \%_{gases} * Cp_{gases}) * \frac{T_{(4)} - T_{pyrolyser}}{1000}$$

$$Q_{sensible_{pyro}} = 290 \frac{kg}{t} * (35\% * 1.1 \frac{kJ}{kg \cdot ^\circ C} + 30\% * 2.5 \frac{kJ}{kg \cdot ^\circ C} + 35\% * 1.1 \frac{kJ}{kg \cdot ^\circ C})$$

$$* \frac{600^\circ C - 300^\circ C}{1000}$$

$$Q_{sensible_{pyro}} = 132.24 \frac{MJ}{t}$$

All the portions of heat required by the pyrolyser have now been calculated. Therefore, the total heat input required to the pyrolyser can be calculated.

$$Q_{total\ pyrolyser} = Q_w + Q_{C,dry(300^\circ C)} + Q_{pyro} + Q_{sensible_{pyro}}$$

$$Q_{pyro_{total}} = 238.235 + 109.272 + 121.8 + 132.24 = 601.547 \frac{MJ}{t}$$

The mass and heat of the flows out of the pyrolyser can now be calculated.

The mass of char:

$$M_{char(4)} = M_{C_{dry\ portion(2)}} * \%_{char} = 290 \frac{kg}{t} * 35\% = 101.5 \frac{kg}{t}$$

The heat carried out by the char (i.e. the sensible heat above 20°C):

$$Q_{char(4)} = M_{char(4)} * C_{p_{char}} * \frac{T_{(4)} - T_{(1)}}{1000} = 101.5 \frac{kg}{t} * 1.1 \frac{kJ}{kg \cdot ^\circ C} * \frac{600 - 20}{1000} = 64.757 \frac{MJ}{t}$$

The mass of volatiles, gases, and water vapour leaving the pyrolyser in stream 12:

$$M_{volatiles} = M_{C_{dry\ portion(2)}} * \%_{volatiles} = 290 \frac{kg}{t} * 30\% = 87 \frac{kg}{t}$$

$$M_{gases} = M_{C_{dry\ portion(2)}} * \%_{gases} = 290 \frac{kg}{t} * 35\% = 101.5 \frac{kg}{t}$$

$$M_{vapour(12)} = M_{C_{wet\ portion(2)}} = 72.5 \frac{kg}{t}$$

$$M_{(12)} = M_{volatiles} + M_{gases} + M_{vapour(12)} = 87 + 101.5 + 72.5 = 261 \frac{kg}{t}$$

The heat carried out by the water vapour component in stream 12:

$$\begin{aligned} Q_{vapour(12)} &= Q_w + M_{C_{wet\ portion(2)}} * \frac{Q_{C_{dry(2)}}}{1000} = 238.235 \frac{MJ}{t} + 72.5 \frac{kg}{t} * \frac{336 \frac{kJ}{kg}}{1000} \\ &= 262.595 \frac{MJ}{t} \end{aligned}$$

The heat carried out by the volatiles and gases component in stream 12:

$$Q_{volatiles+gases(12)} = Q_{total\ pyrolyser} + Q_{C_{dry}(2)} - Q_{char(4)} - Q_{vapour(12)} - Q_{pyro}$$

$$Q_{volatiles+gases(12)} = 601.547 + 68.0688 - 64.757 - 262.595 - 121.8$$

$$Q_{volatiles+gases(12)} = 220.4638 \frac{MJ}{t}$$

The total heat carried out by stream 12:

$$Q_{(12)} = Q_{vapour(12)} + Q_{volatiles+gases(12)} = 262.595 + 220.4638 = 483.0588 \frac{MJ}{t}$$

To ensure that the mass and energy balances are correct over the pyrolyser a check is made.

Mass:

$$Mass\ in = M_{(2)} = 362.5kg$$

$$Mass\ out = M_{char(4)} + M_{(12)} = 101.5 + 261 = 362.5kg$$

$$Mass\ in = Mass\ out$$

$$362.5 = 362.5$$

Energy:

$$Energy\ in = Q_{(2)} + Q_{total\ pyrolyser} = 68.0688 + 601.547 = 670$$

$$Energy\ out = Q_{(12)} + Q_{char(4)} + Q_{pyro} = 483.06 + 64.757 + 121.8 = 670$$

$$Energy\ in = Energy\ out$$

$$670 = 670$$

C. The diesel burner: How much heat is generated when the tar and gases are burnt?

Assumptions:

1. The incoming air humidity is negligible compared to the moisture on the fuel side (biomass has 20% mc).

2. The heating value of the volatiles in stream 12 ($HV_{volatiles}$) is assumed to be 20 MJ/kg (Das et al., 2017).
3. The heating value of the gases in stream 12 (HV_{gases}) is assumed to be 10 MJ/kg; this is an estimate.
4. The mass of fuel to air ratio is assumed to be 15 t air/t fuel which is typical for biomass.
5. The specific heat capacity of air (Cp_{air}) is assumed to be 1.08 kJ/kg/K over the 100°C to 1000°C range.
6. The zero-enthalpy line is set at 20°C, the lowest temperature in the system.
7. The specific heat capacity of water vapour at 600°C ($Cp_{vapour(600^\circ C)}$) was found to be 2.2 kJ/kg/K from steam tables.
8. The heat loss from the burner is 5%.

Using the assumed heating values of the volatiles and gases, the average heat of combustion for stream 12 is calculated:

$$\begin{aligned}
 Q_{average\ combustion\ of\ (12)} &= HV_{volatiles} * \frac{\%volatiles}{\%volatiles + \%gases} + HV_{gases} * \frac{\%gases}{\%volatiles + \%gases} \\
 Q_{average\ combustion\ of\ (12)} &= 20 * \frac{30\%}{30\% + 35\%} + 10 * \frac{35\%}{30\% + 35\%} = 14.62 \frac{MJ}{kg}
 \end{aligned}$$

Using the calculated masses of the components within stream 12 and the fuel to air mass ratio assumed, the actual mass of air required for combustion of the volatiles and gases is calculated:

$$\begin{aligned}
 M_{air\ for\ combustion\ of\ volatiles\ and\ gases} &= (M_{volatiles} + M_{gases}) * 15 \frac{t\ air}{t\ fuel} = 188.5 * 15 \\
 M_{air\ for\ combustion\ of\ volatiles\ and\ gases} &= 2827.5kg
 \end{aligned}$$

The heat produced from the combustion of the volatiles and gases is calculated:

$$\begin{aligned}
 Q_{combustion\ of\ (12)} &= Q_{average\ combustion\ of\ (12)} * (M_{volatiles} + M_{gases}) \\
 &= 14.62 \frac{MJ}{kg} * 188.5kg \\
 Q_{combustion\ of\ (12)} &= 2755MJ
 \end{aligned}$$

The Goal Seek function on EXCEL was used to calculate an estimate for the temperature of the flue gas leaving the burner. The ‘sum of sensible heats for water vapour and air’ was set to equal ‘the heat leaving the combustor’ by changing the ‘final temp guess’. The heat of the incoming air into the burner was initially set to zero because any air coming into the burner

will be at 20°C, which is the enthalpy baseline. The following equations were used to find the exit temp estimate.

The heat of incoming air ($Q_{(6)} = 0$ MJ/t

Heat of incoming volatiles, gases, and water vapour ($Q_{(12)} = 483.0588 \frac{MJ}{t}$

Heat leaving the combustor ($Q_{(7)}$)

$$(Q_{(7)}) = Q_{(6)} + Q_{(12)} + Q_{combustion\ of\ (12)} = 483.0588 + 2755$$

$$Q_{(7)} = 3238.0588 \frac{MJ}{t}$$

Heat required for sensible superheating of water vapour from 600°C ($Q_{vapour(600^\circ C)}$):

$$\begin{aligned} Q_{vapour(600^\circ C)} &= M_{C_{wet\ portion(2)}} * C_{p_{vapour(600^\circ C)}} * \frac{T_{flue(7)} - T_{(4)}}{1000} \\ &= 72.5 * 2.2 * \frac{T_{flue(7)} - 600^\circ C}{1000} \end{aligned}$$

Heat required for sensible heating of the air from 20°C ($Q_{air(from\ 20^\circ C)}$):

$$\begin{aligned} Q_{air(from\ 20^\circ C)} &= M_{air\ for\ combustion\ of\ volatiles\ and\ gases} * C_{p_{air}} * \frac{T_{flue(7)} - T_{(1)}}{1000} \\ Q_{air(from\ 20^\circ C)} &= 2827.5 * 1.08 * \frac{T_{flue(7)} - 20^\circ C}{1000} \end{aligned}$$

The sum of heat losses + sensible heats for water vapour and air:

$$Q_{vapour(600^\circ C)} + Q_{air(from\ 20^\circ C)}$$

Using the EXCEL function, it was found that the $T_{flue(7)}$ estimate was 1056.53°C. The above heat flows are then calculated:

$$Q_{vapour(600^\circ C)} = 72.816 \frac{MJ}{t}$$

$$Q_{air(from\ 20^\circ C)} = 3165.243 \frac{MJ}{t}$$

$$Q_{vapour(600^\circ C)} + Q_{air(from\ 20^\circ C)} = 3238.0588 \frac{MJ}{t}$$

Therefore, the heat losses from the burner surfaces are then calculated:

$$Q_{burner\ loss} = Q_{(7)} * 5\% = 3238.0588 * 5\% = 161.90294 \frac{MJ}{t}$$

The heat of the flue leaving the burner is then estimated to be 3076.15586 MJ/t.

$$Q_{flue(7)} = Q_{vapour(600^{\circ}C)} + Q_{air(from\ 20^{\circ}C)} - Q_{burner\ loss} = 3238.0588 - 161.90294$$

$$Q_{flue(7)} = 3076.15586 \frac{MJ}{t}$$

D. The flue gas side of the pyrolyser: What are the outlet conditions of the flue gas?

Assumptions:

1. The pyrolyser has 10% heat loss through its surfaces based on the heat entering.
2. The flue gas has the same specific heat capacity as air.

The heat entering the pyrolyser from the burner (calculated in Section C):

$$Q_{flue(7)} = 3076.15586 \frac{MJ}{t}$$

Therefore, the heat lost in the pyrolyser is calculated:

$$Q_{pyrolyser\ loss} = Q_{flue(7)} * 10\% = 3076.15586 * 10\% = 307.62 \frac{MJ}{t}$$

The amount of heat required to be transferred within the pyrolyser (calculated in Section B):

$$Q_{pyro_{total}} = 601.547 \frac{MJ}{t}$$

The heat leaving the pyrolyser is calculated:

$$Q_{flue(11)} = Q_{flue(7)} - Q_{pyrolyser\ loss} - Q_{pyro_{total}} = 3076.15586 - 307.62 - 601.547$$

$$Q_{flue(11)} = 2166.99 \frac{MJ}{t}$$

The temperature of the flue leaving the pyrolyser was calculated using the Goal Seek function in EXCEL. The 'net loss over the pyrolyser' was set to equal to the 'sum of heat loss for water vapour and air'. The following equations were used to find the exit temp estimate.

The net loss over the pyrolyser:

$$Q_{net\ loss_{pyrolyser}} = Q_{flue(7)} - Q_{flue(11)} = 3076.15586 - 2166.99 = 909.163 \frac{MJ}{t}$$

The heat loss due to cooling of steam ($Q_{loss(steam)}$):

$$\begin{aligned} Q_{loss(steam)} &= M_{C_{wet\ portion}(2)} * C_{p_{vapour}(600^{\circ}C)} * \frac{T_{flue(7)} - T_{flue(11)}}{1000} \\ &= 72.5 * 2.2 * \frac{1056.53^{\circ}C - T_{flue(11)}}{1000} \end{aligned}$$

The heat loss due to cooling of flue gas ($Q_{loss(flue)}$):

$$\begin{aligned} Q_{loss(flue)} &= (M_{air(6)} + M_{volatiles} + M_{gases}) * C_{p_{air}} * \frac{T_{flue(7)} - T_{flue(11)}}{1000} \\ Q_{loss(flue)} &= 2827.5 + 188.5 * 1.08 * \frac{1056.53 - T_{flue(11)}}{1000} \end{aligned}$$

The sum of heat losses for water vapour and air:

$$Q_{loss(steam)} + Q_{loss(flue)}$$

Using the EXCEL function, it was found that the $T_{flue(11)}$ estimate was 790.44°C.

Therefore, the heat losses were found to be:

$$Q_{loss(steam)} = 42.44 \frac{MJ}{t}$$

$$Q_{loss(flue)} = 866.72 \frac{MJ}{t}$$

E. The flue gas side of the dryer: Do the inlet conditions from the pyrolyser flue gas transfer the heat required for the drying of the biomass?

Assumptions:

1. The specific heat capacity of water vapour as steam from 100°C to 140°C ($C_{p_{vapour}(100^{\circ}C-140^{\circ}C)}$) is 2.02 kJ/kg/K.

2. The dryer flue gas temperature is 140°C.

The mass flow of the exiting pyrolyser flue:

$$M_{flue(11)} = M_{air(6)} + M_{(12)} = 2827.5 + 261 = 3088.5 \frac{kg}{t}$$

The temperature of the flue into the dryer:

$$T_{flue(11)} = 790.44^\circ\text{C}$$

The heat flow into the dryer from the flue:

$$Q_{flue(11)} = 2166.99 \frac{MJ}{t}$$

The heat loss in the dryer, as calculated in Section A, not updated, this was the initial estimate:

$$Q_{dryer_{loss}} = 172.3 \frac{MJ}{t}$$

The remainder of heat available for heat transfer within the dryer is then calculated:

$$Q_{available,dryer} = Q_{flue(11)} - Q_{dryer_{loss}} = 2166.99 - 172.3 = 1994.69 \frac{MJ}{t}$$

The dryer flue gas temperature ($T_{flue(10)}$) is assumed to be 140°C.

The heat portion of water vapour ($Q_{vapour(10)}$) leaving the dryer after evaporation of the last 20% of the moisture that was left in the biomass when entering the pyrolyser.

$$\begin{aligned} Q_{vapour(10)} &= M_{C_{wet\ portion(2)}} \\ & * \frac{\Delta H_{water(20^\circ\text{C}-100^\circ\text{C})} + \Delta H_{(3)(20^\circ\text{C}_{water}-100^\circ\text{C}_{water\ vapour})} + Cp_{vapour(100^\circ\text{C}-140^\circ\text{C})} * (T_{flue(10)} - 100)}{1000} \end{aligned}$$

$$Q_{vapour(10)} = 72.5 * \frac{336 * 2569 * 2.02 * (140 - 100)}{1000} = 218.428 \frac{MJ}{t}$$

The heat leaving with the flue gases ($Q_{flue\ portion\ from(9)}$):

$$Q_{flue\ portion\ from(11)} = M_{flue(11)} * Cp_{air} * \frac{T_{flue(10)} - T_{(1)}}{1000} = 3088.5 * 1.08 * \frac{140 - 20}{1000}$$

$$Q_{flue\ portion\ from(11)} = 400.27 \frac{MJ}{t}$$

Therefore, the total heat leaving with the flue gas, expelled water vapour and dried solids is calculated:

$$Q_{flue\ total\ (10)} = Q_{vapour(10)} + Q_{flue\ portion\ from(11)} + Q_{C_{dry}(2)}$$

$$Q_{flue\ total\ (10)} = 218.428 + 400.27 + 68.0688$$

$$Q_{flue\ total\ (10)} = 686.7664 \frac{MJ}{t}$$

The heat that is transferred within the dryer ($Q_{transferred(dryer)}$) is then calculated:

$$\begin{aligned} Q_{transferred(dryer)} &= Q_{available,dryer} - Q_{flue\ total\ (10)} = 1994.69 - 686.7664 \\ &= 1307.925 \frac{MJ}{t} \end{aligned}$$

However, the heat transfer required from the hot flue gas to dry the biomass is 1654.95MJ/t, as calculated in section A. Therefore, extra diesel needs to be added to make up the heat required for drying.

The shortfall at the dryer that diesel needs to make up:

$$Q_{diesel\ required} = Q_{steam(3)} - Q_{transferred(dryer)} = 1654.95 - 1307.92 = 347.025 \frac{MJ}{t}$$

F. The makeup diesel combustion heat: If there is not enough heat entering the dryer, then how much diesel is needed to produce the required heat?

Assumptions:

1. An air-to-fuel mass ratio of 20 t/t is used.
2. The heating value of diesel (HV_{diesel}) is 45.5 MJ/kg.
3. The outlet flue gas temperature of the dryer is 140°C.
4. Flue gas has the same specific heat capacity as air.
5. The diesel has a temperature ($T_{(5)}$) of 20°C.

Using the Goal Seek function in EXCEL the amount of diesel required is calculated. The ‘heat diesel delivered to the dryer’ was set equal to the ‘shortfall at the dryer that diesel needs to make up’. The following equations are used.

$$\text{The amount of air plus diesel } (M_{air+diesel}) = (1 + 20 \frac{t}{t}) * M_{diesel}$$

The heat generated by the combustion of diesel ($Q_{diesel\ combustion} = M_{diesel} * HV_{diesel}$)

The sensible heat leaving with the flue:

$$Q_{sensible(flue)} = M_{air+diesel} * Cp_{air} * \frac{T_{flue(10)} - T_{(5)}}{1000} = M_{air+diesel} * 1.08 * \frac{140 - 20}{1000}$$

The heat diesel delivered to the dryer:

$$Q_{diesel\ delivers} = Q_{diesel\ combustion} - Q_{sensible(flue)}$$

Using the EXCEL SOLVER function it was found that the amount of diesel required (M_{diesel}) was 8.11 kg/t. Therefore, the heat equations above are calculated, and the burner and pyrolysis calculations made in sections D and E need to be recalculated.

$$M_{air+diesel} = 170.355 \frac{kg}{t}$$

$$Q_{diesel\ combustion} = 369.103 \frac{MJ}{t}$$

$$Q_{sensible(flue)} = 22.078 \frac{MJ}{t}$$

$$Q_{diesel\ delivers} = 347.025 \frac{MJ}{t}$$

G. Recalculation of flows affected by the addition of diesel into the system.

Assumptions:

1. The heat losses from the dryer, pyrolyser, and burner are all assumed to be the same for this estimate.
2. The heat required for evaporation, leaving in the water vapour out of the dryer ($Q_{steam(3)}$), stays the same at 1654.95 MJ.
3. The heat leaving with the dried solids ($Q_{C_{dry}(2)}$) remains the same at 68.0688 MJ.

The air required to be entering the burner is recalculated to now include the air required for combustion of the diesel:

$$M_{air(6)recalc} = (M_{air+diesel} - M_{diesel}) + M_{air\ for\ combustion\ of\ volatiles\ and\ gases}$$

$$M_{air(6)recalc} = (170.355 - 8.11) + 2827.5$$

$$M_{air(6)recalc} = 2989.743 \frac{kg}{t}$$

The total mass flow out of the burner is also recalculated:

$$M_{(7)recalc} = M_{(12)} + M_{air \text{ for combustion of volatiles and gases}} + M_{air+diesel}$$

$$M_{(7)recalc} = 261 + 2827.5 + 170.355$$

$$M_{(7)recalc} = 3258.86 \frac{kg}{t}$$

Therefore, the total heat leaving the burner is recalculated:

$$\begin{aligned} Q_{total \text{ heat leaving burner}} &= Q_{(7)} + Q_{diesel \text{ combustion}} = 3238.0588 + 369.103 \\ &= 3607.1618 \frac{MJ}{t} \end{aligned}$$

With the heat losses remaining the same, the total heat leaving the burner and entering the pyrolyser is recalculated:

$$Q_{(7)recalc} = Q_{total \text{ heat leaving burner}} - Q_{incinerator \text{ to evaporate water from biomass at } 100^{\circ}C}$$

$$Q_{(7)recalc} = 3607.1618 - 162.11 = 3445.0518 \frac{MJ}{t}$$

The heat leaving the pyrolyser and entering the dryer is recalculated:

$$Q_{(11)recalc} = Q_{(7)recalc} - Q_{pyrolyser \text{ loss}} - Q_{pyro_{total}} = 3445.0518 - 307.62 - 601.547$$

$$Q_{(11)recalc} = 2535.8848 \frac{MJ}{t}$$

The heat leaving in the flue out of the dryer is recalculated:

$$\begin{aligned} Q_{flue(10)recalc} &= Q_{flue \text{ total } (10)} + Q_{sensible(flue)} - Q_{C_{dry}(2)} \\ &= 686.7664 + 22.078 - 68.0688 \end{aligned}$$

$$Q_{flue(10)recalc} = 640.7756 \frac{MJ}{t}$$

Ensuring an energy balance over the dryer:

$$E_{balance\ check} = Q_{(11)recalc} - Q_{steam(3)} - Q_{flue(10)recalc} - Q_{C_{dry}(2)} - Q_{dryer_{loss}}$$

$$E_{balance\ check} = 2536 - 1655 - 641 - 68 - 172$$

$$E_{balance\ check} = 0$$

The burner flue outlet temperature is recalculated using Goal Seek in EXCEL. The ‘total heat leaving the burner and entering the pyrolyser’ that was recalculated above is set equal to the ‘sum of sensible heat for water vapour and air’. The following equations are used.

The heat required for sensible superheating of water vapour from 600°C is recalculated:

$$\begin{aligned} Q_{vapour(600^{\circ}C)recalc} &= M_{C_{wet\ portion}(2)} * C_{p_{vapour(600^{\circ}C)}} * \frac{T_{flue(7)recalc} - T_{(4)}}{1000} \\ &= 72.5 * 2.2 * \frac{T_{flue(7)} - 600^{\circ}C}{1000} \end{aligned}$$

The heat required for sensible heating of air from 20°C is recalculated:

$$\begin{aligned} Q_{air(from\ 20^{\circ}C)recalc} &= M_{air\ for\ combustion\ of\ volatiles\ and\ gases} * C_{p_{air}} * \frac{T_{flue(7)recalc} - T_{(1)}}{1000} \\ Q_{air(from\ 20^{\circ}C)recalc} &= 2827.5 * 1.08 * \frac{T_{flue(7)} - 20^{\circ}C}{1000} \end{aligned}$$

The sum of heat losses + sensible heats for water vapour and air is recalculated:

$$Q_{vapour(600^{\circ}C)recalc} + Q_{air(from\ 20^{\circ}C)recalc}$$

Using the EXCEL function, it was found that the $T_{flue(7)recalc}$ estimate was 1120.93°C. The above heat flows are then recalculated:

$$Q_{vapour(600^{\circ}C)recalc} = 83 \frac{MJ}{t}$$

$$Q_{air(from\ 20^{\circ}C)recalc} = 3362 \frac{MJ}{t}$$

$$Q_{vapour(600^{\circ}C)recalc} + Q_{air(from\ 20^{\circ}C)recalc} = 3445 \frac{MJ}{t}$$

The pyrolyser flue outlet temperature is recalculated using Goal Seek in EXCEL. The ‘sum of heat losses for water vapour and air’ is set as equal to the ‘net loss over the pyrolyser’. The following equations are used:

The heat loss due to cooling of steam is recalculated:

$$Q_{loss(steam)recalc} = M_{C_{wet\ portion}(2)} * C_{p_{vapour}(600^{\circ}C)} * \frac{T_{flue(7)recalc} - T_{flue(11)recalc}}{1000}$$

$$Q_{loss(steam)recalc} = 72.5 * 2.2 * \frac{1120.93^{\circ}C - T_{flue(11)recalc}}{1000}$$

The heat loss due to cooling of flue gas is recalculated:

$$Q_{loss(flue)recalc} = (M_{air(6)} + M_{volatiles} + M_{gases}) * C_{p_{air}} * \frac{T_{flue(7)recalc} - T_{flue(11)recalc}}{1000}$$

$$Q_{loss(flue)recalc} = 2827.5 + 188.5 * 1.08 * \frac{1120.93 - T_{flue(11)recalc}}{1000}$$

The sum of heat losses for water vapour and air:

$$Q_{loss(steam)recalc} + Q_{loss(flue)recalc}$$

Using the EXCEL function, it was found that the $T_{flue(11)recalc}$ estimate was 855°C.

Therefore, the heat losses were found to be:

$$Q_{loss(steam)recalc} = 42 \frac{MJ}{t}$$

$$Q_{loss(flue)recalc} = 867 \frac{MJ}{t}$$

To ensure that with the recalculated values the mass and energy over the entire system is balanced:

$$Mass\ into\ dryer = Mass\ out\ of\ dryer$$

$$1000 + 3258.86 = 362.5 + 637.5 + 3258.86$$

$$4258.86 = 4258.86$$

$$Energy\ into\ dryer = Energy\ out\ of\ dryer$$

$$0 + 2536.10 = 68.07 + 1654.95 + 640.7756 + 172.3$$

$$2536.10 = 2536.10$$

$$\textit{Mass into pyrolyser} = \textit{Mass out of pyrolyser}$$

$$362.50 + 3258.86 = 3258.86 + 261 + 101.50$$

$$3621.36 = 3621.36$$

$$\textit{Energy into pyrolyser} = \textit{Energy out of pyrolyser}$$

$$68.07 + 3445.0518 = 121.8 + 483.06 + 307.62 + 64.76 + 2536.10$$

$$3513.1218 = 3513.34$$

(The small difference can be accounted for by rounding errors)

$$\textit{Mass into burner} = \textit{Mass out of burner}$$

$$8.11 + 2989.743 + 261 = 3258.86$$

$$3258.853 = 3258.86$$

$$\textit{Energy into burner} = \textit{Energy out of burner}$$

$$0 + 0 + 483.06 + 2755 + 369.1 = 162.11 + 3445.0518$$

$$3607.16 = 3607.1618$$

Appendix E: Electricity consumption

Appendix E.1: Landfill EoL treatment

Assumptions:

- From the respective manufacturers, the shredder is 15hp (Monster Industrial, n.d.) and the mixer is 3hp (Munson, n.d.).
- The screw conveyors have a wattage of 81.16–99.29 watts with a rating of 1.975–3.21 t/hr (Asli-Arden & Mohsenimanesh, 2012).
- A working day will consist of 10 hours of machine operation; this does not include the one hour of start-up or the one hour of pack-down.
- Converting hp to kWh is completed by multiplying the hp by the hours required and dividing it by 1.3403825737.

Shredder

Even though a 10-hour workday is set out in the assumptions, based on the shredders' capacity, it will take the shredder 53.33 hours to process 12 tonnes of plant material (Appendix A.1). Therefore, it will take 4.44 hours per tonne of material.

$$\frac{53.33 \frac{\text{hours}}{\text{cycle}}}{12 \text{ tonnes of material}} = 4.44 \frac{\text{hours}}{\text{FU}}$$

$$\text{kWh} = \frac{\text{hp} * (\text{hours})}{1.3404825737}$$

$$\frac{15\text{hp} * 4.44 \frac{\text{hrs}}{\text{FU}}}{1.3404825737} = 49.68 \frac{\text{kWh}}{\text{FU}}$$

Mixer

As calculated in Appendix A.1, the mixer will take 42.22 hours to process 14.25 tonnes of material per cycle (cannabis material + green waste + bleach). Therefore, 2.96 hours per functional unit.

$$\frac{42.22 \frac{\text{hours}}{\text{cycle}}}{14.25 \text{ tonnes of material}} = 2.96 \frac{\text{hours}}{\text{FU}}$$

$$\text{kWh} = \frac{\text{hp} * (\text{hours})}{1.3404825737}$$

$$\frac{3hp * 2.96 \frac{hours}{FU}}{1.3404825737} = 6.6 \frac{kWh}{FU}$$

Conveyors

According to Asli-Arden & Mohsenimanesh (2012), the electricity requirement of auger conveyors running at 1.975–3.21 ton/hour is 81.16–99.29 watt when the conveyors are running at zero degrees.

This gives a watt:tonne/hour ratio range of 41:1–31:1.

$$\frac{81.16 \text{ watt}}{1.975 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 41:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right) \quad \text{to} \quad \frac{99.29 \text{ watt}}{3.21 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 31:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right)$$

Three conveyors are required: transport the green waste and cannabis material to enter the shredder (1), transport from the shredder to the mixer (2), and transport from the mixer to the truck (3). Appendix A.1 found that it takes the conveyor system 5.5 hours to move 14.25 tonnes of material per cycle; this meant that it would take the conveyor system 0.39 hours to move one tonne of cannabis plant material. Conveyor (1) required one tonne to be moved, conveyor (2) required two tonnes, and conveyor (3) required 2.3 tonnes.

Therefore, conveyor (1) had a watt range of 79–105 watts, which was 0.031–0.041 kWh/FU; conveyor (2) had a watt range of 159–211 watts, which was 0.031–0.041 kWh/FU; and conveyor (3) had a watt range of 188–250 watts, which was 0.031–0.041 kWh/FU. The same equation was used for each conveyor. Conveyor (1) calculations are as follows.

$$\text{Conveyor (1) requires } \frac{1 \text{ tonne}}{0.39 \text{ hours}}$$

$$\text{watt range} = \text{watt}:\frac{\text{tonne}}{\text{hour}} \text{ ratio} * \frac{\text{tonne}}{\text{hour}} = 41 * \frac{1}{0.39} \text{ and } 31 * \frac{1}{0.39} = 79 - 105 \text{ watts}$$

$$kWh = \frac{\text{watt} * \text{hours}}{1000} = \frac{79 * 0.39}{1000} \text{ and } \frac{105 * 0.39}{1000} = 0.031 \text{ kWh and } 0.041 \text{ kWh}$$

Since the functional unit (FU) for this study was one tonne of cannabis plant material ‘as received’, the energy consumption for the conveyor (1) was 0.031–0.041 kWh/FU. Therefore, the total energy consumption of the conveyors could be up to 0.093–0.123 kWh/FU.

Total energy consumption

The total energy consumption range of the shredder, mixer and conveyors is as follows.

$$49.68 + 6.6 + (0.093 - 0.123) = 56.383 - 56.413 \frac{kWh}{FU}$$

Appendix E.2: Composting EoL treatment

Assumptions:

- From the respective manufacturers, the shredder is 15hp (Monster Industrial, n.d.) and the mixer is 3hp (Munson, n.d.).
- The screw conveyors have a wattage of 81.16–99.29 watts with a rating of 1.975–3.21 t/hr (Asli-Arden & Mohsenimanesh, 2012).
- A working day will consist of 10 hours of machine operation; this does not include the one hour of start-up or the one hour of pack-down.
- Converting hp to kWh is completed by multiplying the hp by the hours required and dividing it by 1.3403825737.

Shredder

Even though a 10-hour workday is set out in the assumptions, based on the shredders' capacity, it will take the shredder 53.33 hours to process 12 tonnes of plant material (Appendix A.2). Therefore, it will take 4.44 hours per tonne of material.

$$\frac{53.33 \frac{\text{hours}}{\text{cycle}}}{12 \text{ tonnes of material}} = 4.44 \frac{\text{hours}}{FU}$$

$$kWh = \frac{hp * (\text{hours})}{1.3404825737}$$

$$\frac{15hp * 4.44 \frac{hrs}{FU}}{1.3404825737} = 49.68 \frac{kWh}{FU}$$

Mixer

As calculated in Appendix A.2, the mixer will take 35.56 hours to process 12 tonnes of material per cycle (cannabis material + green waste). Therefore, 2.96 hours per functional unit.

$$\frac{35.56 \frac{\text{hours}}{\text{cycle}}}{12 \text{ tonnes of material}} = 2.96 \frac{\text{hours}}{FU}$$

$$kWh = \frac{hp * (\text{hours})}{1.3404825737}$$

$$\frac{3hp * 2.96 \frac{hours}{FU}}{1.3404825737} = 6.6 \frac{kWh}{FU}$$

Conveyors

According to Asli-Arden & Mohsenimanesh (2012), the electricity requirement of auger conveyors running at 1.975–3.21 ton/hour is 81.16–99.29 watt when the conveyors are running at zero degrees.

This gives a watt:tonne/hour ratio range of 41:1–31:1.

$$\frac{81.16 \text{ watt}}{1.975 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 41:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right) \quad \text{to} \quad \frac{99.29 \text{ watt}}{3.21 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 31:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right)$$

Three conveyors are required: transport the green waste and cannabis material to enter the shredder (1), transport from the shredder to the mixer (2), and transport from the mixer to the truck (3). Appendix A.2 found that it takes the conveyor system 4.63 hours to move 12 tonnes of material per cycle, which would take the conveyor system 0.39 hours to move one tonne of cannabis plant material. Conveyor (1) required one tonne to be moved, conveyor (2) required two tonnes, and conveyor (3) required two tonnes.

Therefore, conveyor (1) had a watt range of 79–105 watts, which was 0.031–0.041 kWh/FU; conveyor (2) had a watt range of 159–211 watts, which was 0.031–0.041 kWh/FU; and conveyor (3) had a watt range of 159–211 watts, which was 0.031–0.041 kWh/FU. The same equation was used for each conveyor; conveyor (1) calculations are as follows.

$$\text{Conveyor (1) requires } \frac{1 \text{ tonne}}{0.39 \text{ hours}}$$

$$\text{watt range} = \text{watt}:\frac{\text{tonne}}{\text{hour}} \text{ ratio} * \frac{\text{tonne}}{\text{hour}} = 41 * \frac{1}{0.39} \text{ and } 31 * \frac{1}{0.39} = 79 - 105 \text{ watts}$$

$$kWh = \frac{\text{watt} * \text{hours}}{1000} = \frac{79 * 0.39}{1000} \text{ and } \frac{105 * 0.39}{1000} = 0.031 \text{ kWh and } 0.041 \text{ kWh}$$

Since the functional unit (FU) for this study was one tonne of cannabis plant material ‘as received’, the energy consumption for the conveyor (1) was 0.031–0.041 kWh/FU. Therefore, the total energy consumption of the conveyors could be up to 0.093–0.123 kWh/FU.

Total energy consumption

The total energy consumption range of the shredder, mixer and conveyors are as follows.

$$49.68 + 6.6 + (0.093 - 0.123) = 56.383 - 56.413 \frac{kWh}{FU}$$

Appendix E.3: Anaerobic digestion EoL treatment

Assumptions:

- After shredding the cannabis mixture will have a similar density to sweepings, 125 kg/m³ (Bioenergy Association, 2021).
- A 15hp shredder was used (Monster Industrial, n.d.).
- The screw conveyors have a wattage of 81.16–99.29 watts with a rating of 1.975–3.21 t/hr (Asli-Arden & Mohsenimanesh, 2012).
- A working day will consist of 10 hours of machine operation, this does not include the one hour of start-up or the one hour of pack-down.
- Converting hp to kWh is completed by multiplying the hp by the hours required and dividing it by 1.3403825737.
- Anaerobic digestion energy consumption uses 0.43 kWh/m³ of waste entering (Ranieri et al., 2021).
- A belt filter press with a rating of 10–30 kWh/t of material is used.

Shredder

Even though a 10-hour workday is set out in the assumptions, based on the shredders' capacity, it will take the shredder 26.67 hours to process 6 tonnes of plant material (Appendix A.3). Therefore, it will take 4.44 hours per tonne of material.

$$\frac{26.67 \frac{hours}{cycle}}{6 \text{ tonnes of material}} = 4.44 \frac{hours}{FU}$$

$$kWh = \frac{hp * (hours)}{1.3404825737}$$

$$\frac{15hp * 4.44 \frac{hrs}{FU}}{1.3404825737} = 49.74 \frac{kWh}{FU}$$

Conveyors

According to Asli-Arden & Mohsenimanesh (2012), the electricity requirement of auger conveyors running at 1.975–3.21 ton/hour is 81.16–99.29 watt when the conveyors are running at zero degrees.

This gives a watt:tonne/hour ratio range of 41:1–31:1.

$$\frac{81.16 \text{ watt}}{1.975 \left(\frac{\text{tonne}}{\text{hour}} \right)} = 41:1 \left(\text{watt} : \frac{\text{tonne}}{\text{hour}} \right) \quad \text{to} \quad \frac{99.29 \text{ watt}}{3.21 \left(\frac{\text{tonne}}{\text{hour}} \right)} = 31:1 \left(\text{watt} : \frac{\text{tonne}}{\text{hour}} \right)$$

Two conveyors are required: transport the cannabis plant material into the shredder (1) and transport the material from the shredder into the anaerobic digester (2). Appendix A.3 found that it takes the conveyor system 2.31 hours to move 6 tonnes of material per cycle; this means it would take the conveyor system 0.39 hours to move one tonne of cannabis plant material. Conveyor (1) and conveyor (2) each required one tonne to be moved.

Therefore, conveyor (1) and conveyor (2) had a watt range of 79–105 watts, which was 0.031–0.041 kWh/FU. The same equation was used for each conveyor; conveyor (1) calculations are as follows.

$$\text{Conveyor (1) requires } \frac{1 \text{ tonne}}{0.39 \text{ hours}}$$

$$\text{watt range} = \text{watt} : \frac{\text{tonne}}{\text{hour}} \text{ ratio} * \frac{\text{tonne}}{\text{hour}} = 41 * \frac{1}{0.39} \text{ and } 31 * \frac{1}{0.39} = 79 - 105 \text{ watts}$$

$$\text{kWh} = \frac{\text{watt} * \text{hours}}{1000} = \frac{79 * 0.39}{1000} \text{ and } \frac{105 * 0.39}{1000} = 0.031 \text{ kWh and } 0.041 \text{ kWh}$$

Since the functional unit (FU) for this study was one tonne of cannabis plant material ‘as received’, the energy consumption for the conveyor (1) was 0.031–0.041 kWh/FU. Therefore, the total energy consumption of the conveyors could be up to 0.062–0.082 kWh/FU.

Anaerobic digester

Using the assumption that the cannabis material would have a similar density to sweepings after shredding, it was found that one tonne of cannabis was equivalent to 8 m³.

$$\text{m}^3 \text{ of feed} * \frac{\text{kWh}}{\text{m}^3} \text{ for anaerobic digestion} = \frac{\text{kWh}}{\text{FU}}$$

$$8 \text{ m}^3 * 0.43 \frac{\text{kWh}}{\text{m}^3} = 3.44 \frac{\text{kWh}}{\text{FU}}$$

Belt filter press

$$\left(10 - 30 \frac{\text{kWh}}{\text{t of sludge entering}} \right) * 1.8583 \frac{\text{t of sludge entering}}{\text{FU}} = 18.58 - 55.75 \frac{\text{kWh}}{\text{FU}}$$

Total energy consumption

Therefore, the total energy consumption range of the shredder, conveyors, anaerobic digester, and belt filter press is

$$49.74 + (0.062 \text{ to } 0.082) + 3.44 + (18.58 \text{ to } 55.75) = 72 \text{ to } 109 \frac{kWh}{FU}$$

Appendix E.4: Incineration EoL treatment

Assumptions:

1. The screw conveyors have a wattage of 81.16–99.29 watts with a rating of 1.975–3.21 t/hr (Asli-Arden & Mohsenimanesh, 2012).
2. A working day will consist of 10 hours of machine operation; this does not include the one hour of start-up or the one hour of pack-down.
3. The mobile unit used for the incineration EoL treatment spends one week on-site per cycle, processing 6 tonnes of waste plant material. There is a one-day set-up, one day of pack down, one day of contingency, and one day for equipment cooling within the processing week, leaving three days for processing.
4. The waste plant material has a moisture content of 71%.
5. The waste plant material has a lower heating value (LHV) of 15 MJ/kg.

Conveyors

According to Asli-Arden & Mohsenimanesh (2012), the electricity requirement of augur conveyors running at 1.975–3.21 ton/hour is 81.16–99.29 watt when the conveyors are running at zero degrees.

This gives a watt:tonne/hour ratio range of 41:1–31:1.

$$\frac{81.16 \text{ watt}}{1.975 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 41:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right) \quad \text{to} \quad \frac{99.29 \text{ watt}}{3.21 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 31:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right)$$

Two conveyors are required: transport the cannabis material into the dryer (1) and transport from the dryer to the incinerator (2). Appendix A.4 found that it takes the conveyor system 2.31 hours to move 6 tonnes of material per cycle; this meant that it would take the conveyor system 0.39 hours to move one tonne of cannabis plant material. Conveyors 1 and 2 will require a capacity of 1 tonne/hour.

Therefore, conveyors (1) and (2) both have a watt range of 79–105 watts, which was 0.031–0.041 kWh/FU. The same equation was used for each conveyor; conveyor (1) calculations are as follows.

$$\text{Conveyor (1) requires } \frac{1 \text{ tonne}}{0.39 \text{ hours}}$$

$$\text{watt range} = \text{watt} : \frac{\text{tonne}}{\text{hour}} \text{ ratio} * \frac{\text{tonne}}{\text{hour}} = 41 * \frac{1}{0.39} \text{ and } 31 * \frac{1}{0.39} = 79 - 105 \text{ watts}$$

$$\text{kWh} = \frac{\text{watt} * \text{hours}}{1000} = \frac{79 * 0.39}{1000} \text{ and } \frac{105 * 0.39}{1000} = 0.031 \text{ kWh and } 0.041 \text{ kWh}$$

Since the functional unit (FU) for this study was one tonne of cannabis plant material ‘as received’, the energy consumption for the conveyor (1) was 0.031–0.041 kWh/FU. Therefore, the total energy consumption of the conveyors could be up to 0.062–0.082 kWh/FU.

Dryer, incinerator, and burner

Using the assumption that the mobile unit used for the incineration EoL treatment spends one week on-site per cycle, processing 6 tonnes of waste plant material. There is one-day of set-up, one day of pack down, one day of contingency, and one day for equipment cooling within the processing week, leaving three days for processing. At a 10-hour working day, the capacity required for processing is 200 kg/hour.

$$M_{\text{processing rate}} = \frac{\frac{6000 \text{ kg}}{3 \text{ days}}}{10 \frac{\text{hours}}{\text{day}}} = 200 \frac{\text{kg}}{\text{hour}}$$

Assuming the plant material has a moisture content of 71% and a lower heating value (LHV) of 15 MJ/kg (dry basis) the capacity of the equipment required (dryer, incinerator, and diesel burner) can be calculated:

$$\begin{aligned} M_{\text{processing rate}_{\text{dry basis}}} &= M_{\text{processing rate}} * (1 - \%MC_{\text{wet}}) = 200 \frac{\text{kg}}{\text{hour}} * (1 - 71\%) \\ &= 58 \frac{\text{kg}}{\text{hour}} \text{ db.} \end{aligned}$$

$$\begin{aligned} Q_{\text{capacity}} &= M_{\text{processing rate}_{\text{dry basis}}} * \text{LHV} = 58 \frac{\text{kg}}{\text{hour}} * 15 \frac{\text{MJ}}{\text{kg}} = \frac{870 \frac{\text{MJ}}{\text{hour}}}{3600 \frac{\text{seconds}}{\text{hour}}} = 0.24 \frac{\text{MJ}}{\text{s}} \\ &= 0.24 \text{ MW} \end{aligned}$$

Therefore, the dryer, incinerator, and burner equipment require a capacity of at least 0.24 MW.

Appendix E.5: Pyrolysis EoL treatment

Assumptions:

1. The screw conveyors have a wattage of 81.16–99.29 watts with a rating of 1.975–3.21 t/hr (Asli-Arden & Mohsenimanesh, 2012).
2. A working day will consist of 10 hours of machine operation; this does not include the one hour of start-up or the one hour of pack-down.
3. The mobile unit used for the incineration EoL treatment spends one week on-site per cycle, processing 6 tonnes of waste plant material. There is one-day set-up, one day of pack-down, one-day of contingency, and one day for equipment cooling within the processing week, leaving three days for processing.
4. The waste plant material has a moisture content of 71%.
5. The waste plant material has a lower heating value (LHV) of 15 MJ/kg.

Conveyors

According to Asli-Arden & Mohsenimanesh (2012), the electricity requirement of augur conveyors running at 1.975–3.21 ton/hour is 81.16–99.29 watt when the conveyors are running at zero degrees.

This gives a watt:tonne/hour ratio range of 41:1–31:1.

$$\frac{81.16 \text{ watt}}{1.975 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 41:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right) \quad \text{to} \quad \frac{99.29 \text{ watt}}{3.21 \left(\frac{\text{tonne}}{\text{hour}}\right)} = 31:1 \left(\text{watt}:\frac{\text{tonne}}{\text{hour}}\right)$$

Two conveyors are required: transport the cannabis material into the dryer (1) and transport from the dryer to the pyrolyser (2). Appendix A.5 found that it takes the conveyor system 2.31 hours to move 6 tonnes of material per cycle; this meant that it would take the conveyor system 0.39 hours to move one tonne of cannabis plant material. Conveyors 1 and 2 will require a capacity of 1 tonne/hour.

Therefore, conveyors (1) and (2) both have a watt range of 79–105 watts, which was 0.031–0.041 kWh/FU. The same equation was used for each conveyor; conveyor (1) calculations are as follows.

$$\text{Conveyor (1) requires } \frac{1 \text{ tonne}}{0.39 \text{ hours}}$$

$$\text{watt range} = \text{watt}:\frac{\text{tonne}}{\text{hour}} \text{ ratio} * \frac{\text{tonne}}{\text{hour}} = 41 * \frac{1}{0.39} \text{ and } 31 * \frac{1}{0.39} = 79 - 105 \text{ watts}$$

$$\text{kWh} = \frac{\text{watt} * \text{hours}}{1000} = \frac{79 * 0.39}{1000} \text{ and } \frac{105 * 0.39}{1000} = 0.031 \text{ kWh and } 0.041 \text{ kWh}$$

Since the functional unit (FU) for this study was one tonne of cannabis plant material ‘as received’, the energy consumption for the conveyor (1) was 0.031–0.041 kWh/FU. Therefore, the total energy consumption of the conveyors could be up to 0.062–0.082 kWh/FU.

Dryer, pyrolyser, and burner

Using the assumption that the mobile unit used for the pyrolysis EoL treatment spends one week on-site per cycle, processing 6 tonnes of waste plant material. There is one-day of set-up, one day of pack down, one day of contingency, and one day for equipment cooling within the processing week, leaving three days for processing. At a 10-hour working day, the capacity required for processing is 200 kg/hour.

$$M_{processing\ rate} = \frac{6000\ \frac{kg}{days}}{10\ \frac{hours}{day}} = 200\ \frac{kg}{hour}$$

Assuming the plant material has a moisture content of 71%, and a lower heating value (LHV) of 15 MJ/kg (dry basis) the capacity of the equipment required (dryer, pyrolyser, and diesel burner) can be calculated:

$$\begin{aligned} M_{processing\ rate_{dry\ basis}} &= M_{processing\ rate} * (1 - \%MC_{wet}) = 200\ \frac{kg}{hour} * (1 - 71\%) \\ &= 58\ \frac{kg}{hour}\ db. \end{aligned}$$

$$\begin{aligned} Q_{capacity} &= M_{processing\ rate_{dry\ basis}} * LHV = 58\ \frac{kg}{hour} * 15\ \frac{MJ}{kg} = \frac{870\ \frac{MJ}{hour}}{3600\ \frac{seconds}{hour}} = 0.24\ \frac{MJ}{s} \\ &= 0.24\ MW \end{aligned}$$

Therefore, the dryer, pyrolyser, and burner equipment require a capacity of at least 0.24 MW.

Appendix F: GaBi modelling

Appendix F.1: Landfill EoL treatment

To model this scenario, several dataset decisions were made:

- There was no specific shredding dataset for green waste, so ‘wood chipping, industrial residual wood, stationary electric chipper’ was chosen as the closest representative.
- Bleach production was straightforward with a ‘sodium hypochlorite production’ dataset, which provided the required amount of NaOCl and the ‘market for tap water’ dataset provided the dilution required for disinfection.
- There are two main types of landfills: unsanitary and sanitary. It was found that the sanitary dataset was more representative of NZ landfills with a base seal, leachate collection system and treatment of leachate in a municipal wastewater treatment plant, were all considered.
 - Several sanitary landfill datasets could be used for the cannabis plant and green waste mixture; these included: ‘waste wood, untreated’, ‘waste packaging paper’, and ‘waste graphical paper’. It was found that ‘waste wood, untreated’ was the most representative. ‘Waste packaging paper’ and ‘waste graphical paper’ contained higher heavy metal emissions, which were not likely to be present in the inputs of this scenario.
- Which electricity values would be used, either the ecoinvent dataset data or those from the engineering calculations?
 - For several activities in this scenario, the choice was made; since there was no mixing dataset, the calculated electricity value was used. The landfills dataset requirements were also used.
 - Only one process had a conflicting value, the conveyor and shredder were calculated to be 180 MJ, but in the ‘wood chipping’ dataset, it was found that 144 MJ was required. Since the ‘wood chipping’ dataset did not take any form of the conveyor into account, the difference was understandable. The higher, more conservative value was used to ensure a realistic model.
- Re freight transport dataset truck size to use within the EURO6 class:
 - In Figure 29, there are two transport decisions.
 - The transport of the green waste to on-site (an assumed 100 km). For one cycle, six tonnes of green waste is required. Therefore, a 3.5-7.5 metric tons GVW transport is required.
 - The transport of bleach from its production facility to on-site (an assumed 100 km). For one cycle, less than one tonne is required, therefore, the smallest freight truck of 3.5-7.5 metric tons GVW transport is required.
 - In Figure 30, there are two transport decisions.

- The transport of the mixed material from the processing facility to the transfer station (as assumed 100 km). For one cycle, 12.4 tonnes are produced, therefore, a 7.5-16 metric tons GVW transport is required.
- The transport of the mixed material from the transfer station to the landfill (a known 119 km away). For one cycle, even though only 12.4 tonnes are produced, transport would not only include the mixed material, but other materials required to be landfilled. Therefore, the largest truck, >32-ton GVW transport is required. The emissions for each transportation leg are allocated amongst the different materials being transported in each load so that emissions per functional unit can be obtained.
- Organic waste composting
 - The ‘treatment of biowaste, industrial composting’ dataset was the only choice in the ecoinvent database with no other industrial composting datasets available. Per cycle on-site, six tonnes of green waste is converted from being composted. Therefore, for the subtraction of the organic waste composting process, a 3.5-7.5-ton GVW transport is required to transport the green waste to the composting facility.

Figure 29: Landfill EoL treatment on-site activities (GaBi model)

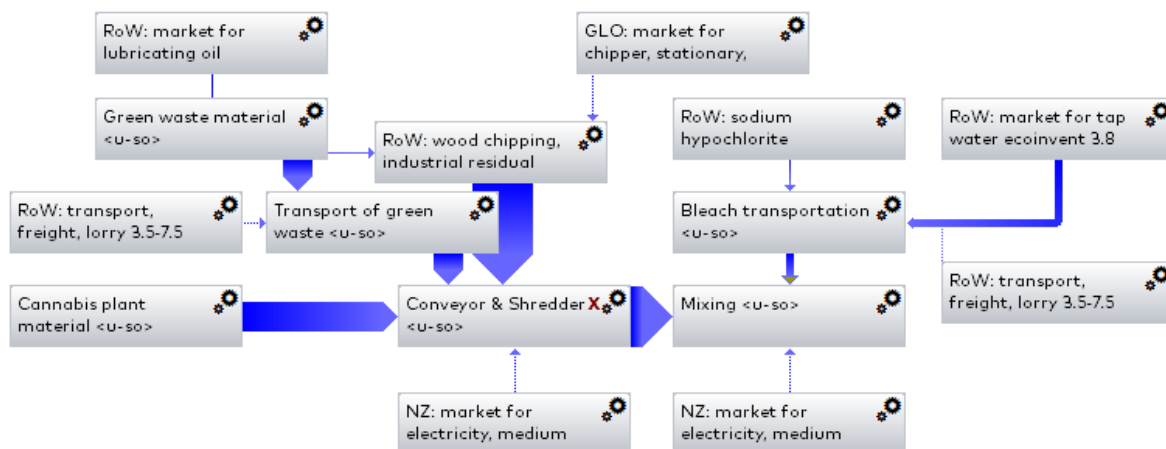


Figure 30: Landfill EoL treatment transport activities (GaBi model)

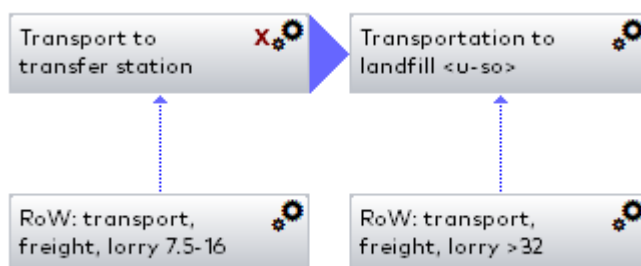


Figure 31: Landfill EoL treatment off-site activities (GaBi model)

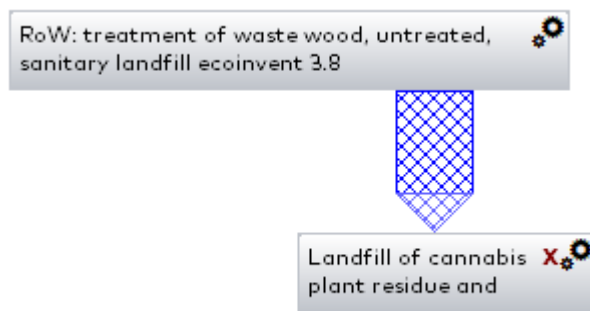


Figure 32: Landfill EoL treatment displaced organic waste composting and soil application (GaBi model)

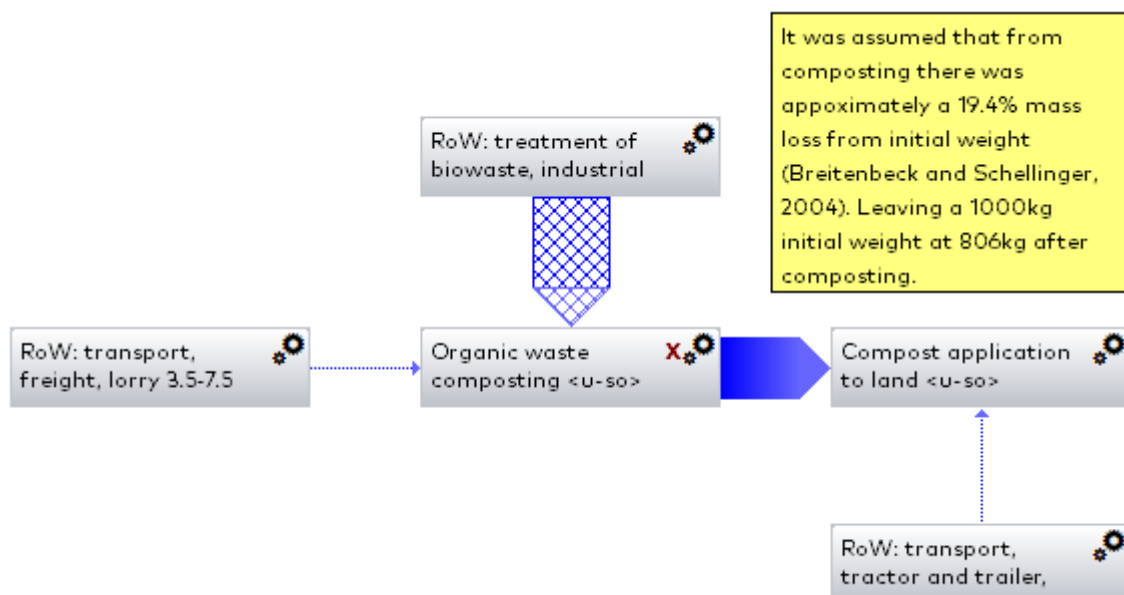
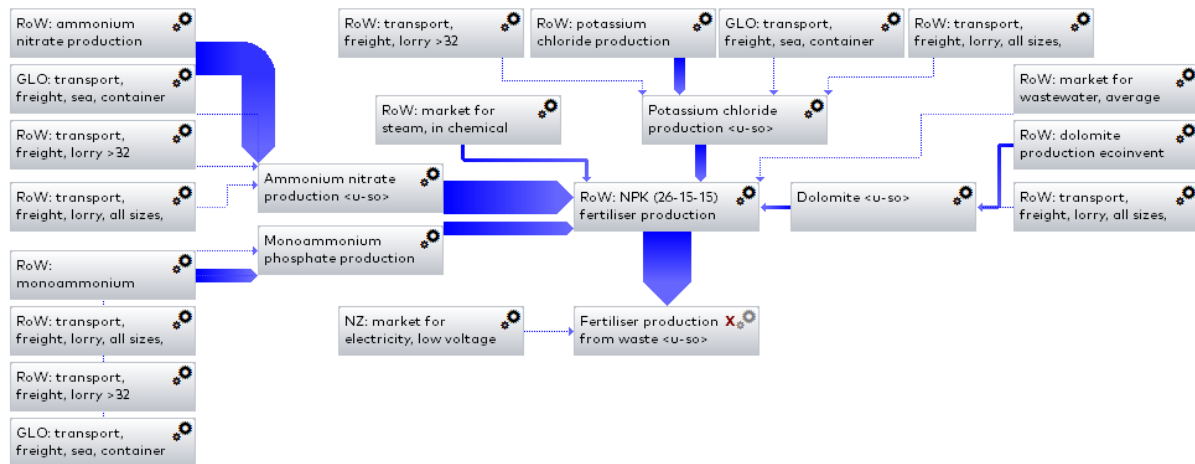


Figure 33: Landfill EoL treatment added synthetic fertiliser production of nutrients equivalent to green waste compost (GaBi model)



Appendix F.2: Composting EoL treatment

To model this scenario, several dataset decisions were made:

- On-site activities
 - The ‘wood chipping’ dataset was used to represent shredding the material, and the mixer required a new process to be created and the calculated electricity to be used.
 - Figure 34 shows that freight transport was required to get the green waste to the processing site, for one cycle, six tonnes of green waste was required.
- Electricity on-site
 - The calculated electricity value for the conveyor and shredder process was 180 MJ whereas the dataset value was 144 MJ, to be conservative, the calculated value for use.
- Composting and land spreading off-site
 - As in Figure 36, the ‘treatment of biowaste, industrial composting’ dataset was used along with its’ allocated electricity value. According to Breitenbeck and Schellinger (2004), 19.4% mass loss is a reasonable assumption for the conversion of green waste into compost. The application of the resulting compost onto land utilised the ‘transport, tractor and trailer, agricultural’ dataset which accounted for the diesel use and emissions based on the weight of the tractor and trailer.

Figure 34: Composting EoL treatment on-site activities (GaBi model)



Figure 35: Composting EoL treatment transport activities (GaBi model)

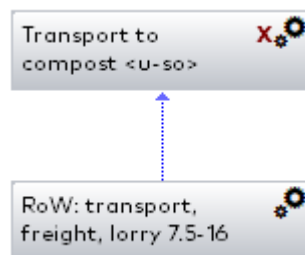


Figure 36: Composting EoL treatment off-site activities (GaBi model)

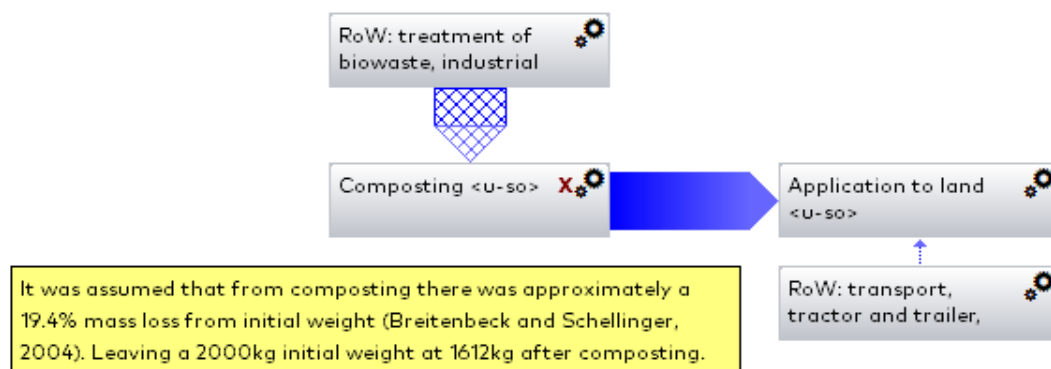
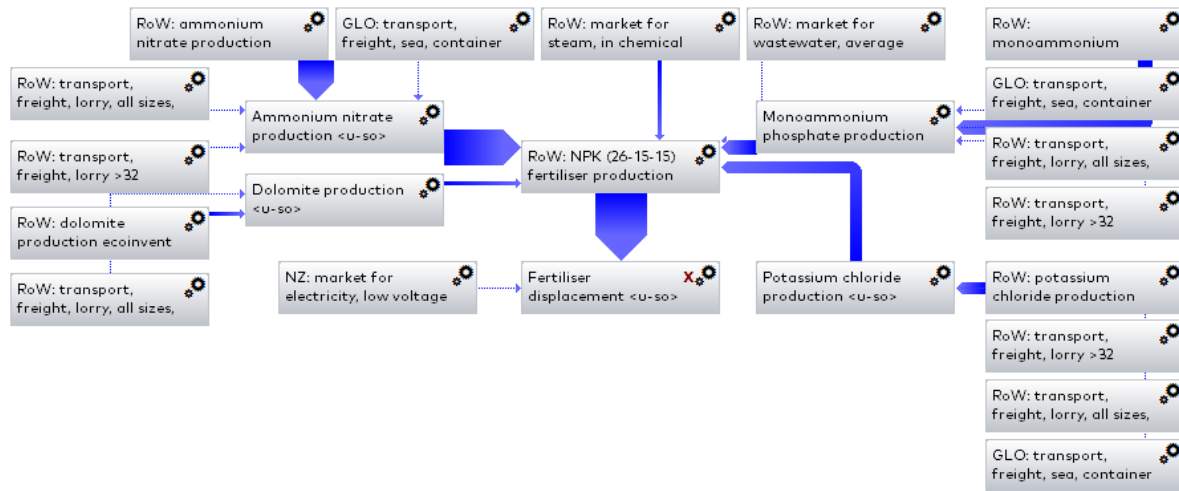


Figure 37: Composting EoL treatment displaced synthetic fertiliser production of cannabis waste nutrients (GaBi model)



Appendix F.3: Anaerobic digestion EoL treatment

To model this scenario, several dataset decisions were made:

- Shredding on-site
 - The ‘wood chipping’ dataset was used to represent the shredding of material.
- Anaerobic digestion on-site
 - The ecoinvent database only had three ‘treatment of material by anaerobic digestion’ datasets: biowaste, sewage sludge and used vegetable oil. The ‘treatment of biowaste by anaerobic digestion’ was used in this scenario.
- Belt filter press on-site
 - The ‘drying sewage sludge’ dataset was used to represent the belt filter press after digestion. The biogas produced by digestion was put into a heat and power cogeneration unit to be utilised on-site. From the belt filter press, a solid product at 80% moisture was produced and sent to an off-site composting facility using the ‘treatment of biowaste, industrial composting’ dataset. A liquid phase was also produced and sent to a wastewater treatment facility.
- Land spreading transport decision
 - Once the solid material has been composted, a tractor is assumed to apply the compost to the soil.
- Electricity dataset decisions and energy discrepancies
 - There were several discrepancies with the electricity required for the process technologies in this EoL scenario. Engineering calculations found that the electricity required for the conveyor and shredder, digester, and belt filter press were 180 MJ, 12 MJ, and 67-200 MJ (average used), respectively. However, the dataset electricity values were 72 MJ, 8 MJ, and 15 MJ, respectively. The higher more conservative values were used in every discrepancy, this was to keep the model relative to a real-world scenario. A district heating dataset was unable to be used as it was not the technology used in NZ, therefore, the ‘heat

generated from natural gas’ dataset was used to account for the conversion of biogas into heat in Figure 38.

Figure 38: Anaerobic digestion EoL treatment on-site activities (GaBi model)

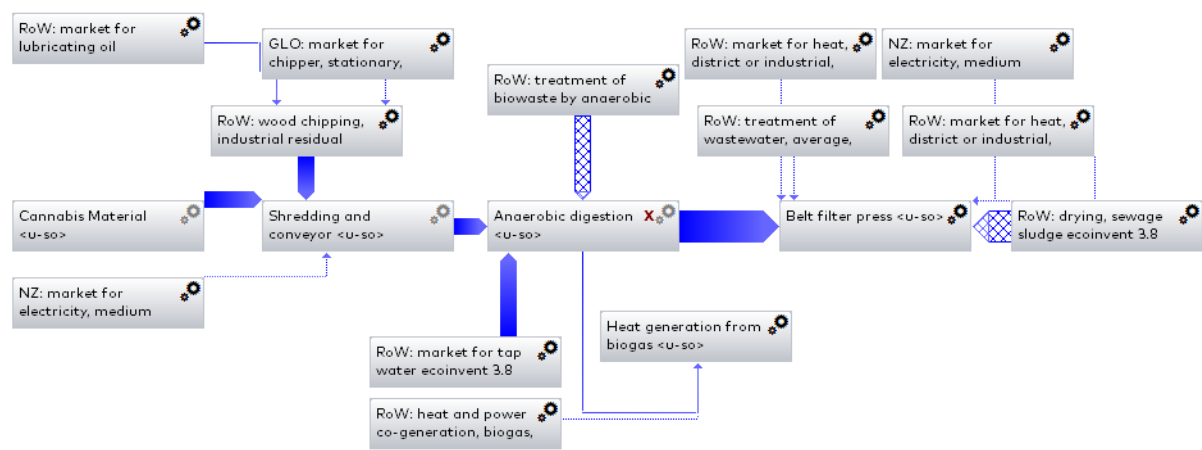


Figure 39: Anaerobic digestion EoL treatment transport activities (GaBi model)

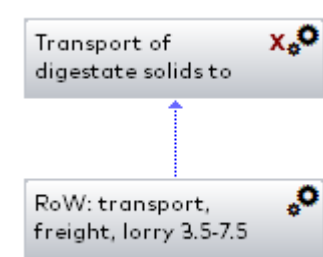


Figure 40: Anaerobic digestion EoL treatment off-site activities (GaBi model)

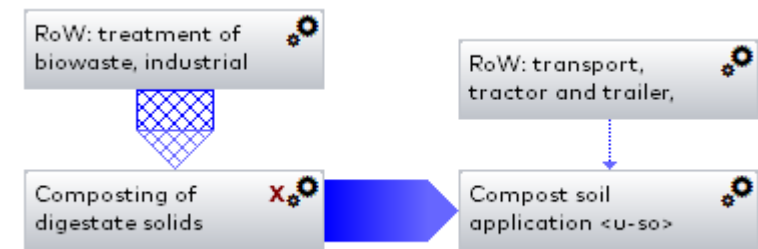


Figure 41: Anaerobic digestion EoL treatment heat displacement by digestion gases (GaBi model)

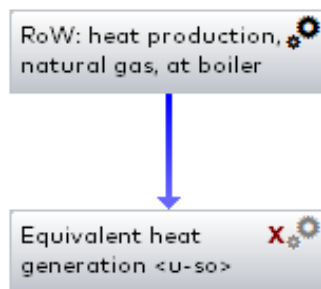
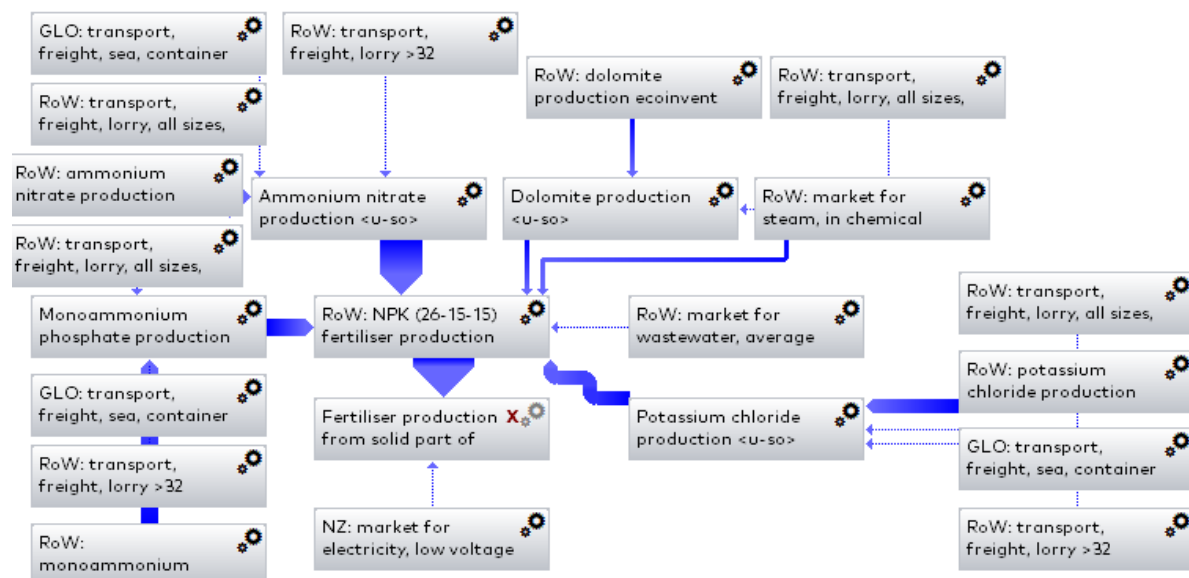


Figure 42: Anaerobic digestion EoL treatment displaced synthetic fertiliser production of nutrients in the solid phase of digestate



Appendix F.4: Incineration EoL treatment

To model this scenario, several dataset decisions were made:

- Shredding on-site
 - An industrial wood chipping dataset was used to represent the shredding of the cannabis plant material.
- Drying on-site
 - The only dataset available for drying green material was the ‘drying of grass’ dataset, it also incorporated the infrastructure of building a facility such as a ‘hall for drying’ input. Since infrastructure was not being incorporated for modelling this input was left out.
- Diesel burning on-site including diesel allocation

- To represent the diesel burner activity the dataset, ‘diesel, burned in building machine’ was used, as it was the most reasonable with diesel, burned in a building machine representing both the acquisition of the diesel as well as the emissions from diesel burnt. The allocation of diesel in the respected dataset was done by using the calculated required volume per start-up period and assuming each day a new start-up period was run. The time taken to process all the waste per cycle (six tonnes in one week), allowed for the flow rate required of two tonnes of cannabis plant material per day. Therefore, the required amount of diesel for the start-up was divided by two to account for the entire model being in the FU of one tonne of cannabis plant material. It should be noted that diesel was used as start-up fuel only, the system was assumed to then be able to run on the recycling of dried biomass.
- Electricity requirement
 - For this treatment the size and electricity requirement were specifically for two tonnes of cannabis plant waste to be processed per day, therefore, the electricity requirement of the equipment was a 0.24 MW heating capacity for the dryer, incinerator, and diesel burner.
- Excess heat generation
 - Since this EoL treatment incorporated the use of a mobile unit, the heat generated in the form of flue gas from the processes was not collected for reuse. However, a sensitivity analysis looked at the potential heat that can be displaced if the flue gas was reused on-site instead of natural gas. Finally, the ash produced was sent to the landfill as inert matter using the ‘treatment of inert waste, sanitary landfill’ dataset.

Figure 43: Incineration EoL treatment transport of the mobile unit (GaBi model)

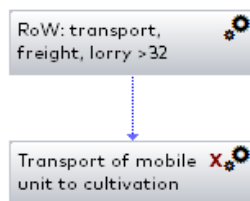


Figure 44: Incineration EoL treatment on-site activities (GaBi model)

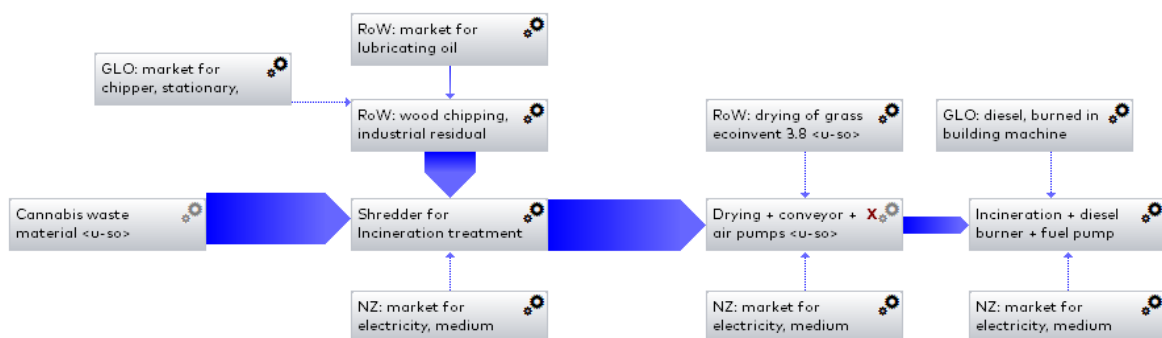


Figure 45: Incineration EoL treatment transport of ash to landfill (GaBi model)

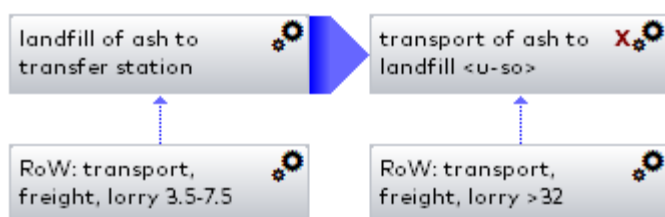
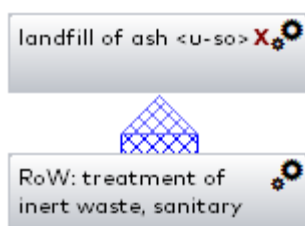


Figure 46: Incineration EoL treatment off-site activities (GaBi model)



Appendix F.5: Pyrolysis EoL treatment

To model this scenario, several dataset decisions were made:

- Shredding on-site
 - An industrial chipper dataset was used to represent the shredding of the cannabis plant material before thermal processing.
- Thermal activities on-site
 - Unfortunately, the ecoinvent database does not have a pyrolysis burner dataset therefore, only the ‘drying of grass’ and ‘diesel, burned in building machine’ datasets were used to represent the drying and diesel burner processes, respectively.
- Synthetic fertiliser production
 - As there was no dataset in ecoinvent for phosphorus or potassium fertiliser, the datasets ‘nutrient supply from phosphorus rock, beneficiated’ and ‘potassium chloride production’ were used as these represented the main production methods for these fertilisers. The ‘nutrient supply from phosphate rock’ dataset assumed that 1 kg of phosphate rock produces 0.32 kg of inorganic P fertiliser; this was in line with *Potassium chloride* (n.d.), stating 38% P availability. Therefore, this dataset was suitable. However, KCl production does not consider the usable K. Therefore, it was assumed that 50% K was available.

Figure 47: Pyrolysis EoL treatment transport of mobile unit to cultivation site (GaBi model)

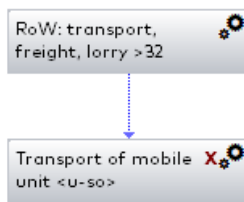


Figure 48: Pyrolysis EoL treatment on-site activities (GaBi model)

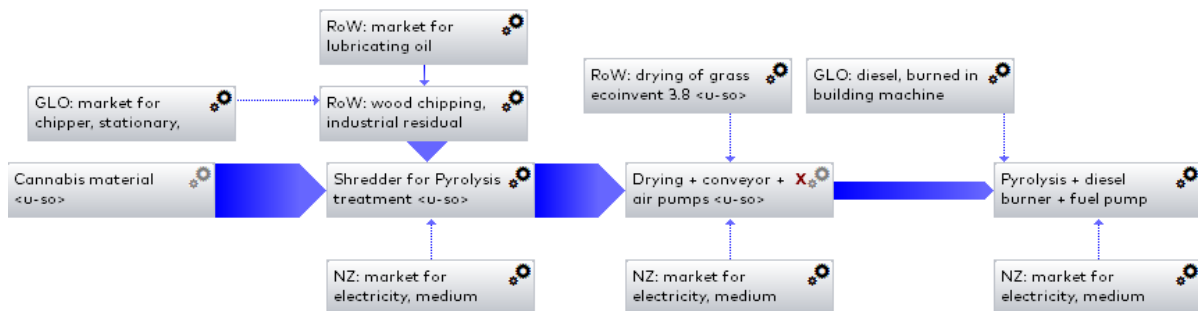


Figure 49: Pyrolysis EoL treatment transport of biochar to land (GaBi model)

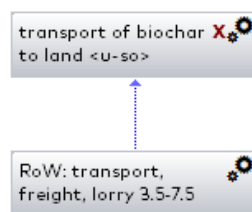


Figure 50: Pyrolysis EoL treatment land spreading of biochar (GaBi model)

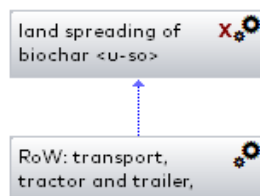
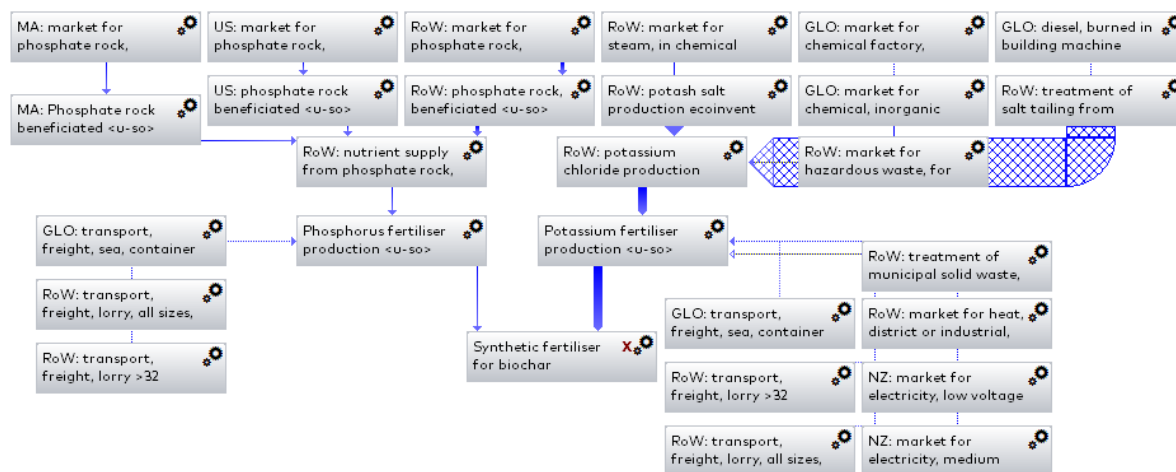


Figure 51: Pyrolysis EoL treatment displaced synthetic fertiliser production of nutrients equivalent to biochar (GaBi model)



Appendix G: Synthetic fertiliser production calculations

Appendix G.1: Landfill EoL treatment

In the landfill EoL treatment, one tonne of green waste per functional unit was required. A mass loss of 19.4% was considered for this study (Breitenbeck & Schellinger, 2004). Therefore, only 806 kg of green waste compost would be produced per functional unit.

$$1000 \text{ kg green waste} - (1000 * 19.4\% \text{ mass loss}) = 806 \text{ kg green waste}$$

Compost had an assumed moisture content of 60% meaning that 322.4 kg of dry green waste composting would go into the soil. A nitrogen content of 1% dry mass was assumed based on data from Biala and Wynen (1998), therefore, 3.224 kg N per functional unit was required.

$$806 \text{ kg green waste} - (806 * 60\% \text{ moisture content}) = 322.4 \text{ kg dry green waste}$$

$$322.4 \text{ kg dry green waste} * 1\% \text{ N} = 3.224 \text{ kg N per FU}$$

Using an NPK (26-15-15) fertiliser there is 0.26 kg N per kg, and to make up to 3.224 kg N required, 12.4 kg of fertiliser was required per functional unit.

$$\frac{3.224 \frac{\text{kg N required}}{\text{functional unit}}}{0.26 \frac{\text{kg N}}{\text{kg NPK}(26 - 15 - 15) \text{ fertiliser}}} = 12.4 \frac{\text{kg NPK}(26 - 15 - 15) \text{ fertiliser}}{\text{functional unit}}$$

Appendix G.2: Composting EoL treatment

In the composting EoL treatment, one tonne of fresh cannabis material at 71% moisture content means that 290 kg of dry cannabis waste was produced.

$$1000 \frac{\text{kg wet plant material}}{\text{FU}} - (1000 * 71\%) = 290 \frac{\text{kg dry plant material}}{\text{FU}}$$

The nitrogen content was assumed to remain in the cannabis waste through composting. Therefore, with an assumed nitrogen composition of 3.64% dry basis (db.) (Harper et al., 1934), 10.556 kg of N per FU was required.

$$290 \frac{\text{kg dry plant material}}{\text{FU}} * 3.64\% \text{ N db.} = 10.556 \frac{\text{kg N}}{\text{FU}}$$

With an NPK (26-15-15) fertiliser, per kg there is 0.26 kg N. Therefore, to make up to 10.556 kg of N required to balance, 40.6 kg of fertiliser was required per functional unit.

$$\frac{10.556 \frac{kg\ N}{FU}}{0.26 \frac{kg\ N}{kg\ fertiliser}} = 40.6 \frac{kg\ fertiliser}{FU}$$

Appendix G.3: Anaerobic digestion EoL treatment

In the anaerobic digestion EoL treatment, 375.6 kg of digestate solids are produced at 80% moisture content after the belt filter press. Therefore, there will be 75.12 kg dry digestate solids present per functional unit.

$$375.6 \frac{kg\ digestate\ solids}{FU} - (375.6 * 80\%) = 75.12 \frac{kg\ dry\ digestate\ solids}{FU}$$

The nitrogen content was assumed to be 0.325% N db., 0.085% P db., and 0.325% K db. (NNFCC, n.d.). Therefore, 0.24414 kg N is present in the digestate solids per functional unit.

$$75.12 \frac{kg\ dry\ digestate\ solids}{FU} * 0.325\% N\ db. = 0.24414 \frac{kg\ N\ in\ digestate\ solids}{FU}$$

With an NPK (26-15-15) fertiliser, per kg there is 0.26 kg N. Therefore, to make up to 0.24414 kg of N required to balance, 0.939 kg of fertiliser was required per functional unit.

$$\frac{0.24414 \frac{kg\ N\ in\ digestate\ solids}{FU}}{0.26 \frac{kg\ N}{kg\ fertiliser}} = 0.939 \frac{kg\ fertiliser}{FU}$$

Appendix G.4: Pyrolysis EoL treatment

To keep this assessment in line with the functional unit, 101.5 kg of biochar per functional unit was produced. It was assumed that 1% of the biochar was lost during transport, as this was also assumed for the long-term carbon storage of the biochar on the land.

$$101.5kg * 1\% = 1.015\ kg$$

$$101.5 - 1.015 = 100.485 \frac{kg\ of\ biochar\ to\ land}{FU}$$

Assuming the biochar has a moisture content of 5%, this gives

$$100.485kg - (100.485 * 5\%) = 95.46\ kg\ of\ dry\ biochar\ to\ land\ per\ functional\ unit$$

Phosphorus (P)
0.1% – 0.8% db.

Average = 0.45% db.

Leaving 0.43 kg P required

$$95.46 \frac{\text{kg dry biochar to land}}{FU} * 0.45\% P \text{ db.} = 0.43 \frac{\text{kg P required}}{FU}$$

Potassium (K)

1.08% – 6.20% db.

Average = 3.64% db.

Leaving 3.47 kg K required

$$95.46 \frac{\text{kg dry biochar to land}}{FU} * 3.64\% K \text{ db.} = 3.47 \frac{\text{kg K required}}{FU}$$

Since KCl was used to model the K fertiliser the amount of K available per kg of KCl needed to be considered. Approximately, 50% K was available in KCl (*Potassium chloride.*, n.d.). Therefore, 0.5 kg K per kg KCl was available and since we needed 3.47 kg K, 6.94 kg of KCl was required to match the nutrients. The ‘potassium chloride production’ dataset accounted for this difference.

Appendix H: Conditions for biochar to be a net carbon sink

Conditions to be met if the biochar addition to the soil is to be a net carbon sink compiled by Ernsting and Smolker (2009) and Bruges (2010) (as cited in Lal, 2016):

- The carbon in the biochar must remain in the soil long term, it must be ensured that it won't release back into the atmosphere.
- The biochar application into soil must not interfere with the existing humus or its growth in the soil.
- A life cycle assessment (LCA) must be completed to confirm that the net soil-ecosystem carbon pools have been increased.
- The biochar must improve the soil quality and the net primary productivity (NPP) of the soil.

Appendix I: Suppression of N₂O calculations

The average N₂O field emissions per ha per year is 102 kg CO₂-eq (Roberts et al., 2010). Roberts et al. (2010) also assumed that 8.8 tonnes of biochar are required for 50% N₂O suppression. Therefore, for this study, approximately 100 kg of biochar would be produced per year, if this was applied per year to one hectare approximately 1.1 kg CO₂-eq of N₂O field emissions would be suppressed each year.

$$\text{Ratio of biochar to obtain 50\% N}_2\text{O suppression} = \frac{100\text{kg}}{8.8 \text{ tonnes}} * 100 = 1.13\%$$

$$\text{Therefore, } 1.13\% \text{ of } 102\text{kg CO}_{2\text{-eq}} = 1.1 \text{ kg CO}_{2\text{-eq}}$$

Appendix J: Pyrolysis experiment temperature profiles

Figure 52: Pyrolysis unit hemp trial 1 using leaf cannabis material

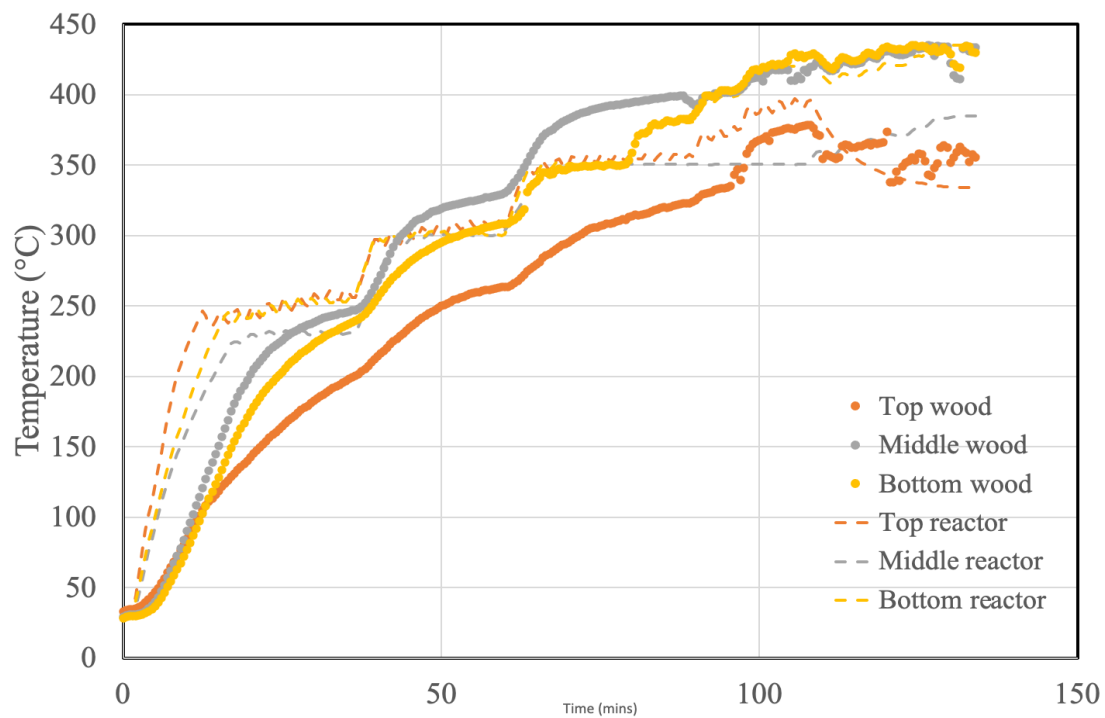


Figure 53: Pyrolysis unit hemp trial 2 using root cannabis material

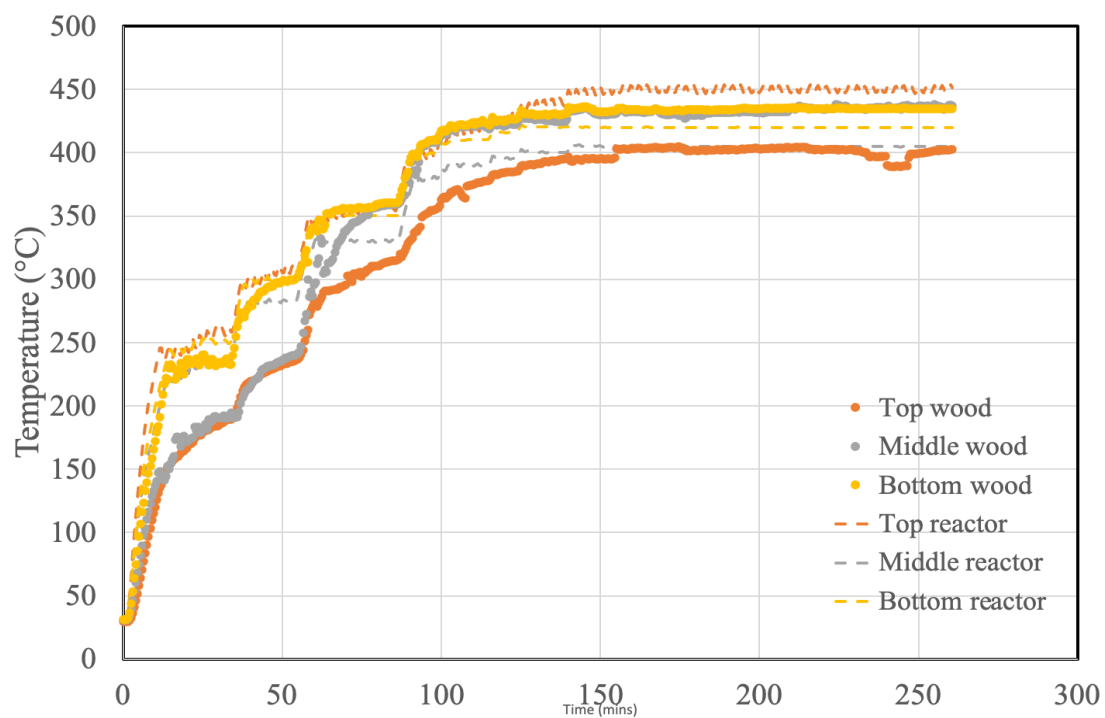


Figure 54: Pyrolysis unit hemp trial 3 using mixture of leaf, root, and stem cannabis material

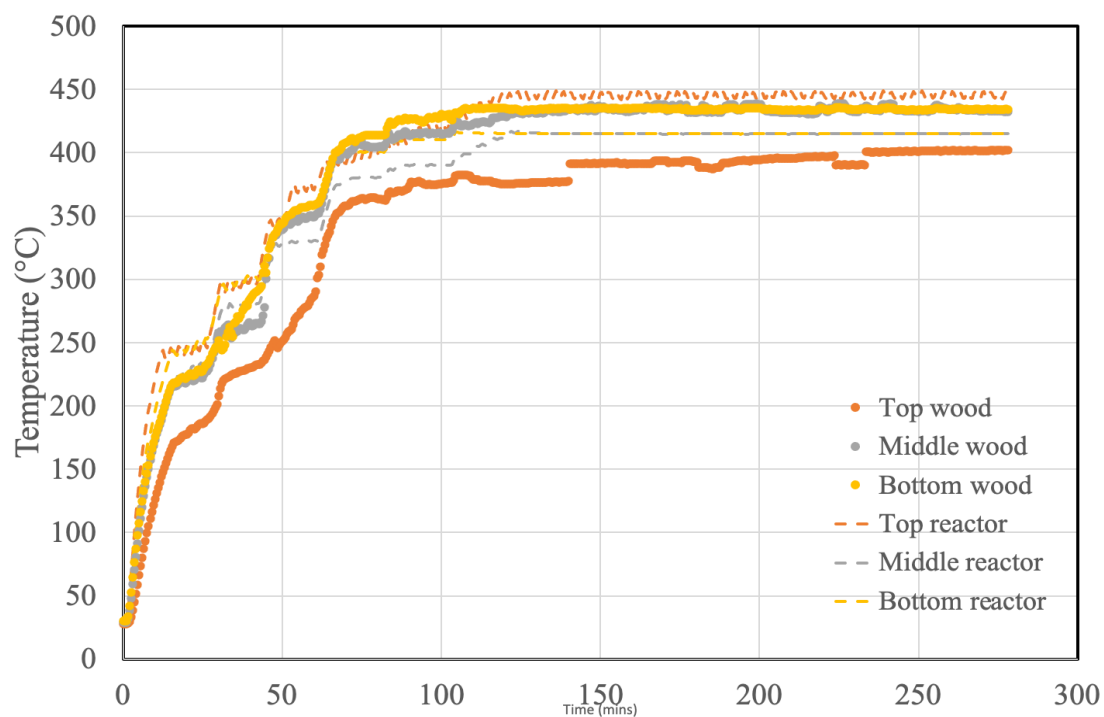


Figure 55: Pyrolysis unit medicinal cannabis trial 1 using leaf cannabis material

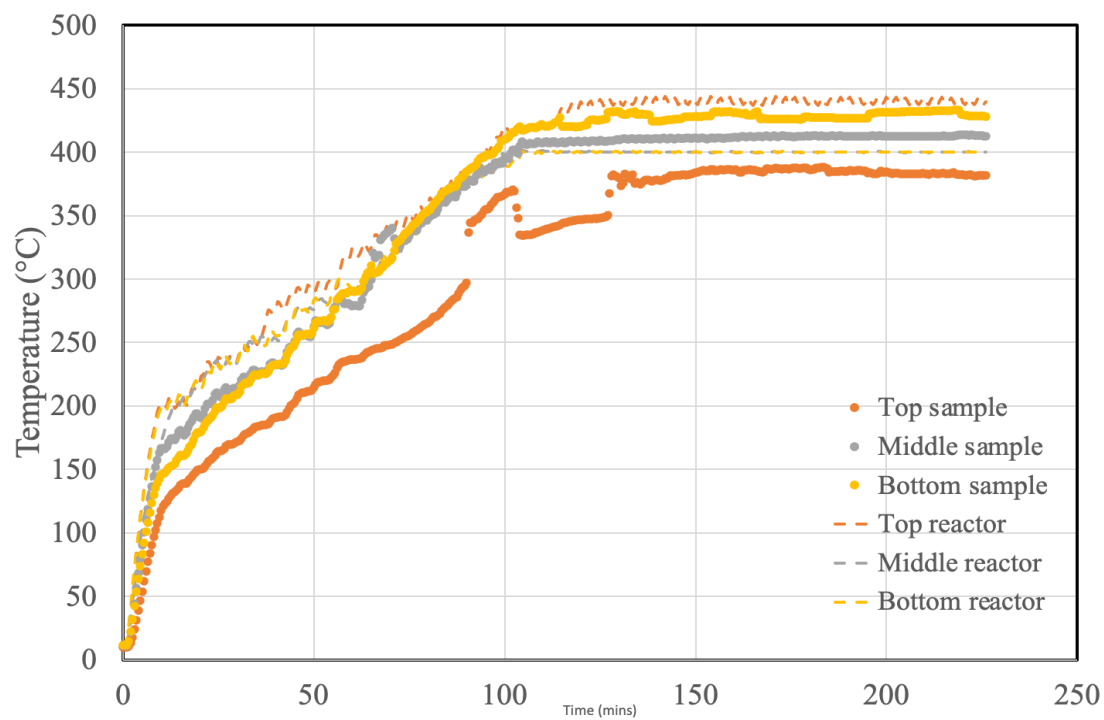


Figure 56: Pyrolysis unit medicinal cannabis trial 2 using stalk cannabis material

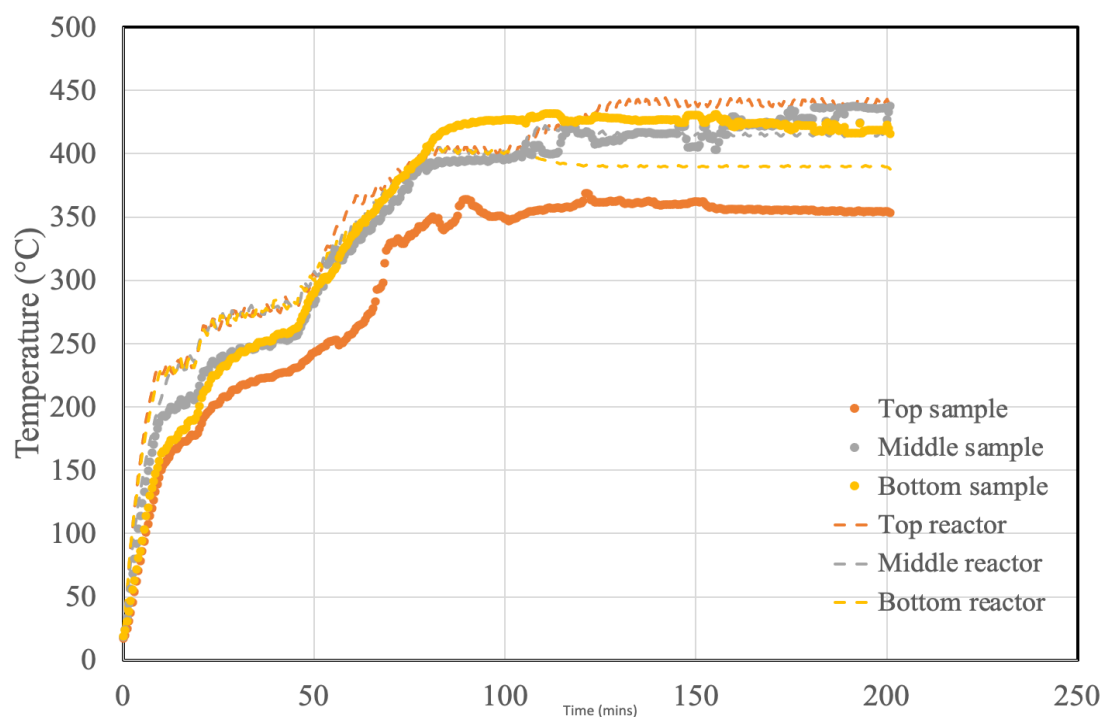
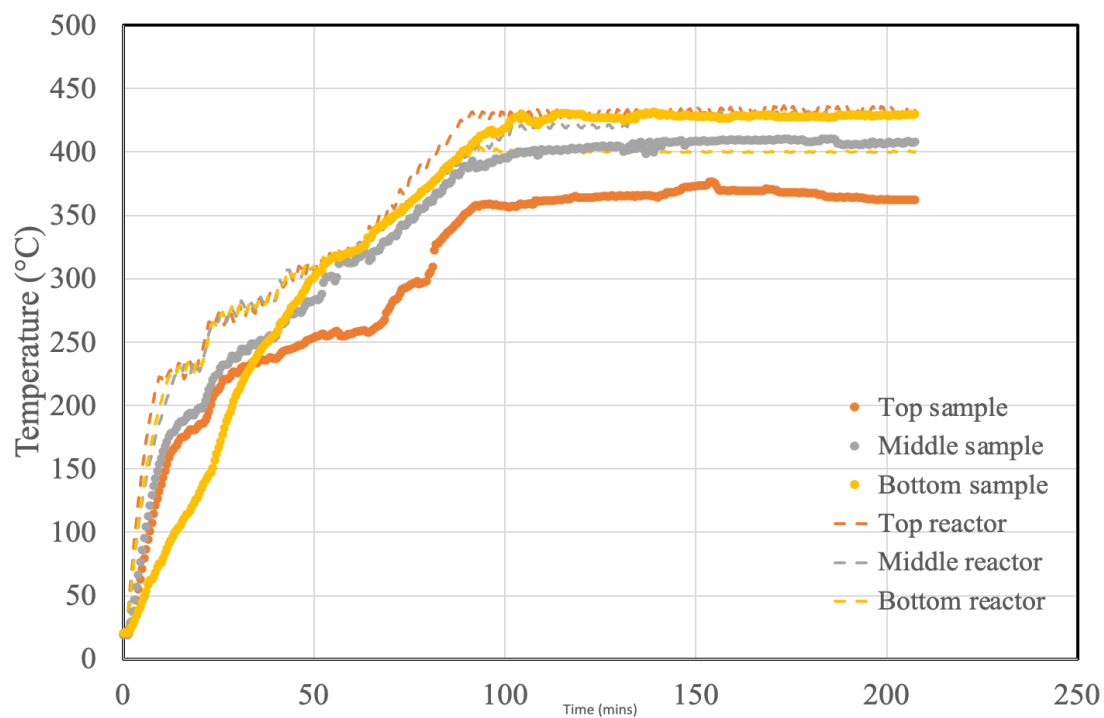


Figure 57: Pyrolysis unit medicinal cannabis trial 3 using mixture of leaf, root, and stalk cannabis material



Appendix K: Py-GCMS results

Figure 58: Biochar of leaf hemp pyrolysis trial, Py-GCMS analysis

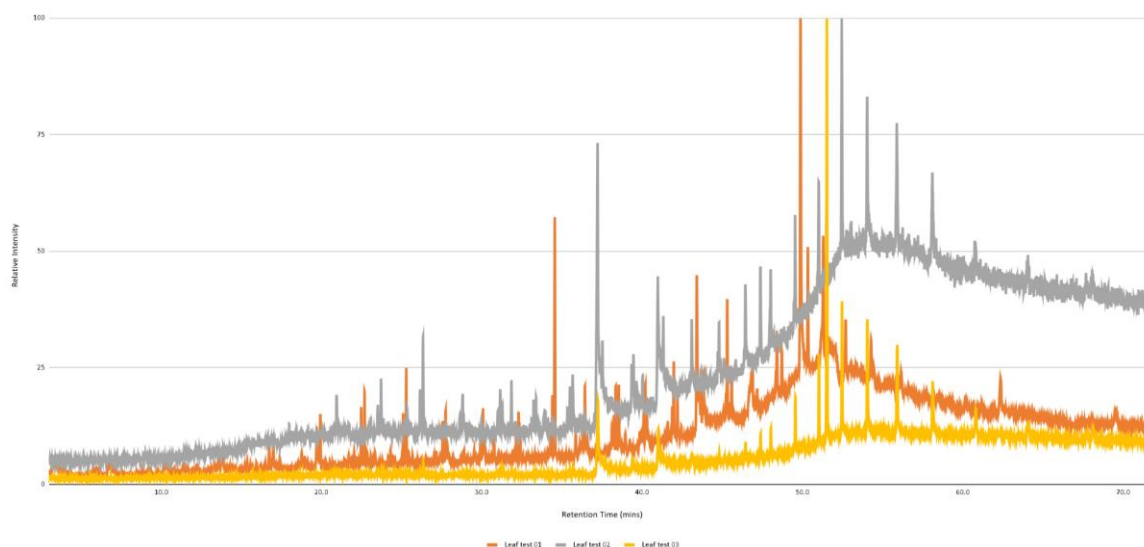


Figure 59: Biochar of root hemp pyrolysis trial, Py-GCMS analysis

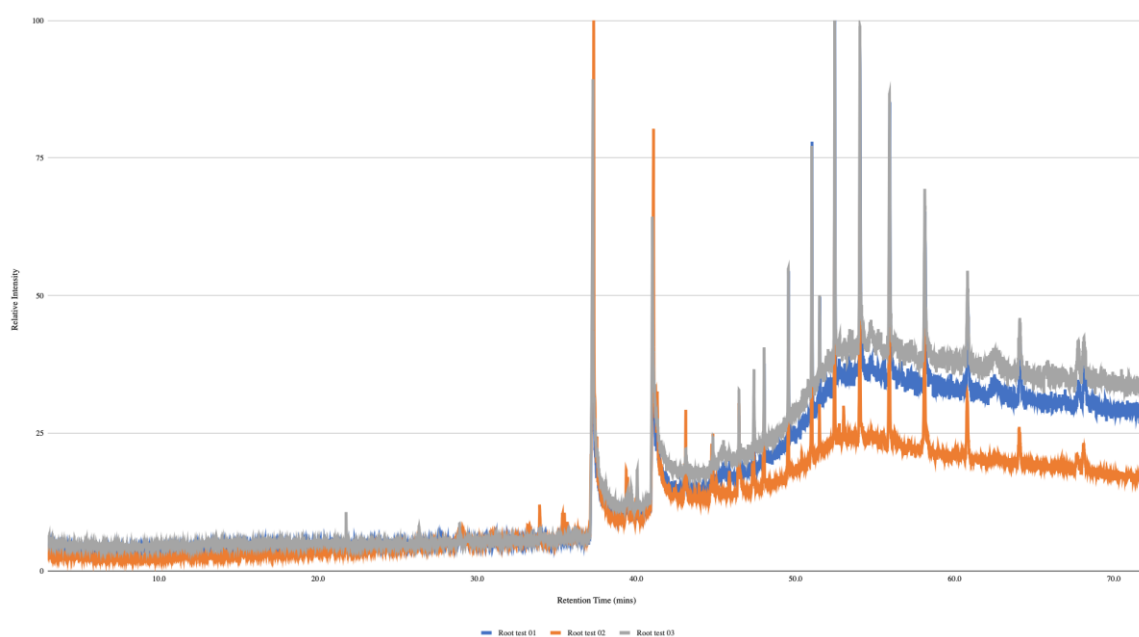


Figure 60: Biochar of stalk hemp pyrolysis trial, Py-GCMS analysis

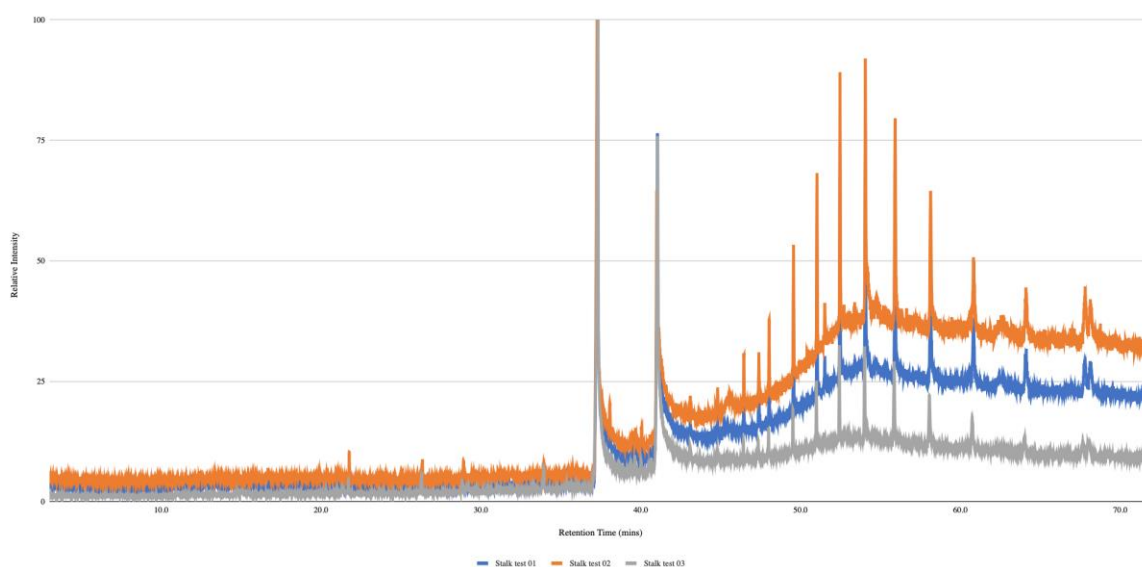


Figure 61: Biochar of mixed hemp pyrolysis trial, Py-GCMS analysis

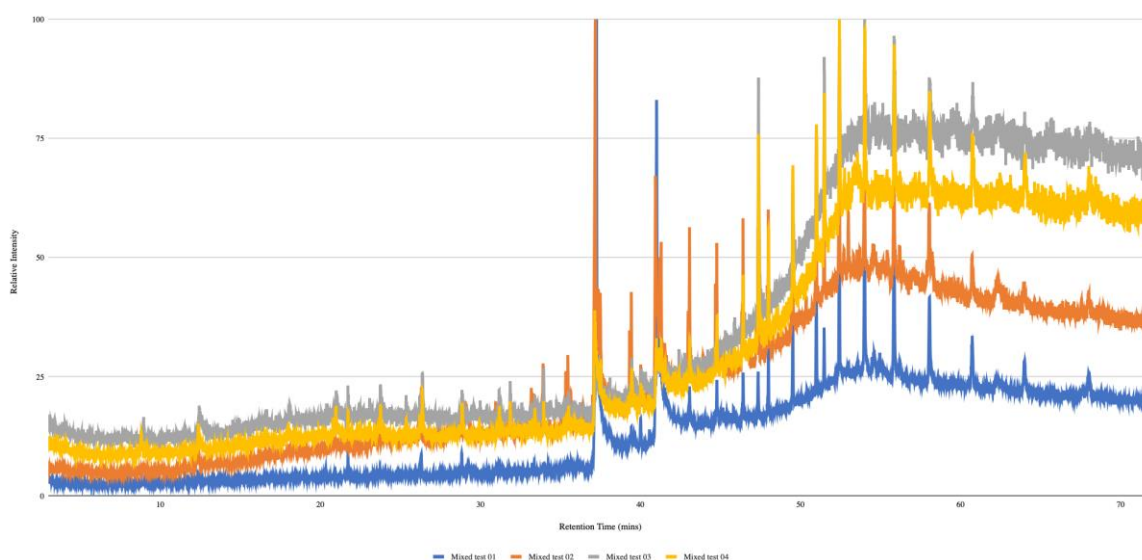


Table 27: Compounds identified in the char samples of hemp pyrolysis trials of the leaf (orange), root (yellow), mix (blue), and stalk (green), from Py-GCMS analysis

Name	Molecular Weight	Molecular Formula	Retention Time (min)
Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.23
Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.26
Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.26
Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.27
Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.005
Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.035

Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.035
Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.045
2,3-Dimethyldodecane	198	C ₁₄ H ₃₀	46.41
Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	46.41
Tetradecane	198	C ₁₄ H ₃₀	46.41
Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.425
Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.445
Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.47
Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.35
Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.355
Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.38
Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.41
7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.015
Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.015
7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.025
Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.025
7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.045
7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.045
Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.045
Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.045
2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.53
2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.545
2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.545
2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.58
2-methyloctacosane	408	C ₂₉ H ₆₀	50.98
Docosane, 11-butyl-	366	C ₂₆ H ₅₄	50.98
Heptadecane	240	C ₁₇ H ₃₆	50.98
Tetratetracontane	618	C ₄₄ H ₉₀	50.98
2-methyloctacosane	408	C ₂₉ H ₆₀	50.99
2-methyloctacosane	408	C ₂₉ H ₆₀	51
2-methyloctacosane	408	C ₂₉ H ₆₀	51.015
9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1- [[[(trimethylsilyl)oxy]methyl]ethyl ester, (Z,Z,Z)-	496	C ₂₇ H ₅₂ O ₄ Si ₂	51.495
2-methyloctacosane	408	C ₂₉ H ₆₀	51.51
Squalene	410	C ₃₀ H ₅₀	51.515
Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.44
Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.46
Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.46
Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.47
2-methyloctacosane	408	C ₂₉ H ₆₀	54

Table 28: Outliers found in the comparison of char Py-GCMS analysis compounds identified for hemp

Outliers	Present	Retention time (mins)
2,3-Dimethyldodecane	only in mix	46.41
Heptadecane, 2,6,10,15-tetramethyl-	only in mix	46.41
Tetradecane	only in mix	46.41
Sulfurous acid, pentadecyl 2-propyl ester	only in root, leaf, stalk	46.42 to 46.47

Docosane, 11-butyl-	only in mix	50.98
Heptadecane	only in mix	50.98
Tetratetracontane	only in mix	50.98
9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[[(trimethylsilyl)oxy)methyl]ethyl ester, (Z,Z,Z)-	only in stalk	51.495
2-methyloctacosane	only in mix	51.51
Squalene	only in leaf	51.515
Heptadecane, 2,6,10,15-tetramethyl-	only in stalk	60.725
Hexacosane, 9-octyl-	only in leaf, root, mix	60.7 to 60.81
Nonadecane, 2-methyl-	only in leaf, root, mix	60.7 to 60.81

Figure 62: Condensate of leaf hemp pyrolysis trial, Py-GCMS analysis

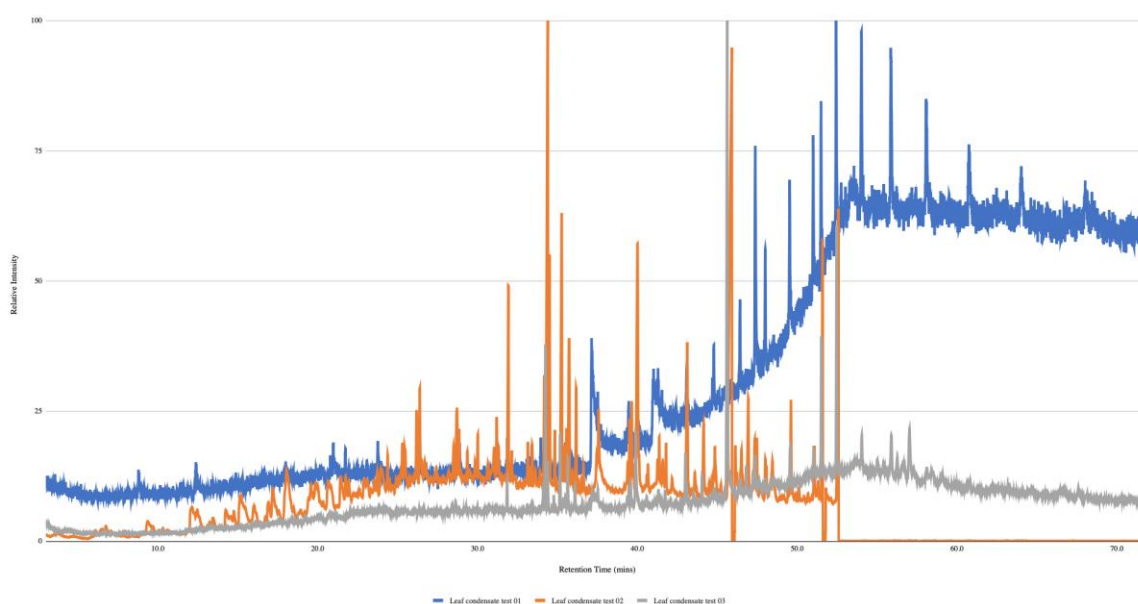


Figure 63: Condensate from the root hemp pyrolysis trial, Py-GCMS analysis

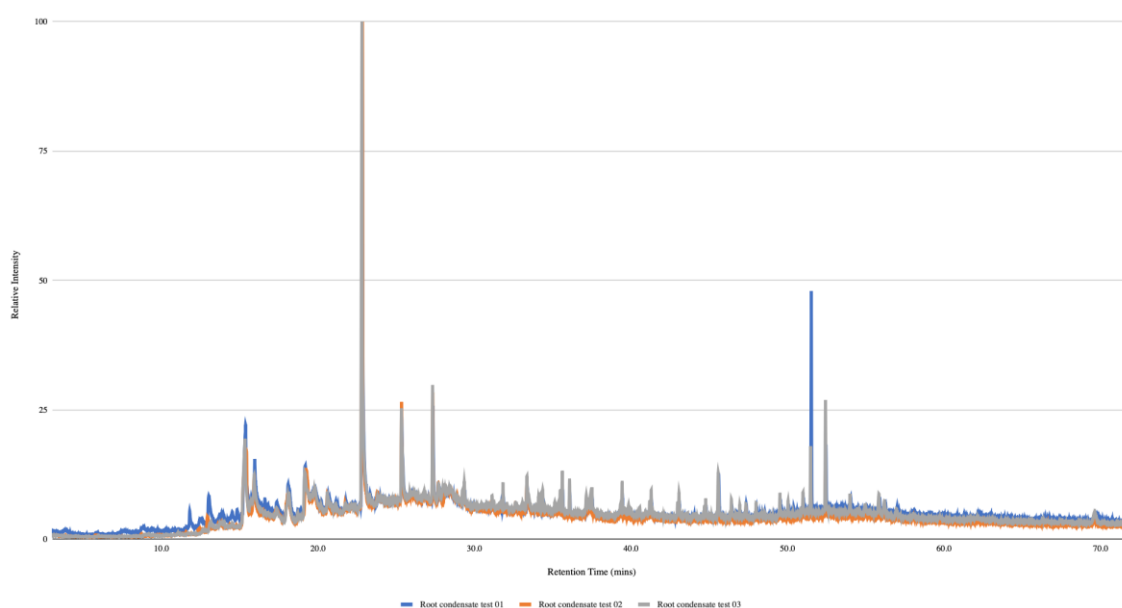


Figure 64: Condensate from the mix hemp pyrolysis trial, Py-GCMS analysis

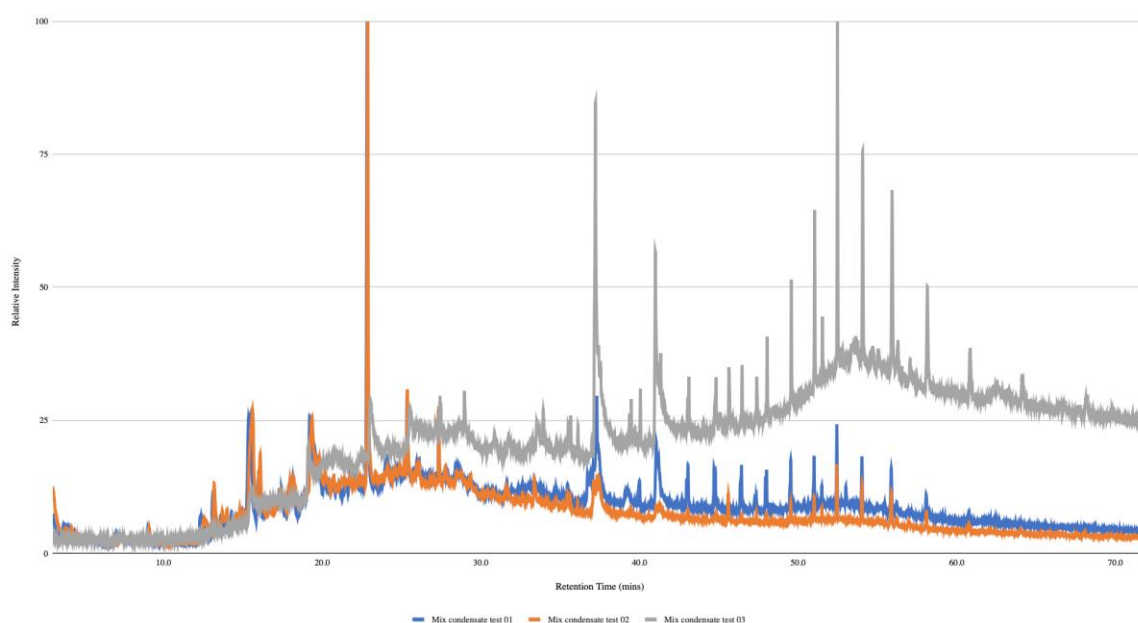


Table 29: Compounds identified in the condensate samples from the hemp pyrolysis trials of leaf (orange), root (yellow), and mix (blue), Py-GCMS analysis

Name	Molecular Weight	Molecular Formula	Retention Time (mins)
Phenol	94	C ₆ H ₆ O	11.94
Diazene, bis(1,1-dimethylethyl)-	142	C ₈ H ₁₈ N ₂	15
Trimethylaluminum	72	C ₃ H ₉ Al	15
Diazene, bis(1,1-dimethylethyl)-	142	C ₈ H ₁₈ N ₂	15.395
Trimethylaluminum	72	C ₃ H ₉ Al	15.395
Phenol, 3-methoxy-2-methyl-	138	C ₈ H ₁₀ O ₂	18
Phenol, 3-methoxy-2-methyl-	138	C ₈ H ₁₀ O ₂	18.03
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	144	C ₆ H ₈ O ₄	19.25
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	144	C ₆ H ₈ O ₄	19.25
Cyclopropane, trimethyl(2-methyl-1-propenylidene)-	136	C ₁₀ H ₁₆	20.705
Methanol, [6,8,9-trimethyl-4-(1-propenyl)-3-oxabicyclo[3.3.1]non-6-en-1-yl]-	236	C ₁₅ H ₂₄ O ₂	20.705
5H-1-Pyridine	117	C ₈ H ₇ N	21.395
4-(6-Oxabicyclo[3.1.0]hex-1-yl)-but-3-yn-2-one	150	C ₉ H ₁₀ O ₂	21.75
Phenol, 3,4-dimethoxy-	154	C ₈ H ₁₀ O ₃	22.835
Phenol, 3,4-dimethoxy-	154	C ₈ H ₁₀ O ₃	23
11,11-Dimethyl-spiro[2,9]dodeca-3,7-dien	190	C ₁₄ H ₂₂	24.36
1,2,3-Trimethoxybenzene	168	C ₉ H ₁₂ O ₃	25.34
1,2,3-Trimethoxybenzene	168	C ₉ H ₁₂ O ₃	25.5
5-Octadecene, (E)-	252	C ₁₈ H ₃₆	26.16
8-Heptadecene, 1-chloro-	272	C ₁₇ H ₃₃ Cl	26.16
Pentadecane	212	C ₁₅ H ₃₂	26.36
Phenol, 2,6-dimethyl-4-nitro-	167	C ₈ H ₉ NO ₃	27.325

Phenol, 2,6-dimethyl-4-nitro-	167	C ₈ H ₉ NO ₃	27.5
2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	336	C ₂₂ H ₄₀ O ₂	28.665
2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	336	C ₂₂ H ₄₀ O ₂	29
Heptadecane	240	C ₁₇ H ₃₆	31
Heptadecane	240	C ₁₇ H ₃₆	31.175
2-Hexadecene, 2,6,10,14-tetramethyl-	280	C ₂₀ H ₄₀	31.895
2-Hexadecene, 2,6,10,14-tetramethyl-	280	C ₂₀ H ₄₀	32
No known compound			33.345
No known compound			33.5
2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	280	C ₂₀ H ₄₀	34.155
Phytol, acetate	338	C ₂₂ H ₄₂ O ₂	34.345
2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	280	C ₂₀ H ₄₀	34.455
13-Heptadecyn-1-ol	252	C ₁₇ H ₃₂ O	35.225
E-6-Octadecen-1-ol acetate	310	C ₂₀ H ₃₈ O ₂	35.225
2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.5
2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.6
2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.685
Pentadecanoic acid, 14-methyl-, methyl ester	270	C ₁₇ H ₃₄ O ₂	36
Pentadecanoic acid, 14-methyl-, methyl ester	270	C ₁₇ H ₃₄ O ₂	36.135
4-Fluoro-1-methyl-5-carboxylic acid, ethyl(ester)	172	C ₇ H ₉ FN ₂ O ₂	37.26
Heptadecanoic acid, heptadecyl ester	508	C ₃₄ H ₆₈ O ₂	37.26
Pentadecanoic acid	242	C ₁₅ H ₃₀ O ₂	37.4
2-methyltetracosane	352	C ₂₅ H ₅₂	39.48
1-Tetradecen-3-yne	192	C ₁₄ H ₂₄	39.5
2-methyltetracosane	352	C ₂₅ H ₅₂	39.5
9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	292	C ₁₉ H ₃₂ O ₂	39.5
1-Tetradecen-3-yne	192	C ₁₄ H ₂₄	39.62
9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	292	C ₁₉ H ₃₂ O ₂	39.62
Phytol	296	C ₂₀ H ₄₀ O	39.955
Phytol	296	C ₂₀ H ₄₀ O	40
Octadecanoic acid	284	C ₁₈ H ₃₆ O ₂	41
3-Methyl-4-(phenylthio)-2-prop-2-enyl-2,5-dihydrothiophene 1,1-dioxide	280	C ₁₄ H ₁₆ O ₂ S ₂	41.227
Ethyl iso-allocholate	436	C ₂₆ H ₄₄ O ₅	41.227
Cannabicyclol (CBL)	314	C ₂₁ H ₃₀ O ₂	43
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	43
Cannabicyclol (CBL)	314	C ₂₁ H ₃₀ O ₂	43.07
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	43.07
Cannabichromene (CBC)	314	C ₂₁ H ₃₀ O ₂	44.11
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.5
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.575
Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.895
1-Octadecanesulphonyl chloride	352	C ₁₈ H ₃₇ ClO ₂	46.415
1-Chloroeicosane	316	C ₂₀ H ₄₁ Cl	46.482
Morphinone, 7,8-dihydro-3-desoxy-	269	C ₁₇ H ₁₉ NO ₂	46.5
Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.5
Morphinone, 7,8-dihydro-3-desoxy-	269	C ₁₇ H ₁₉ NO ₂	46.885
Dronabinol (Δ9-Tetrahydrocannabinol, Δ9-THC)	314	C ₂₁ H ₃₀ O ₂	47.295
Bis(tridecyl) phthalate	530	C ₃₄ H ₅₈ O ₄	47.43

9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl)oxy)methyl]ethyl ester, (Z,Z,Z)-	496	27H ₅₂ O ₄ Si ₂	47.5
Dronabinol	314	C ₂₁ H ₃₀ O ₂	47.5
2-methyltetracosane	352	C ₂₅ H ₅₂	48
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	48
1-Chloroeicosane	316	C ₂₀ H ₄₁ Cl	48.025
2-methylhexacosane	380	C ₂₇ H ₅₆	48.025
Cannabinol (CBN)	310	C ₂₁ H ₂₆ O ₂	48.405
Cannabinol (CBN)	310	C ₂₁ H ₂₆ O ₂	48.5
Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	49.5
Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.5
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	49.5
2-methyltetracosane	352	C ₂₅ H ₅₂	49.511
Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.511
Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	49.58
Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.58
Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₈ O ₂	51
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	51
2-methyltetracosane	352	C ₂₅ H ₅₂	51.015
2,2-Dimethyl-6-methylene-1-[3,5-dihydroxy-1-pentenyl]cyclohexanol	256	C ₁₄ H ₂₄ O ₄	51.47
Ethyl iso-allocholate	436	C ₂₆ H ₄₄ O ₅	51.47
Squalene	410	C ₃₀ H ₅₀	51.5
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	51.505
Squalene	410	C ₃₀ H ₅₀	51.57
2-methyltetracosane	352	C ₂₅ H ₅₂	52.415
Tritetracontane	604	C ₄₃ H ₈₈	52.415
2-methyltetracosane	352	C ₂₅ H ₅₂	52.5
Tetratetracontane	618	C ₄₄ H ₉₀	52.5
Tetratetracontane	618	C ₄₄ H ₉₀	52.55
2-methylhexacosane	380	C ₂₇ H ₅₆	54
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	54
2-methyltetracosane	352	C ₂₅ H ₅₂	54.082
Tritetracontane	604	C ₄₃ H ₈₈	54.082
Tetratetracontane	618	C ₄₄ H ₉₀	55.945
Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	56
Tetratetracontane	618	C ₄₄ H ₉₀	56
dl- α -Tocopherol	430	C ₂₉ H ₅₀ O ₂	57.15
Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	58
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	58
Heptadecanoic acid, heptadecyl ester	508	C ₃₄ H ₆₈ O ₂	58.575
Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	61
No known compound			64
9,19-Cycloergost-24(28)-en-3-ol, 4,14-dimethyl-, (3 β ,4 α ,5 α .)-	426	C ₃₀ H ₅₀ O	67.7
No known compound			68
No known compound			68

Table 30: Outliers found in the comparison of condensate Py-GCMS analysis compounds identified for hemp

Outliers	Present	Retention time (mins)
Phenol	only in leaf	11.94
Diazene, bis(1,1-dimethylethyl)-	only in root and mixed	15 to 15.4
Trimethylaluminum	only in root and mixed	15 to 15.4
Phenol, 3-methoxy-2-methyl	only in leaf and mixed	18
1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	only in root and mixed	19.25
Cyclopropane, trimethyl(2-methyl-1-propenylidene)-	only in leaf	20.705
Methanol, [6,8,9-trimethyl-4-(1-propenyl)-3-oxabicyclo[3.3.1]non-6-en-1-yl]-	only in leaf	20.705
5H-1-Pyridine	only in leaf	21.395
4-(6-Oxabicyclo[3.1.0]hex-1-yl)-but-3-yn-2-one	only in leaf	21.75
Phenol, 3,4-dimethoxy-	only in root and mixed	22.8 to 23
11,11-Dimethyl-spiro[2,9]dodeca-3,7-dien	only in leaf	24.4
1,2,3-Trimethoxybenzene	only in root and mixed	25.3 to 25.5
5-Octadecene, (E)-	only in leaf	26.16
8-Heptadecene, 1-chloro-	only in leaf	26.16
Pentadecane	only in leaf	26.36
Phenol, 2,6-dimethyl-4-nitro-	only in root and mixed	27.325 to 27.5
2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	only in leaf and mixed	28.665 to 29
Heptadecane	only in leaf and mixed	31 to 31.175
2-Hexadecene, 2,6,10,14-tetramethyl-	only in leaf and mixed	31.895 to 32
2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	only in leaf	34.155
Phytol, acetate	only in leaf	34.345
2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	only in leaf	34.455
13-Heptadecyn-1-ol	only in leaf	35.225
E-6-Octadecen-1-ol acetate	only in leaf	35.225
Pentadecanoic acid, 14-methyl-, methyl ester	only in leaf and mixed	36 to 36.135
4-Fluoro-1-methyl-5-carboxylic acid, ethyl(ester)	only in leaf	37.26
Heptadecanoic acid, heptadecyl ester	only in leaf	37.26
Pentadecanoic acid	only in mix	37.4
2-methyltetracosane	only in leaf and mixed	39.48 to 39.5
1-Tetradecen-3-yne	only in leaf and mixed	39.5 to 39.62
9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	only in leaf and mixed	39.5 to 39.62
Phytol	only in leaf and mixed	39.9 to 40
Octadecanoic acid	only in mix	41
3-Methyl-4-(phenylthio)-2-prop-2-enyl-2,5-dihydrothiophene 1,1-dioxide	only in leaf	41.227
Ethyl iso-allocholate	only in leaf	41.227
1H-4-Oxabenzo(f)cyclobut(cd)inden-8-ol, 1a-.alpha.,2,3,3a,8b-.alpha.,8c-.alpha.-hexahydro-1,1,3a-trimethyl-6-pentyl- (Cannabicyclol)	only in leaf and mixed	43 to 43.07
Cannabidiol (CBD)	only in leaf and mixed	43 to 43.07
Cannabichromene	only in leaf	44.11
Cannabidiol (CBD)	only in mix	45
1-Octadecanesulphonyl chloride	only in root	46.415
1-Chloroeicosane	only in leaf	46.482

Morphinone, 7,8-dihydro-3-desoxy-	only in leaf and mixed	46.5 to 46.885
Sulfurous acid, pentadecyl 2-propyl ester	only in mix	46.5
Dronabinol (Δ^9 -Tetrahydrocannabinol, Δ^9 -THC)	only in leaf and mixed	47.295 to 47.5
Bis(tridecyl) phthalate	only in leaf	47.43
9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl)oxy)methyl]ethyl ester, (Z,Z,Z)-	only in mix	47.5
2-methyltetracosane	only in mix	48
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	48
1-Chloroeicosane	only in leaf	48.025
2-methylhexacosane	only in leaf	48.025
Cannabinol (CBN)	only in leaf and mixed	48.025 to 48.5
Heptadecane, 2,6,10,15-tetramethyl-	only in leaf and mixed	49.5 to 49.58
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	49.5
2-methyltetracosane	only in root	49.511
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	51
2-methyltetracosane	only in leaf	51.015
2,2-Dimethyl-6-methylene-1-[3,5-dihydroxy-1-pentenyl]cyclohexanol	only in root	51.47
Ethyl iso-allocholate	only in root	51.47
Squalene	only in leaf and mixed	51.5 to 51.57
Sulfurous acid, 2-propyl tetradecyl ester	only in leaf	51.505
2-methyltetracosane	only in root and mixed	52.415 to 52.5
Tritetracontane	only in root	52.415
Tetratetracontane	only in leaf and mixed	52.5 to 52.55
2-methylhexacosane	only in mix	54
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	54
2-methyltetracosane	only in leaf	54.082
Tritetracontane	only in leaf	54.082
Tetratetracontane	only in leaf and mixed	55.945 to 56
Heptacosane, 1-chloro-	only in mix	56
dl- α -Tocopherol	only in leaf	57.15
Heptacosane, 1-chloro-	only in mix	58
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	58
Heptadecanoic acid, heptadecyl ester	only in leaf	58.575
Sulfurous acid, 2-propyl tetradecyl ester	only in mix	61
9,19-Cycloergost-24(28)-en-3-ol, 4,14-dimethyl-, (3 β ,4 α ,5 α .)-	only in leaf	67.7

Figure 65: Char from the leaf medicinal cannabis pyrolysis trial, Py-GCMS analysis

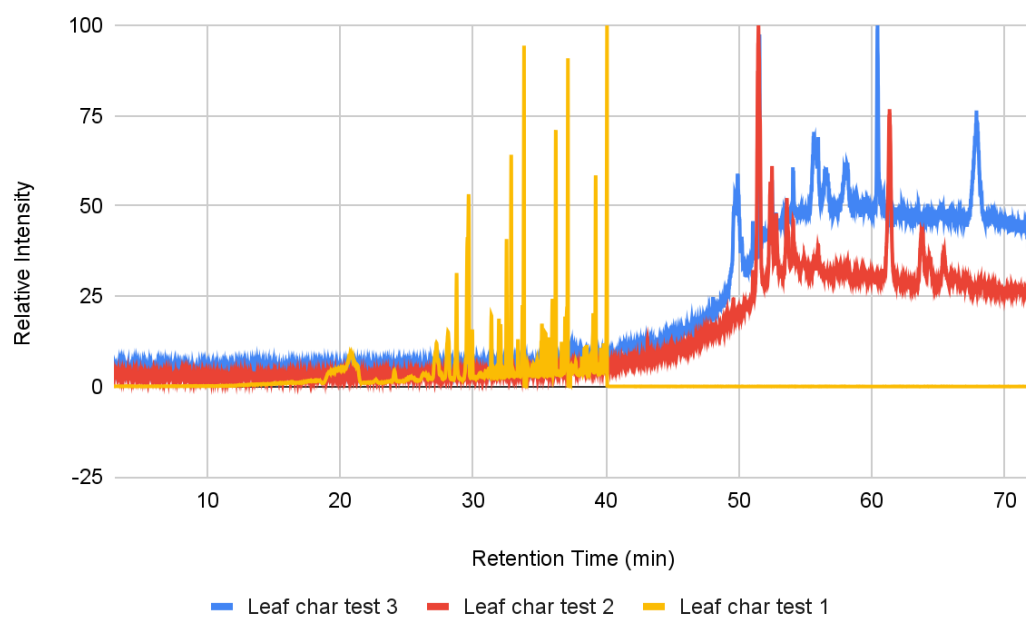


Figure 66: Char from the root medicinal cannabis pyrolysis trial, Py-GCMS analysis

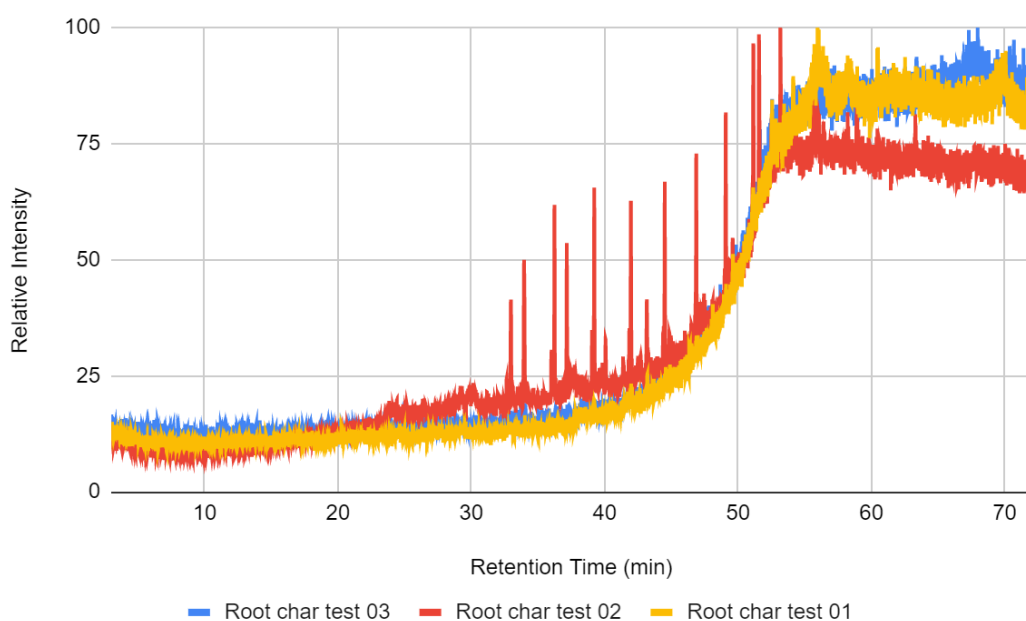


Figure 67: Char from the stalk medicinal cannabis pyrolysis trial, Py-GCMS analysis

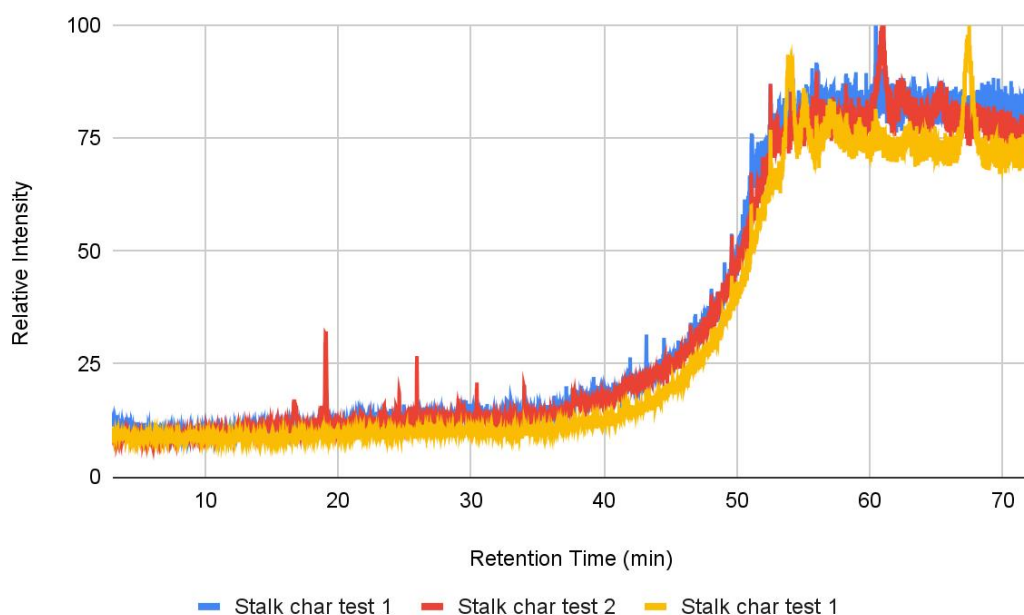


Table 31: Comparison of compounds identified in the char samples for hemp and medicinal cannabis pyrolysis trials of leaf (orange), root (yellow), and stalk (green), Py-GCMS results

HEMP or MC	Name	Molecular Weight	Molecular Formula	Retention Time (min)
BOTH	No known compound			16.787
MC	Cyclohexasiloxane, dodecamethyl-			19.213
BOTH	1,1,1,3,5,7,9,11,11,11-Decamethyl-5-(trimethylsiloxy)hexasiloxane			25.959
BOTH	No known compound			29.039
MC	No known compound			30.397
BOTH	No known compound			34.006
MC	No known compound			36.237
BOTH	Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.183
HEMP	Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.23
HEMP	Tridecanoic acid	214	C ₁₃ H ₂₆ O ₂	37.27
MC	No known compound			39.227
MC	No known compound			40.096
HEMP	Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.035
MC	Octadecanoic acid, 2-(2-hydroxyethoxy)ethyl ester	372	C ₂₂ H ₄₄ O ₄	41.045
MC	No known compound			41.987
MC	No known compound			43.167

MC	No known compound			43.188
MC	No known compound			44.517
HEMP	Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.425
BOTH	Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.825
BOTH	Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.868
HEMP	Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.355
HEMP	Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.38
HEMP	Diisooctyl phthalate	390	C ₂₄ H ₃₈ O ₄	47.41
HEMP	7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.015
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.015
HEMP	7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.025
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.025
BOTH	7,7-Diethylheptadecane	296	C ₂₁ H ₄₄	48.081
BOTH	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	48.081
MC	No known compound			49.092
HEMP	2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.545
BOTH	2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.635
BOTH	2-Bromotetradecane	276	C ₁₄ H ₂₉ Br	49.852
HEMP	2-methyloctacosane	408	C ₂₉ H ₆₀	51.015
BOTH	2-methyloctacosane	408	C ₂₉ H ₆₀	51.052
BOTH	2-methyloctacosane	408	C ₂₉ H ₆₀	51.096
MC	3,7,11-Tridecatrienitrile, 4,8,12-trimethyl-			51.162
MC	Squalene			51.162
HEMP	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[[(trimethylsilyl)oxy]methyl]ethyl ester, (Z,Z,Z)-	496	C ₂₇ H ₅₂ O ₄ Si ₂	51.495
BOTH	Squalene	410	C ₃₀ H ₅₀	51.557
BOTH	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.5
BOTH	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.532
BOTH	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	52.541
MC	No known compound			53.18
MC	No known compound			53.602
HEMP	2-methyloctacosane	408	C ₂₉ H ₆₀	54.045
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	54.045
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	54.07
BOTH	2-methyloctacosane	408	C ₂₉ H ₆₀	54.073
MC	Eicosane, 2-methyl-	296	C ₂₁ H ₄₄	54.073
BOTH	2-methyloctacosane	408	C ₂₉ H ₆₀	54.184
BOTH	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	54.184
BOTH	Eicosane, 2-methyl-	296	C ₂₁ H ₄₄	55.71

HEMP	Eicosane, 2-methyl-	296	C ₂₁ H ₄₄	55.865
BOTH	Eicosane, 2-methyl-	296	C ₂₁ H ₄₄	55.98
MC	No known compound			56.078
HEMP	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	58.12
HEMP	Eicosane, 9-octyl-	394	C ₂₈ H ₅₈	58.12
BOTH	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	58.195
BOTH	Eicosane, 9-octyl-	394	C ₂₈ H ₅₈	58.195
BOTH	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	58.208
BOTH	Eicosane, 9-octyl-	394	C ₂₈ H ₅₈	58.208
MC	No known compound			58.93
HEMP	Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	60.725
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	60.805
HEMP	Hexacosane, 9-octyl-	478	C ₃₄ H ₇₀	60.81
HEMP	Nonadecane, 2-methyl-	282	C ₂₀ H ₄₂	60.81
MC	Cyclononasiloxane, octadecamethyl-			60.989
BOTH	Hexacosane, 9-octyl-	478	C ₃₄ H ₇₀	61.343
MC	2-methyloctacosane	408	C ₂₉ H ₆₀	61.343
MC	Heptadecane, 9-octyl-			61.343
MC	Tritetracontane	604	C ₄₃ H ₈₈	61.343
MC	Docosane, 11-butyl-	366	C ₂₆ H ₅₄	63.762
MC	Docosane, 7-hexyl-			63.762
MC	Eicosane, 7-hexyl-	366	C ₂₆ H ₅₄	63.762
MC	Heptadecane, 9-hexyl-			63.762
MC	Heptadecane, 9-octyl-			63.762
MC	Hexacosane, 9-octyl-	478	C ₃₄ H ₇₀	63.762
MC	Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	63.762
HEMP	Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₉ O ₂	63.99
HEMP	Stearic acid, 3-(octadecyloxy)propyl ester	594	C ₃₉ H ₇₈ O ₃	63.99
HEMP	Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₉ O ₂	64.08
HEMP	Stearic acid, 3-(octadecyloxy)propyl ester	594	C ₃₉ H ₇₈ O ₃	64.08
HEMP	Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₉ O ₂	64.091
HEMP	Stearic acid, 3-(octadecyloxy)propyl ester	594	C ₃₉ H ₇₈ O ₃	64.091
MC	2-methyloctacosane	408	C ₂₉ H ₆₀	64.359
MC	Heneicosane, 11-(1-ethylpropyl)-			64.359
MC	Tetratetracontane	618	C ₄₄ H ₉₀	64.359
MC	2-methyloctacosane	408	C ₂₉ H ₆₀	65.394
MC	Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	65.394
HEMP	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[[(trimethylsilyl)oxy)methyl]ethyl ester, (Z,Z,Z)-	496	C ₂₇ H ₅₂ O ₄ Si ₂	67.65

HEMP	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl]oxy]methyl]ethyl ester, (Z,Z,Z)-	496	C ₂₇ H ₅₂ O ₄ Si ₂	67.72
HEMP	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl]oxy]methyl]ethyl ester, (Z,Z,Z)-	496	C ₂₇ H ₅₂ O ₄ Si ₂	67.72
HEMP	Docosanoic acid, docosyl ester	648	C ₄₄ H ₈₈ O ₂	68.02
HEMP	Docosanoic acid, docosyl ester	648	C ₄₄ H ₈₈ O ₂	68.02
HEMP	Eicosanoic acid	312	C ₂₀ H ₄₀ O ₂	68.02
HEMP	Eicosanoic acid	312	C ₂₀ H ₄₀ O ₂	68.02
HEMP	Docosanoic acid, docosyl ester	648	C ₄₄ H ₈₈ O ₂	68.11

Figure 68: Condensate from leaf medicinal cannabis pyrolysis trial, Py-GCMS analysis

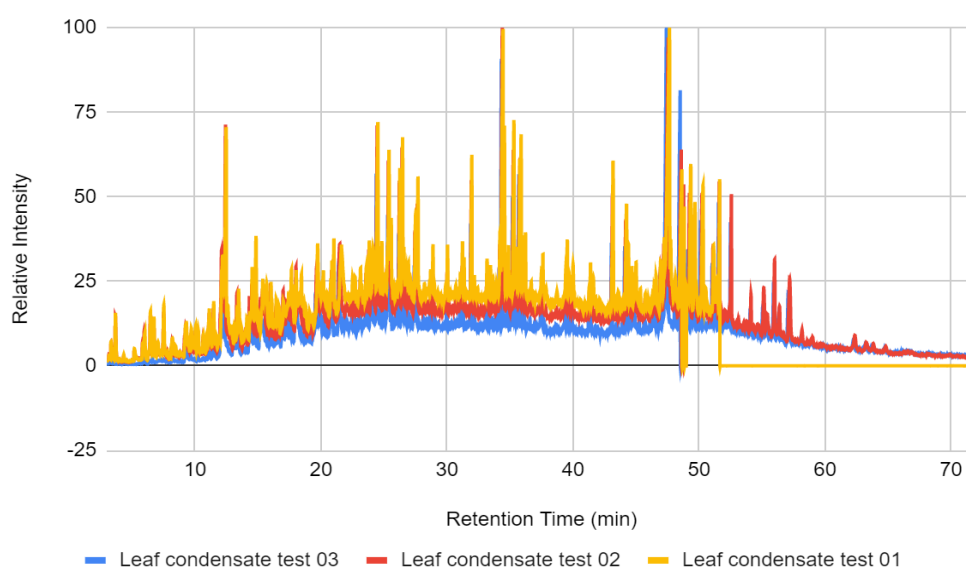


Figure 69: Condensate from stalk medicinal cannabis pyrolysis trial, Py-GCMS analysis

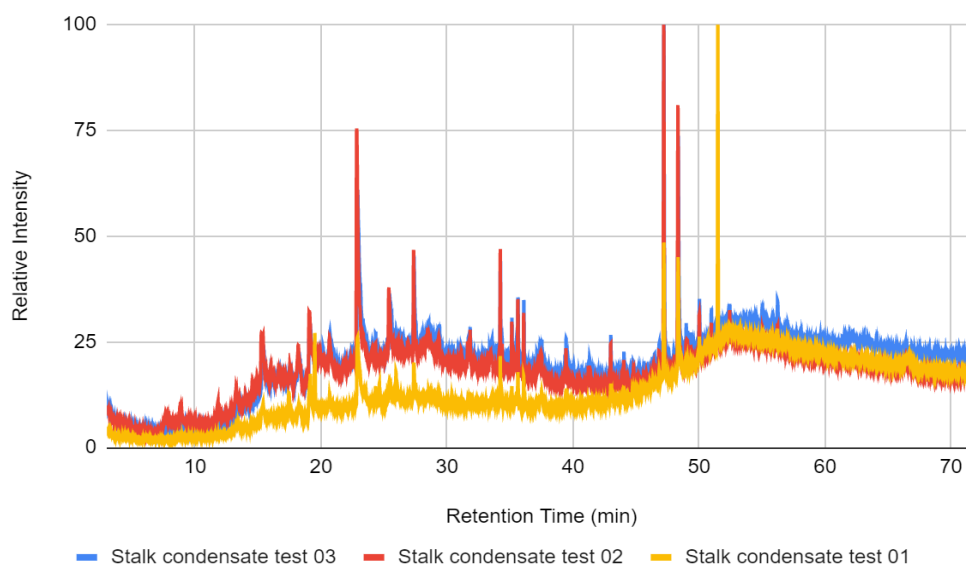


Figure 70: Condensate from mix medicinal cannabis pyrolysis trial, Py-GCMS analysis

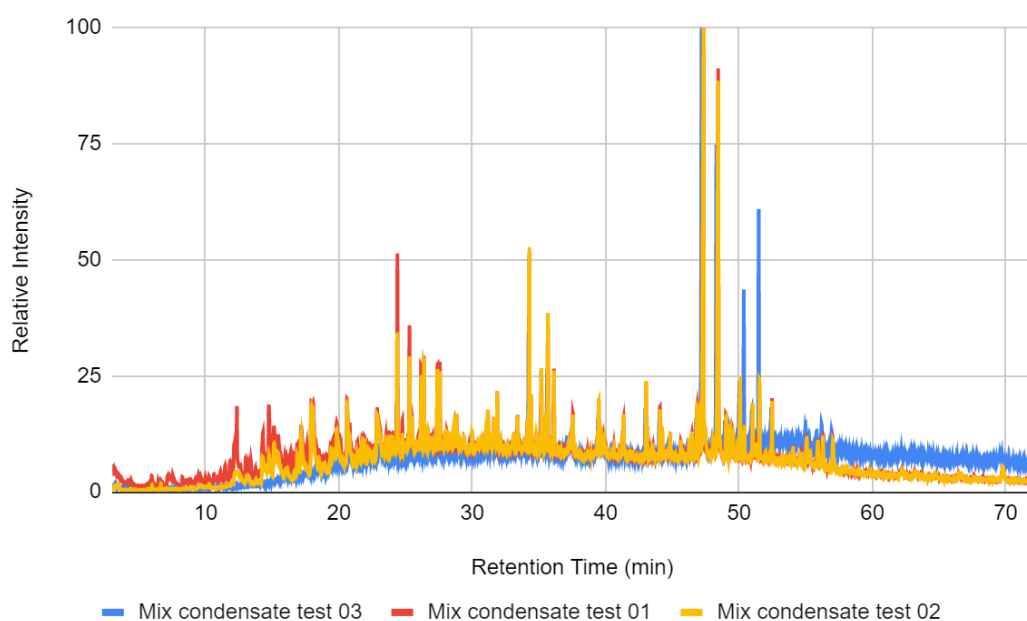


Table 32: Comparison of compounds identified in the condensate samples for hemp and medicinal cannabis pyrolysis trials of leaf (orange), root (yellow), and mix (blue), Py-GCMS results

HEMP or MC	Name	Molecular Weight	Molecular Formula	Retention Time (min)
BOTH	Phenol	94	C ₆ H ₆ O	12.14
MC	No known compound			12.322
MC	Ethyl 3-aminopicolinate			14.784
HEMP	Diazene, bis(1,1-dimethylethyl)-	142	C ₈ H ₁₈ N ₂	15
HEMP	Trimethylaluminum	72	C ₃ H ₉ Al	15
BOTH	Diazene, bis(1,1-dimethylethyl)-	142	C ₈ H ₁₈ N ₂	15.287
BOTH	Trimethylaluminum	72	C ₃ H ₉ Al	15.287
BOTH	No known compound			16.046
BOTH	Phenol, 3-methoxy-2-methyl-	138	C ₈ H ₁₀ O ₂	17.992
MC	Acetonitrile, 2,2'-iminobis-			17.992
BOTH	Phenol, 3-methoxy-2-methyl-	138	C ₈ H ₁₀ O ₂	18.02
BOTH	Phenol, 3-methoxy-2-methyl-	138	C ₈ H ₁₀ O ₂	18.202
MC	1,2-Epoxy-nonane			18.202
BOTH	1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	144	C ₆ H ₈ O ₄	19.079
HEMP	1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	144	C ₆ H ₈ O ₄	19.264
BOTH	Cyclopropane, trimethyl(2-methyl-1-propenylidene)-	136	C ₁₀ H ₁₆	19.596
MC	1,4:3,6-Dianhydro-.alpha.-d-glucopyranose	144	C ₆ H ₈ O ₄	20.691

BOTH	Methanol, [6,8,9-trimethyl-4-(1-propenyl)-3-oxabicyclo[3.3.1]non-6-en-1-yl]-	236	C ₁₅ H ₂₄ O ₂	20.812
BOTH	5H-1-Pyridine	117	C ₈ H ₇ N	21.404
HEMP	4-(6-Oxabicyclo[3.1.0]hex-1-yl)-but-3-yn-2-one	150	9H ₁₀ O ₂	21.75
BOTH	Phenol, 3,4-dimethoxy-	154	C ₈ H ₁₀ O ₃	22.86
BOTH	Phenol, 3,4-dimethoxy-	154	C ₈ H ₁₀ O ₃	22.871
MC	No known compound			24.353
BOTH	11,11-Dimethyl-spiro[2,9]dodeca-3,7-dien	190	C ₁₄ H ₂₂	24.395
BOTH	1,2,3-Trimethoxybenzene	168	C ₉ H ₁₂ O ₃	25.321
BOTH	1,2,3-Trimethoxybenzene	168	C ₉ H ₁₂ O ₃	25.407
BOTH	5-Octadecene, (E)-	252	C ₁₈ H ₃₆	26.17
BOTH	8-Heptadecene, 1-chloro-	272	C ₁₇ H ₃₃ Cl	26.17
MC	No known compound			26.207
BOTH	Pentadecane	212	C ₁₅ H ₃₂	26.351
BOTH	Phenol, 2,6-dimethyl-4-nitro-	167	C ₈ H ₉ NO ₃	27.374
MC	Benzene, 1,2,3-trimethoxy-5-methyl-			27.374
BOTH	Phenol, 2,6-dimethyl-4-nitro-	167	C ₈ H ₉ NO ₃	27.617
BOTH	2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	336	C ₂₂ H ₄₀ O ₂	28.701
HEMP	2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	336	C ₂₂ H ₄₀ O ₂	29
BOTH	2H-Pyran, 2-(7-heptadecynyloxy)tetrahydro-	336	C ₂₂ H ₄₀ O ₂	29.365
HEMP	Heptadecane	240	C ₁₇ H ₃₆	31
BOTH	Heptadecane	240	C ₁₇ H ₃₆	31.083
BOTH	Heptadecane	240	C ₁₇ H ₃₆	31.792
BOTH	2-Hexadecene, 2,6,10,14-tetramethyl-	280	C ₂₀ H ₄₀	31.876
BOTH	2-Hexadecene, 2,6,10,14-tetramethyl-	280	C ₂₀ H ₄₀	31.905
HEMP	2-Hexadecene, 2,6,10,14-tetramethyl-	280	C ₂₀ H ₄₀	32
BOTH	No known compound			33.398
BOTH	No known compound			33.5
HEMP	2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	280	C ₂₀ H ₄₀	34.155
BOTH	Phytol, acetate	338	C ₂₂ H ₄₂ O ₂	34.329
HEMP	2-Hexadecene, 3,7,11,15-tetramethyl-, [R-[R*,R*-(E)]]-	280	C ₂₀ H ₄₀	34.455
BOTH	2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.168
BOTH	13-Heptadecyn-1-ol	252	C ₁₇ H ₃₂ O	35.216
BOTH	E-6-Octadecen-1-ol acetate	310	C ₂₀ H ₃₈ O ₂	35.216
BOTH	2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.6
BOTH	2-Pentadecanone, 6,10,14-trimethyl-	268	C ₁₈ H ₃₆ O	35.689
BOTH	Pentadecanoic acid, 14-methyl-, methyl ester	270	C ₁₇ H ₃₄ O ₂	36.049
HEMP	Pentadecanoic acid, 14-methyl-, methyl ester	270	C ₁₇ H ₃₄ O ₂	36.135
BOTH	Pentadecanoic acid, 14-methyl-, methyl ester	270	C ₁₇ H ₃₄ O ₂	36.136

HEMP	4-Fluoro-1-methyl-5-carboxylic acid, ethyl(ester)	172	C ₇ H ₉ FN ₂ O ₂	37.26
HEMP	Heptadecanoic acid, heptadecyl ester	508	C ₃₄ H ₆₈ O ₂	37.26
BOTH	Pentadecanoic acid	242	C ₁₅ H ₃₀ O ₂	37.491
BOTH	Pentadecanoic acid	242	C ₁₅ H ₃₀ O ₂	37.492
BOTH	1-Tetradecen-3-yne	192	C ₁₄ H ₂₄	39.431
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	39.431
BOTH	9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	292	C ₁₉ H ₃₂ O ₂	39.431
BOTH	1-Tetradecen-3-yne	192	C ₁₄ H ₂₄	39.479
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	39.479
BOTH	9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	292	C ₁₉ H ₃₂ O ₂	39.479
HEMP	2-methyltetracosane	352	C ₂₅ H ₅₂	39.48
HEMP	1-Tetradecen-3-yne	192	C ₁₄ H ₂₄	39.62
HEMP	9,12,15-Octadecatrienoic acid, methyl ester, (Z,Z,Z)-	292	C ₁₉ H ₃₂ O ₂	39.62
BOTH	Phytol	296	C ₂₀ H ₄₀ O	39.947
HEMP	Phytol	296	C ₂₀ H ₄₀ O	40
HEMP	Phytol	296	C ₂₀ H ₄₀ O	40
HEMP	3-Methyl-4-(phenylthio)-2-prop-2-enyl-2,5-dihydrothiophene 1,1-dioxide	280	C ₁₄ H ₁₆ O ₂ S ₂	41.227
HEMP	Ethyl iso-allocholate	436	C ₂₆ H ₄₄ O ₅	41.227
BOTH	Octadecanoic acid	284	C ₁₈ H ₃₆ O ₂	41.323
BOTH	Octadecanoic acid	284	C ₁₈ H ₃₆ O ₂	41.338
BOTH	1H-4-Oxabenzo(f)cyclobut(cd)inden-8-ol, 1a-.alpha.,2,3,3a,8b-.alpha.,8c-.alpha.-hexahydro-1,1,3a-trimethyl-6-pentyl- (Cannabicyclol or Cannabipinol)	314	C ₂₁ H ₃₀ O ₂	43.025
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	43.025
BOTH	1H-4-Oxabenzo(f)cyclobut(cd)inden-8-ol, 1a-.alpha.,2,3,3a,8b-.alpha.,8c-.alpha.-hexahydro-1,1,3a-trimethyl-6-pentyl- (Cannabicyclol or Cannabipinol)	314	C ₂₁ H ₃₀ O ₂	43.03
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	43.03
BOTH	1H-4-Oxabenzo(f)cyclobut(cd)inden-8-ol, 1a-.alpha.,2,3,3a,8b-.alpha.,8c-.alpha.-hexahydro-1,1,3a-trimethyl-6-pentyl- (Cannabicyclol or Cannabipinol)	314	C ₂₁ H ₃₀ O ₂	43.069
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	43.069
BOTH	Cannabichromene (CBC)	314	C ₂₁ H ₃₀ O ₂	44.122
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	44.728
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	44.805
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.603
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.625
BOTH	Cannabidiol (CBD)	314	C ₂₁ H ₃₀ O ₂	45.75
BOTH	Morphinone, 7,8-dihydro-3-desoxy-	269	C ₁₇ H ₁₉ NO ₂	46.454
BOTH	Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.454

BOTH	1-Chloroeicosane	316	C ₂₀ H ₄₁ Cl	46.51
BOTH	Morphinone, 7,8-dihydro-3-desoxy-	269	C ₁₇ H ₁₉ NO ₂	46.865
BOTH	Sulfurous acid, pentadecyl 2-propyl ester	334	C ₁₈ H ₃₈ O ₃ S	46.865
BOTH	Morphinone, 7,8-dihydro-3-desoxy-	269	C ₁₇ H ₁₉ NO ₂	46.896
BOTH	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl]oxy]methyl]ethyl ester, (Z,Z,Z)-	496	27H ₅₂ O ₄ Si ₂	47.235
BOTH	Dronabinol (Δ9-Tetrahydrocannabinol, Δ9-THC)	314	C ₂₁ H ₃₀ O ₂	47.235
HEMP	Dronabinol (Δ9-Tetrahydrocannabinol, Δ9-THC)	314	C ₂₁ H ₃₀ O ₂	47.295
BOTH	9,12,15-Octadecatrienoic acid, 2-[(trimethylsilyl)oxy]-1-[[trimethylsilyl]oxy]methyl]ethyl ester, (Z,Z,Z)-	496	27H ₅₂ O ₄ Si ₂	47.317
BOTH	Dronabinol (.DELTA.9-Tetrahydrocannabinol)	314	C ₂₁ H ₃₀ O ₂	47.317
BOTH	Bis(tridecyl) phthalate	530	C ₃₄ H ₅₈ O ₄	47.373
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	47.992
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	47.992
HEMP	2-methyltetracosane	352	C ₂₅ H ₅₂	48
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	48
BOTH	1-Chloroeicosane	316	C ₂₀ H ₄₁ Cl	48.057
BOTH	2-methylhexacosane	380	C ₂₇ H ₅₆	48.057
BOTH	Cannabinol (CBN)	310	C ₂₁ H ₂₆ O ₂	48.37
BOTH	Cannabinol (CBN)	310	C ₂₁ H ₂₆ O ₂	48.405
BOTH	Cannabinol (CBN)	310	C ₂₁ H ₂₆ O ₂	48.444
BOTH	Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	49.363
BOTH	Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.363
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	49.363
BOTH	Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	49.578
BOTH	Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.578
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	49.578
BOTH	Heptadecane, 2,6,10,15-tetramethyl-	296	C ₂₁ H ₄₄	49.605
BOTH	Octadecane, 2-methyl-	268	C ₁₉ H ₄₀	49.605
BOTH	No known compound			50.096
BOTH	Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₈ O ₂	50.995
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	50.995
BOTH	Oxirane, [(hexadecyloxy)methyl]-	298	C ₁₉ H ₃₈ O ₂	51.035
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	51.035
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	51.064
BOTH	Squalene	410	C ₃₀ H ₅₀	51.468
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	51.505
BOTH	Squalene	410	C ₃₀ H ₅₀	51.554
BOTH	Squalene	410	C ₃₀ H ₅₀	51.57

BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	52.458
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	52.458
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	52.461
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	52.461
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	52.478
BOTH	2-methylhexacosane	380	C ₂₇ H ₅₆	54.022
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	54.022
BOTH	2-methylhexacosane	380	C ₂₇ H ₅₆	54.055
BOTH	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	54.055
BOTH	2-methyltetracosane	352	C ₂₅ H ₅₂	54.1
BOTH	Tritetracontane	604	C ₄₃ H ₈₈	54.1
BOTH	No known compound			55.112
BOTH	Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	55.843
BOTH	Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	55.902
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	55.902
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	55.931
BOTH	Tetratetracontane	618	C ₄₄ H ₉₀	56.221
BOTH	No known compound			56.34
BOTH	dl-.alpha.-Tocopherol	430	C ₂₉ H ₅₀ O ₂	57.15
HEMP	Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	58
HEMP	Heptacosane, 1-chloro-	414	C ₂₇ H ₅₅ Cl	58
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	58
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	58
HEMP	Heptadecanoic acid, heptadecyl ester	508	C ₃₄ H ₆₈ O ₂	58.575
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	61
HEMP	Sulfurous acid, 2-propyl tetradecyl ester	320	C ₁₇ H ₃₆ O ₃ S	61
HEMP	No known compound			64
HEMP	No known compound			64
HEMP	9,19-Cycloergost-24(28)-en-3-ol, 4,14-dimethyl-, (3.beta.,4.alpha.,5.alpha.)-	426	C ₃₀ H ₅₀ O	67.7
HEMP	No known compound			68
HEMP	No known compound			68
HEMP	No known compound			68
HEMP	No known compound			68

Appendix L: General description of each impact category

Climate change

On a global scale climate change is quantified in many different ways but most commonly it is quantified using the average surface temperature of the planet (Climate Change Committee, n.d.). The life cycle assessment (LCA) ReCiPe 2016 v1.1 framework quantifies climate change as the increase of greenhouse gas (GHG) (Huijbregts et al., 2017a). Another common quantification of climate change or the impact a system or company has is carbon footprint. In contrast, the ReCiPe 2016 v1.1 framework doesn't specifically have a carbon footprint impact category, the ecoinvent database states that the climate change impact category is used to quantify the carbon footprint (Ecoinvent, n.d.). Therefore, the calculated results in this section can be classed as carbon footprint results and compared against other carbon footprint data.

Fine particulate matter

Particulate matter (PM) is an air pollutant, it consists of solid and liquid particles suspended in the air (WHO, 2006). Fine particles (PM_{2.5}), particles with a diameter <2.5 μm , are one of the most important environmental impacts, negatively contributing to global health disease (Fantke et al., 2015; Hänninen et al., 2014; Lim et al., 2012).

Fossil depletion

Fossil depletion or fossil resources scarcity uses the indicator of Fossil Fuel Potential (FFP) defined as the higher heating value of a fossil resource to the energy content of crude oil (Huijbregts et al., 2017a); it assesses the reduction of fossil fuel energy resources (Cashman et al., 2014).

Freshwater consumption (inventory indicator)

Freshwater consumption is an inventory indicator that represents either withdrawals that are evaporated, incorporated into products and waste, transferred to watersheds at different locations, or disposed of into the sea after use (Pfister et al., 2009). For this study, depending on the EoL treatment discussed, this inventory indicator can represent any or all of these aspects.

Freshwater ecotoxicity

Freshwater ecotoxicity uses the hazard-weighted increase in freshwater to indicate the freshwater ecotoxicity potential (FETP) of the system (Huijbregts et al., 2017a). Specifically, chemicals can be emitted into the environment, whether soil, air, or water, during all system stages (LC-Impact, n.d.). This impact category analyses the impact that they have on freshwater.

Freshwater eutrophication

Freshwater eutrophication occurs due to the increase of nutrient levels by the discharge of nutrients into either soil or freshwater ecosystems (Azevedo et al., n.d.). While the nutrient levels in water systems can be measured by nitrogen and phosphorus, depending on the life cycle assessment method, some use both or just one to determine the impact of freshwater eutrophication. For the ReCiPe 2016 v1.1 assessment method, the phosphorus increase in freshwater is used (Huijbregts et al., 2017a).

Human toxicity (cancer)

For the ReCiPe 2016 v1.1 assessment method, the risk increase in cancer disease incidence in urban air is used as the indicator for the human toxicity (cancer) impact category (Huijbregts et al., 2017a). By inhaling toxic substances in the air, human beings can suffer adverse health effects (EU, 2018). Therefore, this is an important impact category for this study.

Human toxicity (non-cancer)

For the ReCiPe 2016 v1.1 assessment method, the risk increase in non-cancer disease incidence in urban air is used as the indicator for the human toxicity (non-cancer) impact category (Huijbregts et al., 2017a). Human beings can have adverse health effects when toxic substances are present in the air (EU, 2018). Therefore, this is an important impact category for this study.

Ionising radiation

Radiation affects both human health and ecosystems. For the ReCiPe 2016 v1.1 assessment method, the collective absorbed dose increase resulting from the emission of radionuclides is used as the indicator for the impact category, ionising radiation (Huijbregts et al., 2017a).

Marine ecotoxicity

Ecotoxicity levels are determined by the release of chemicals into the environment, whether it be to the soil, water, or air (LC-Impact, n.d.). Specifically, the impact on marine ecosystems is determined using the indicator, hazard-weighted increase in marine water, with the characterisation factor being marine ecotoxicity potential (METP) (Huijbregts et al., 2017a).

Marine eutrophication

Any increase in the nitrogen and phosphorus nutrient levels in marine water determines the eutrophication impact of a system. However, for the ReCiPe 2016 v1.1 assessment method, the marine eutrophication impact category uses nitrogen levels of marine water rather than phosphorus, as used in the freshwater eutrophication impact category.

Photochemical ozone formation (ecosystems)

The photochemical ozone formation represents the increase in ozone in a specific environment; for this impact category looking at ecosystems, the ReCiPe 2016 v1.1 method uses the indicator of tropospheric ozone increase (Huijbregts et al., 2017a). Additionally, the unit used is kg NO_x-eq. which is the sum of ozone concentration differences between the hourly mean and 40 ppm. during daylight hours over the relevant seasons (Huijbregts et al., 2017a).

Photochemical ozone formation (human health)

This impact category looks at the impact that photochemical ozone formation has on human health. The damage pathway utilised in the ReCiPe 2016 v1.1 assessment method is the years of life lost related to an increase in respiratory diseases caused by ozone exposure, measured in kg NO_x-eq. (the change in the ambient concentration of ozone after the emission of a precursor) (Huijbregts et al., 2017a).

Terrestrial acidification

Acidification is measured in kg SO₂-eq, which represents the changes in acid deposition following the changes in the air emissions of NO_x, NH₃, and SO₂; this leads to the loss of plant species due to the decrease in soil pH (Huijbregts et al., 2017a). Therefore, the impact category of terrestrial acidification uses the indicator of proton increase in natural soils (Huijbregts et al., 2017a).

Terrestrial ecotoxicity

As for the marine and freshwater ecotoxicity impact categories, the terrestrial ecotoxicity impact category represents the effect that pollutants have on land-dependent organisms and their ecosystems (Fairbrother & Hope, 2005). The ReCiPe 2016 v1.1 method uses the indicator of the hazard-weighted increase in natural soils.

Appendix M: Transport fuel emission truck size

Table 33: Freight transport decisions for comparison of LCA modelling to available MfE truck sizes for the climate change impact category

EoL treatment	Transport route	Mass	LCA truck size	MfE truck size
Landfill	Transport of green waste for use on-site	6 t/cycle	3.5 - 7.5 ton	All trucks
	Transport of bleach for use on-site	Smallest	3.5 - 7.5 ton	All trucks
	Transport of mixed material to the transfer station	12 t/cycle	7.5 - 16 ton	All trucks
	Transport of material from the transfer station to the landfill	Largest	> 32 ton	Long haul heavy truck
	Organic composting transport	6 t/cycle	3.5 - 7.5 ton	All trucks
	Land spreading of organic compost	No tractor MfE value present		
	Synthetic fertiliser production by truck freight	Largest	> 32 ton	Long haul heavy truck
	Synthetic fertiliser production by sea freight	Container ship		
Composting	Transport of green waste for use on-site	6 t/cycle	3.5 – 7.5 ton	All trucks
	Transport of mixed material off-site	12 t/cycle	7.5 – 16 ton	All trucks
	Application of compost to land	No tractor MfE value present		
	Synthetic fertiliser production by truck freight	Largest	> 32 ton	Long haul heavy truck
	Synthetic fertiliser production by sea freight	Container ship		
Anaerobic Digestion	Transport of digestate solids off-site	2.28 t/cycle	3.5 - 7.5 ton	All trucks
	Soil application of compost	No tractor MfE value present		
	Synthetic fertiliser production by truck freight	Largest	> 32 ton	Long haul heavy truck
	Synthetic fertiliser production by sea freight	Container ship		

Incineration	Transport of processing unit for use on-site	Largest	> 32 ton	Long haul heavy truck
	Transport of ash to the transfer station	Smallest	3.5 - 7.5 ton	All trucks
	Transport of ash from the transfer station to the landfill	Largest	> 32 ton	Long haul heavy truck
Pyrolysis	Transport of mobile unit for use on-site	Largest	> 32 ton	Long haul heavy truck
	Transport of biochar to land	0.612 t/cycle	3.5 - 7.5 ton	All trucks
	Land spreading of biochar	No tractor MfE value present		
	Synthetic fertiliser production by truck freight	Largest	> 32 ton	Long haul heavy truck
	Synthetic fertiliser production by sea freight	Container ship		

Appendix N: Economic analysis

Appendix N.1: Capital costs

Tables 35-39 show the process and capital cost adapted for 2022 prices; these tables allows for a total estimate to be made without Lang factors for each EoL treatment. The conversion from the capital costing used initially by Bouman et al. (2005) was made using the March 2022 business price index obtained from Statistics NZ. Where the power consumption is used for the mixer, the maximum required electricity requirement was used instead of per FU, the maximum being one cycle (6*FU). Calculations are below each table. The Lang factors are shown in Table 34, and while they incorporate engineering, infrastructure construction is omitted from this analysis. Infrastructure does not apply to the mobile units, and landfill charges (operational costs) already include infrastructure costs. Therefore, infrastructure is only emitted for the composting and anaerobic digestion EoL treatments. Composting would require an impervious barrier, leachate control, and roofing, while anaerobic digestion would require foundations and construction of the digester. All Lang factors were incorporated for the landfill, composting, and anaerobic digestion EoL treatment capital costs. A truck was required for the incineration and pyrolysis EoL treatments; therefore, it did not require all the Lang factor operations. An estimation of a container installation and alterations required for the truck was considered instead of using the Lang factors. The Lang factors were used for all other equipment (excluding the truck) for the incineration and pyrolysis EoL treatments capital costs.

Table 34: Lang factors used for the capital cost of alternative EoL treatments

Lang Factors Used	Solid-fluid Processing
Equipment (delivered) ($f_{equip,del}$)	1
Equipment, installation ($f_{equip,install}$)	0.41
Piping (f_{piping})	0.345
Electrical (f_{elect})	0.125
Instruments (f_{instru})	0.13
Auxiliaries (f_{aux})	0.515
Field expense ($f_{f,exp}$)	0.39
Engineering (f_{eng})	0.39
Contractors' fees, overhead, profit (f_{cfop})	0.13
Contingency (f_{cont})	0.39
WORKING CAPITAL	15%

Note. Averaged from data in Bouman et al. (2005) and Perry et al. (1997).

Landfill

Table 35: Capital cost estimate for the landfill EoL treatment

Process	Process used	Measurement	Cost
Shredder	Jaw crusher	1 kg/s	\$ 33,808.50

Mixer	Open tank agitator	39.78 kW	\$ 73,094.28
Conveyor	Auger conveyor	Diameter = 0.46 m Distance = 2 m	\$ 3,526.03
Bleach storage tank	Polyethylene liquid storage tank	Volume = 2.5 m ³	\$ 1,224.41
Container for green waste storage on-site	--	20'	\$ 8,280.00
Total without Lang factors (EMPIC)			\$119,933.23
Total with Lang factors incorporated ($C_{landfill}$)			\$578,677.82

The shredder is 15hp with a capacity of 225 kg/hr which is less than 1 kg/s, however, within Bouman et al. (2005), a jaw crusher has the lowest capacity being 1 kg/s. Therefore, that capacity was used. The conversion was also used (1478/988) to inflate the cost from the 2004 value to March 2022 value based on the category 'other plant, machinery, and equipment' in the price index spreadsheet.

$$22.6 * 10^3 * 1 \frac{kg}{s}^{0.611} * (\frac{1478}{988}) = \$33,808.50$$

The mixer is 3hp with an electricity requirement of 6.63 kWh/FU, but for the capital cost, the maximum requirement per cycle was used. Therefore, 39.78 kW was used for the equipment calculation. The conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category 'other plant, machinery, and equipment' in the price index spreadsheet.

$$(1.13 * 10^3 * 39.78kW + 3.91 * 10^3) * (\frac{1478}{988}) = \$73,094.28$$

When calculating the electricity requirement and the processing time of the conveyors, an assumed 2 m distance, 0.78 m diameter, and 0.5 m pitch was used from Asli-Arden (Asli-Arden & Mohsenimanesh, 2012). However, this diameter was not available for the capital cost calculation. Therefore, a diameter of 0.46 m was used along with a distance of 2 m. A conversion was used (1351/988) to convert the cost from the 2004 value to March 2022 value based on the category 'lifting and handling equipment' in the price index spreadsheet.

$$(1.93 * 10^3 * 2^{0.418}) * (\frac{1351}{988}) = \$3,526.03$$

The bleach storage tank required a maximum volume of 2.05 m³ to hold the required bleach for one cycle. However, a conservative value of 2.5 m³ was used for the capital cost. A

conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘metal tanks, reservoirs, and containers’ in the price index spreadsheet. A stainless-steel tank may seem like a better option for a liquid storage tank, but bleach and steel create a chemical reaction, the only metal tanks that would be appropriate and not create a reaction would be titanium which is infeasible. Fibreglass is also appropriate, but no capital cost is available for this option. Instead, a polyethylene tank is available, which is chemically resistant to bleach. Therefore, the PE tank capital cost is used.

$375 \frac{kg}{FU}$ is required for bleach, which means that $375 \frac{kg}{FU} * 6 \frac{FU}{cycle} = 2250 \frac{kg}{cycle}$ assuming that bleach has a density of $1100 \frac{kg}{m^3}$, a volume of $\frac{2250 \frac{kg}{cycle}}{1100 \frac{kg}{m^3}} = 2.05 \frac{m^3}{cycle}$.

$$(358 * 2.5^{0.609}) * (\frac{1934}{988}) = \$1,224.41$$

The capital cost of a 20’ container required for the storage of green waste was obtained from the supplier, NZBox (Personal communication, May 30, 2022).

Final total calculation:

$$C_{landfill} = (1 + f_a + f_b + \dots) * \Sigma MPIC$$

$$C_{landfill} = (1 + f_{equip,del} + f_{equip,install} + f_{piping} + f_{elect} + f_{instru} + f_{aux} + f_{f,exp} + f_{eng} + f_{cfop} + f_{cont}) * \$119,933.23$$

$$C_{landfill} = \$578,677.82$$

Composting

Table 36: Capital cost estimate for the composting EoL treatment

Process	Process used	Measurement	Cost
Shredder	Jaw crusher	1 kg/s	\$ 33,808.50
Mixer	Open tank agitator	39.78 kW	\$ 73,094.28
Conveyor	Auger conveyor	Diameter = 0.46 m Distance = 2 m	\$ 3,526.03
Container for green waste storage on-site	--	20’	\$ 8,280.00
Total without Lang factors ($\Sigma MPIC$)			\$118,708.81

Total with Lang factors incorporated ($C_{composting}$)			\$572,770.03
---	--	--	---------------------

The shredder is 15hp with a capacity of 225 kg/hr which is less than 1 kg/s, however, within Bouman et al. (2005), a jaw crusher has the lowest capacity being 1 kg/s. Therefore, that capacity was used. The conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘other plant, machinery, and equipment’ in the price index spreadsheet.

$$22.6 * 10^3 * 1 \frac{kg}{s}^{0.611} * \left(\frac{1478}{988}\right) = \$33,808.50$$

The mixer is 3hp with an electricity requirement of 6.63 kWh/FU, but for the capital cost, the maximum requirement per cycle was used. Therefore, 39.78 kW was used for the equipment calculation. The conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘other plant, machinery, and equipment’ in the price index spreadsheet.

$$(1.13 * 10^3 * 39.78kW + 3.91 * 10^3) * \left(\frac{1478}{988}\right) = \$73,094.28$$

When calculating the electricity requirement and the processing time of the conveyors, an assumed 2 m distance, 0.78 m diameter, and 0.5 m pitch was used from Asli-Arden (Asli-Arden & Mohsenimanesh, 2012). However, this diameter was not available for the capital cost calculation. Therefore, a diameter of 0.46 m was used along with a distance of 2 m. A conversion was used (1351/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘lifting and handling equipment’ in the price index spreadsheet.

$$(1.93 * 10^3 * 2^{0.418}) * \left(\frac{1351}{988}\right) = \$3,526.03$$

The capital cost of a 20’ container required for the storage of green waste was obtained from the supplier, NZBox (Personal communication, May 30, 2022).

Final total calculation:

$$C_{composting} = (1 + f_a + f_b + \dots) * \Sigma MPIC$$

$$C_{composting} = (1 + f_{equip,del} + f_{equip,install} + f_{piping} + f_{elect} + f_{instru} + f_{aux} + f_{f,exp} + f_{eng} + f_{cfop} + f_{cont}) * \$118,708.81$$

$$C_{composting} = \$572,770.03$$

Anaerobic Digestion

Table 37: Capital cost estimate for the anaerobic digestion EoL treatment

Process	Process used	Measurement	Cost
Shredder	Jaw crusher	1 kg/s	\$ 33,808.50
Digester	Clarifiers and thickeners - Separator	Diameter = 4 m	\$ 88,126.44
Conveyor	Auger conveyor	Diameter = 0.46 m Distance = 2 m	\$ 3,526.03
Water storage tank	Stainless steel liquid storage tank	Volume = 1.5 m ³	\$ 6,184.12
Belt filter press	Filter press - simple plate and frame	2 m ²	\$ 7,170.54
Gas storage tank	Stainless steel storage tank	Volume = 842 m ³	\$ 268,033.00
Flare	--	--	\$ 5,733.21
Air indirect heat exchanger	--	--	\$ 4,308.00
Air blowers	Centrifugal blower	1.515 kW	\$ 25,861.47
Total without Lang factors (<i>EMPIC</i>)			\$ 438,443.72
Total with Lang factors incorporated (<i>C_{anaerobic digestion}</i>)			\$2,136,278.69

The shredder is 15hp with a capacity of 225 kg/hr which is less than 1 kg/s, however, within Bouman et al. (2005), a jaw crusher has the lowest capacity being 1 kg/s. Therefore, that capacity was used. The conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘other plant, machinery, and equipment’ in the price index spreadsheet.

$$22.6 * 10^3 * 1 \frac{kg}{s}^{0.611} * \left(\frac{1478}{988}\right) = \$33,808.50$$

When calculating the electricity requirement and the processing time of the conveyors, an assumed 2 m distance, 0.78 m diameter, and 0.5 m pitch were used from Asli-Arden (Asli-Arden & Mohsenimanesh, 2012). However, this diameter was not available for the capital cost calculation. Therefore, a diameter of 0.46 m was used along with a distance of 2 m. A conversion was used (1351/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘lifting and handling equipment’ in the price index spreadsheet.

$$(1.93 * 10^3 * 2^{0.418}) * (\frac{1351}{988}) = \$3,526.03$$

The water storage tank required a maximum volume of 1 m³ to hold the required bleach for one cycle. However, a conservative value of 1.5 m³ was used for the capital cost. A conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘metal tanks, reservoirs, and containers’ in the price index spreadsheet.

$$(2.48 * 10^3 * 1.5^{0.597}) * (\frac{1934}{988}) = \$6,184.12$$

For the belt filter press an assumed average size of 2 m² was used (Climate Policy Watcher, 2022).

$$(2.91 * 10^3 * 2^{0.72}) * \frac{1478}{988} = \$7,170.54$$

The gas storage tank requires a variable volume vessel due to the pressure and volume of gas held. According to Jones (personal communication, December 1, 2022), an inverted cylindrical tank would be best for gas storage. The gas production per FU is 140,203L at atmospheric pressure, made up of carbon dioxide (CO₂) and methane (CH₄). The gas pressure would be slightly higher due to the weight of the inverted tank, but this is a good estimate. The gas storage must be able to hold one cycle of gas production. Therefore, 841,218 L is required to be held. Rounding to 842,000 L, this means that at an 842 m³ tank size, a 9.5 m diameter and 12 m high cylindrical tank is required. The capital cost was calculated to be \$268,033.

$$CH_4 = \frac{50 \text{ kg}}{0.554 \frac{\text{kg}}{\text{m}^3}} = 90.253 \text{ m}^3 * 1000 = 90,253 \frac{\text{L } CH_4}{\text{FU}}$$

$$CO_2 = \frac{91.7 \text{ kg}}{1.836 \frac{\text{kg}}{\text{m}^3}} 49.95 \text{ m}^3 * 1000 = 49,950 \frac{\text{L } CO_2}{\text{FU}}$$

$$\text{Total gas volume} = 140,203 \frac{\text{L gas}}{\text{FU}}$$

$$\text{Gas storage required} = 140,203 * 6 = 841,218\text{L}$$

$$(2.48 * 10^3 * 842^{0.597}) * \frac{1934}{988} = \$268,033$$

A flare is required as both a safety device for the process and as a way to convert biogas to heat for injection into the indoor cultivation facility. There are two methods for this, (1) the gas is

stored daily and then burnt and pumped through an air indirect heat exchanger at night when it is cold, or (2) a combustor and heat exchanger can be used to make hot water which is stored during the day and pumped through the facility at night. Since the gas is already being stored, option (1) will be used for this study. The capital cost for the flare was obtained from an estimated range of \$1,000 to \$5,000 (EPA, 2011). The conservative value of \$5,000 was used, but this value was from 2011, and an increase to 2022 prices would have occurred. Therefore, the conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category 'plant, machinery, and equipment' in the price index spreadsheet.

$$\$5,000 * \frac{1212}{1057} = \$5,733.21$$

An air indirect heat exchanger will be used to transfer the heat from the flared gas to air used for heating in the cultivation facility. From the mass and energy balance, it was found that 141.7 kg of gas is produced per FU. For this study, it was assumed that 30 tonnes of cannabis plant material is processed each year. To estimate the cost of a heat exchanger, the exchanger surface area must be estimated. It was assumed that the methane production occurs over 90 days/year so that the gas production overlaps the harvests and heating can be provided all year round; a biogas calorific value of 23 MJ/kg (db.) was also assumed.

$$\begin{aligned} \text{Heat production rate} &= \frac{141.7 \text{ kg} * 30 \frac{\text{FU}}{\text{year}} * 23 \frac{\text{MJ}}{\text{kg}} * 1,000,000 \frac{\text{J}}{\text{MJ}}}{365 \frac{\text{days}}{\text{year}} * 24 \frac{\text{hours}}{\text{day}} * 3600 \frac{\text{sec}}{\text{hour}}} = 3.1 \frac{\text{J}}{\text{s}} \\ &= 3.1 \frac{\text{kW of heat}}{\text{year}} \end{aligned}$$

It is assumed that 2 kW of the 3.1 kW of heat produced is transferable and the rest goes up the flue. An assumed air-to-air overall heat transfer coefficient of 5 W/m²/K is used for these calculations. The system's temperatures are assumed to be 820°C for the gas entering the system after being combusted; this then drops to 220°C out of the system; the cool side air enters counter current at 20°C which is then heated to 420°C and leaves the heat exchanger where it is mixed with entrained air to cool it before entering the cultivation facility. The log mean temperature difference (LMTD) was calculated to be 400°C, which produced a heat exchanger area of 1 m². Even though the heat exchanger area is small and does not account for surface losses, it is a reasonable estimate for this cost analysis. The capital cost of the double pipe shell and tube heat exchanger was estimated to be \$4,308 considering the conversion using the price index from 2004 to March 2022 of (1478/988).

$$LMTD = \Delta T_{lm} = \frac{\Delta T_2 - \Delta T_1}{\ln(\frac{\Delta T_2}{\Delta T_1})} = \frac{200 - 400}{\ln(\frac{200}{400})} = 400^\circ\text{C}$$

$$HEx Area = A = \frac{Q}{(U * LMTD)} = \frac{2000 W}{5 \frac{W}{m.K} * 400^{\circ}C} = 1 m^2$$

$$Capital Cost = 2.88 * 10^3 * A^{0.539} * \left(\frac{1478}{988}\right) = 2.88 * 10^3 * 1^{0.539} * \left(\frac{1478}{988}\right) = \$4,308$$

The air blower required for this EoL treatment had a total rating of 1.515 kW. The conversion was used (1653/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘pumping and compressing equipment’ in the price index spreadsheet.

$$(962 * 1.515kW + 14 * 10^3) * \frac{1653}{988} = \$25,861.47$$

Final total calculation:

$$C_{anaerobic\ digestion} = (1 + f_a + f_b + \dots) * \Sigma MPIC$$

$$\begin{aligned} C_{anaerobic\ digestion} &= (1 + f_{equip,del} + f_{equip,install} + f_{piping} + f_{elect} + f_{instru} + f_{aux} + f_{f,exp} \\ &+ f_{eng} + f_{Cfop} + f_{cont}) * \$438,443.72 \end{aligned}$$

$$C_{anaerobic\ digestion} = \$2,136,279$$

Incineration

Table 38: Capital cost estimate for the incineration EoL treatment

Process	Process used	Measurement	Cost
Shredder	Jaw crusher	1 kg/s	\$ 33,808.50
Conveyors	Auger conveyor	Diameter = 0.46 m Distance = 2 m	\$ 3,526.03
Water storage tank	Stainless steel liquid storage tank	Volume = 1.5 m ³	\$ 6,184.12
Diesel storage tank	Stainless steel liquid storage tank	Volume = 1.5 m ³	\$ 6,184.12
Dryer	Industrial oven	Internal volume = 3 m ³	\$ 8,916.01
Incinerator	Industrial oven	Internal volume = 3 m ³	\$ 29,721.91
Burner	Industrial oven	Internal volume = 1 m ³	\$ 14,649.09
Flare	--	--	\$ 5,733.21

Air blowers	Centrifugal blower	191.06 kW (total for 4 blowers)	\$ 401,203.38
40' Container**	--	--	\$ 14,950.00
Total without Lang factors (<i>ΣMPIC</i>)			\$ 524,876.36
Total with Lang factors incorporated			\$2,532,528.46
Truck*			\$ 449,000.00
Container installation and alterations for process specifications			\$ 100,000.00
Total capital cost(<i>C_{incineration}</i>)			\$3,081,528.46

*From HINO (2022). **From NZBox (personal communication, May 31, 2022).

The shredder is 15hp with a capacity of 225 kg/hr, which is less than 1 kg/s. However, within Bouman et al. (2005), a jaw crusher has the lowest capacity being 1 kg/s. Therefore, that capacity was used. A conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category 'other plant, machinery, and equipment' in the price index spreadsheet.

$$22.6 * 10^3 * 1 \frac{kg^{0.611}}{s} * (\frac{1478}{988}) = \$33,808.50$$

When calculating the electricity requirement and the processing time of the conveyors, an assumed 2 m distance, 0.78 m diameter, and 0.5 m pitch were used from Asli-Arden (Asli-Arden & Mohsenimanesh, 2012). However, this diameter was not available for the capital cost calculation. Therefore, a diameter of 0.46 m was used along with a distance of 2 m. A conversion was used (1351/988) to convert the cost from the 2004 value to March 2022 value based on the category 'lifting and handling equipment' in the price index spreadsheet.

$$(1.93 * 10^3 * 2^{0.418}) * (\frac{1351}{988}) = \$3,526.03$$

The water storage tank required a maximum volume of 1 m³ to hold the required bleach for one cycle. However, a conservative value of 1.5 m³ was used for the capital cost. A conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category 'metal tanks, reservoirs, and containers' in the price index spreadsheet.

$$(2.48 * 10^3 * 1.5^{0.597}) * (\frac{1934}{988}) = \$6,184.12$$

The diesel storage tank was assumed to require the same sized tank as water in this EoL treatment. Therefore, a conservative value of 1.5 m³ was used for the capital cost. A conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘metal tanks, reservoirs, and containers’ in the price index spreadsheet.

$$(2.48 * 10^3 * 1.5^{0.597}) * (\frac{1934}{988}) = \$6,184.12$$

The dryer and incinerator were assumed to require an internal volume of 3 m³ for their operations. However, each requires a different maximum internal temperature. The dryer would require a maximum temperature of 500°C. A conversion was used (1433/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘oven and furnace burners’ in the price index spreadsheet.

$$((3 * 10^3) * 3m^{3^{0.653}}) * \frac{1433}{988} = \$8,916.01$$

The incinerator would require a maximum temperature of 1000°C.

$$((10.1 * 10^3) * 3m^{3^{0.644}}) * \frac{1433}{988} = \$29,721.91$$

The burner was assumed to have an internal volume of 1 m³ and due to the availability of furnace capital costs, a maximum temperature of 1000°C was chosen to represent the burner.

$$((10.1 * 10^3) * 1m^{3^{0.644}}) * \frac{1433}{988} = \$14,649.09$$

The capital cost for the flare was obtained from an estimated range of \$1,000 to \$5,000 (EPA, 2011). The conservative value of \$5,000 was used, but this value was from 2011, and an increase to 2022 prices would have occurred. Therefore, a conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category ‘plant, machinery, and equipment’ in the price index spreadsheet.

$$\$5,000 * \frac{1212}{1057} = \$5,733.21$$

The air blowers required for this EoL treatment had a total rating of 191.06 kW (8.8 kW, 66.16 kW, 32.84 kW, and 83.26 kW). A conversion was used (1653/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘pumping and compressing equipment’ in the price index spreadsheet.

$$((962 * 8.8kW + 14 * 10^3) * \frac{1653}{988}) + ((962 * 66.16kW + 14 * 10^3) * \frac{1653}{988})$$

$$+((962 * 32.84kW + 14 * 10^3) * \frac{1653}{988}) + ((962 * 83.26kW + 14 * 10^3) * \frac{1653}{988})$$

$$= \$401,203.38$$

The capital cost of a 40' container required for the storage of green waste was obtained from the supplier, NZ Box (Personal communication, May 31, 2022).

Final total calculation:

$$C_{incineration} = (1 + f_a + f_b + \dots) * \Sigma MPIC$$

$$C_{incineration} = (1 + f_{equip,del} + f_{equip,install} + f_{piping} + f_{elect} + f_{instru} + f_{aux} + f_{f,exp} + f_{eng} + f_{c,op} + f_{cont}) * \$524,876.36$$

$$C_{incineration} = \$2,532,528.46 + \$449,000 + \$100,000 = \$3,081,528.46$$

Pyrolysis

Table 39: Capital cost estimate for the pyrolysis EoL treatment

Process	Process used	Measurement	Cost
Shredder	Jaw crusher	1 kg/s	\$ 33,808.50
Conveyors	Auger conveyor	Diameter = 0.46 m Distance = 2 m	\$ 3,526.03
Water storage tank	Stainless steel liquid storage tank	Volume = 1.5 m ³	\$ 6,184.12
Diesel storage tank	Stainless steel liquid storage tank	Volume = 1.5 m ³	\$ 6,184.12
Dryer	Industrial oven	Internal volume = 3 m ³	\$ 8,916.01
Pyrolyser	Industrial oven	Internal volume = 3 m ³	\$ 29,721.91
Burner	Industrial oven	Internal volume = 1 m ³	\$ 31,328.74
Flare	--	--	\$ 5,733.21
Air blowers	Centrifugal blower	18.32 kW (x2 blowers)	\$ 105,818.23
40' Container**	--	--	\$ 14,950.00
Total without Lang factors ($\Sigma MPIC$)			\$ 246,170.88

Total with Lang factors incorporated			\$1,187,774.48
Truck*			\$ 449,000.00
Container installation and alterations for process specifications			\$ 100,000.00
Total capital cost($C_{pyrolysis}$)			\$1,736,774.48

*From HINO (2022). **From NZBox (personal communication, May 31, 2022).

The shredder is 15hp with a capacity of 225 kg/hr, which is less than 1 kg/s; however, within Bouman et al. (2005), a jaw crusher has the lowest capacity being 1 kg/s. Therefore, that capacity was used. The conversion was also used (1478/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘other plant, machinery, and equipment’ in the price index spreadsheet.

$$22.6 * 10^3 * 1 \frac{kg}{s}^{0.611} * \left(\frac{1478}{988}\right) = \$33,808.50$$

When calculating the electricity requirement and the processing time of the conveyors, an assumed 2 m distance, 0.78 m diameter, and 0.5 m pitch were used from Asli-Arden (Asli-Arden & Mohsenimanesh, 2012). However, this diameter was not available for the capital cost calculation. Therefore, a diameter of 0.46 m was used along with a distance of 2 m. The conversion was used (1351/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘lifting and handling equipment’ in the price index spreadsheet.

$$(1.93 * 10^3 * 2^{0.418}) * \left(\frac{1351}{988}\right) = \$3,526.03$$

The water storage tank required a maximum volume of 1 m³ to hold the required bleach for one cycle. However, a conservative value of 1.5 m³ was used for the capital cost. A conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘metal tanks, reservoirs, and containers’ in the price index spreadsheet.

$$(2.48 * 10^3 * 1.5^{0.597}) * \left(\frac{1934}{988}\right) = \$6,184.12$$

The diesel storage tank was assumed to require the same sized tank as water in this EoL treatment. Therefore, a conservative value of 1.5 m³ was used for the capital cost. A conversion was used (1934/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘metal tanks, reservoirs, and containers’ in the price index spreadsheet.

$$(2.48 * 10^3 * 1.5^{0.597}) * \left(\frac{1934}{988}\right) = \$6,184.12$$

The dryer and pyrolyser were assumed to require an internal volume of 3 m³ for their operations. However, each requires a different maximum internal temperature. Due to the availability of costs for furnaces, it was chosen that the dryer would require a maximum temperature of up to 500°C (the lowest maximum temperature furnace cost available). The conversion was used (1433/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘oven and furnace burners’ in the price index spreadsheet.

$$((3 * 10^3) * 3m^{3^{0.653}}) * \frac{1433}{988} = \$8,916.01$$

Due to the availability of costs for furnaces, it was chosen that the pyrolyser would require a maximum temperature of between 500-1000°C, with an assumed internal volume of 3 m³.

$$((10.1 * 10^3) * 3m^{3^{0.663}}) * \frac{1433}{988} = \$29,721.91$$

The burner was assumed to have an internal volume of 1 m³. Due to the availability of costs for furnaces, it was chosen that the burner would require a maximum temperature of between 1000-1500°C. The burner should not get above 1200°C because NOx release and potassium and sodium slags become an issue; therefore, the temperature is controlled using excess air.

$$((21.6 * 10^3) * 1m^{3^{0.663}}) * \frac{1433}{988} = \$31,328.74$$

The capital cost for the flare was obtained from an estimated range of \$1,000-\$5,000 (EPA, 2011). The conservative value of \$5,000 was used, but this value was from 2011, and an increase to 2022 prices would have occurred. Therefore, a conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category ‘plant, machinery, and equipment’ in the price index spreadsheet.

$$\$5,000 * \frac{1212}{1057} = \$5,733.21$$

The air blowers required for this EoL treatment had a total rating of 18.32 kW (18.32 kW and 0 kW). The 0-kW air blower is on standby in case the flue gas entering the dryer from the pyrolyser is required to be cooled. Therefore, this 0-kW air blower is assumed to be the same price as the 18.32 kW air blower to be held on standby as a safety precaution. The conversion was used (1653/988) to convert the cost from the 2004 value to March 2022 value based on the category ‘pumping and compressing equipment’ in the price index spreadsheet.

$$((962 * 18.32kW + 14 * 10^3) * \frac{1653}{988}) * 2 = \$105,818.23$$

The capital cost of a 40’ container required for the storage of green waste was obtained from the supplier, NZBox (Personal communication, May 31, 2022).

Final total calculation:

$$C_{pyrolysis} = (1 + f_a + f_b + \dots) * \Sigma MPIC$$

$$C_{pyrolysis} = (1 + f_{equip,del} + f_{equip,install} + f_{pipng} + f_{elect} + f_{instru} + f_{aux} + f_{f,exp} + f_{eng} + f_{Cfop} + f_{cont}) * \$246,170.88$$

$$C_{pyrolysis} = \$1,187,774 + \$449,000 + \$100,000 = \$1,736,774$$

Appendix N.2: Operational costs

Tables 40-44 show the operating cost of each EoL treatment. Calculations are below the tables. There are several costs that all EoL treatments use, and they will be explained here. The electricity cost is set at the 2021 average of 29.36 cents/kWh (Granwal, 2022), with each year an assumption that 30 tonnes of biomass are processed (30*FU). The cost of using water will be \$315 per year for Rotorua ratepayers in 2021 (Rotorua Lakes Council, 2021). Employees are required for all EoL treatments per employee the rate includes the salary and wage rate, non-wage costs (15.61%), compliance costs, and office costs (MBIE, 2020). The maintenance of each piece of equipment purchased is assumed to be conservative at 6% of its capital cost.

Landfill

Table 40: Operational cost estimate for the landfill EoL treatment

Process	Measurement	Operational cost
Electricity	1720.8 kWh/year	\$ 505.23
Water use	--	\$ 315.00
Maintenance	6% Capital Equipment	\$ 6,699.19
Labour	132 hrs/year	\$ 9,999.88
Bleach	375 kg/FU = 11,250 kg/year	\$ 40,909.09
Bleach transport	Estimate	\$ 5,000.00
Dump charge	\$207.60/tonne	\$ 14,942.00
Transport of material to transfer station	12-14 m ³ tip truck*	\$ 8,500.00
Transport of green waste to on-site facility	12-14 m ³ tip truck*	\$ 8,500.00
Green waste cost	30 tonnes/year	\$ 2,250.00
Diesel for transport	\$2.2/L	\$ 5,280.00

Total	--	\$102,900**
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Note. *From CostOwl (2022). **Rounded to the nearest whole number.

The shredder, mixer, and conveyors are the only objects that require electricity in this EoL treatment; they each require 49.73 kWh/FU, 6.63 kWh/FU, and conservative for the conveyors 1 kWh/FU.

$$(49.73 + 6.63 + 1) \frac{kWh}{FU} * 30 \frac{FU}{yr} * 0.2936 \frac{\$}{kWh} = \$2,904.08$$

For the landfill EoL treatment, the minimum operators required are assumed to be two technical operators of the equipment, one supervisor, and one administration employee added to the company. According to the MBIE (2020), three waste-trade/service off-site employees (assuming the supervisor is paid 55k per year and the technical hands are paid 50k per year) and one admin employee at 45k per year salaries excluding the fringe benefits tax or industry insurance, costs the company \$305,451.00 per year for labour. However, this cost is for full-time work (48 weeks/year at 12 hours/day) over an entire year; employees were found to be required for 132 hours/year for this role based on the functional unit of 30 tonnes/year (Section 6.2.1). Therefore, the revised cost is \$9,999.88.

The price of bleach was estimated by Arnold Products Ltd. (n.d.) to be \$82.41inc.GST for 20 L meant that it cost approximately \$4/L of bleach. The landfill EoL treatment requires 375.06 kg of bleach per FU; at 30 functional units per year, 11250 kg of bleach is required per year.

$$375.06 \frac{kg}{FU} * 30 \frac{FU}{yr} = 11250 \frac{kg}{yr}$$

$$\frac{11250 \frac{kg}{yr}}{1100 \frac{kg}{m^3}} = 10.2273 \frac{m^3}{yr}$$

$$10.2273 \frac{m^3}{yr} * 1000 \frac{L}{m^3} = 10227.3 \frac{L}{yr}$$

$$10227.3 \frac{L}{yr} * 4 \frac{\$}{L} = \$40,909.09$$

According to Rotorua Lakes Council (n.d.), it costs \$207.60 per tonne of refuse waste as well as a \$10 weight charge for each entry into the dump. The landfill EoL treatment requires 2375.06 kg/FU of material to be dumped. It is assumed that per cycle, three trips to the dump will be made, and there are 5 cycles per year.

$$2375.06 \frac{kg}{FU} * 30 \frac{FU}{yr} = 71251.8 \frac{kg}{yr} = 71.2518 \frac{t}{yr}$$

$$71.2518 \frac{t}{yr} * 207.60 \frac{\$}{t} = 14,791.87 \frac{\$}{yr} \text{ for dump charge}$$

$$10 \frac{\$}{trip \text{ to dump}} * 3 \frac{trips}{cycle} * 5 \frac{cycles}{yr} = 150 \frac{\$}{yr} \text{ for weight charge}$$

$$14,791.87 + 150 = \$14,942$$

To obtain the green waste required to be mixed with the biomass it would cost approximately \$30/m³ of green waste, this is assumed using mulch pricing in the Auckland to Rotorua area (PNCC, n.d.).

$$\frac{30 \frac{t \text{ of green waste}}{yr}}{0.4 \frac{t}{m^3}} = 75 \frac{m^3}{yr} \quad (\text{ANL, n.d.})$$

$$75 \frac{m^3}{yr} * 30 \frac{\$}{m^3} = 2250 \frac{\$}{yr}$$

It was assumed that the trucks used for transport in this EoL treatment had a fuel usage of 40 L/100 km, assuming two 100 km journeys per outing from the facility at three times per cycle and 5 cycles/yr., the diesel cost for the hired trucks was estimated at \$2.2/L.

$$(2.2 \frac{\$}{L} * 40 \frac{L}{100km}) * 2 \frac{100km}{journey} * 3 \frac{journeys}{cycle} * 5 \frac{cycles}{yr} * 2 \text{ trucks} = \$5,280$$

Composting

Table 41: Operational cost estimate for the composting EoL treatment

Process	Measurement	Operational cost
Electricity	1720.8 kWh/year	\$ 505.23
Water use	--	\$ 315.00
Maintenance	6% Capital Equipment	\$ 6,625.73
Labour	132 hrs/year	\$ 9,999.88
Cost of composting material	\$50/tonne	\$ 3,000.00
Transport of material to composting facility	12-14 m ³ tip truck*	\$ 8,500.00
Transport of green waste to on-site facility	12-14 m ³ tip truck*	\$ 8,500.00

Green waste cost	30 tonnes/yr.	\$ 2,250.00
Diesel for transport	\$2.2/L	\$ 5,280.00
Total	--	\$ 44,976.00**

Note. *From CostOwl (2022). **Rounded to the nearest whole number.

The shredder, mixer, and conveyors are the only objects that require electricity in this EoL treatment, they each require 49.73 kWh/FU, 6.63 kWh/FU, and being conservative for the conveyors 1 kWh/FU.

$$(49.73 + 6.63 + 1) \frac{kWh}{FU} * 30 \frac{FU}{yr} * 0.2936 \frac{\$}{kWh} = \$505.23$$

For the composting EoL treatment, the minimum operators required are assumed to be two technical operators of the equipment, one supervisor, and one administration employee added to the company. According to the MBIE (2020), three waste-trade/service off-site employees (assuming the supervisor is paid 55k per year and the technical hands are paid 50k per year) and one admin employee at 45k per year salaries excluding the fringe benefits tax or industry insurance, costs the company \$305,451.00 per year for labour. However, this cost is for full-time work (48 weeks/year at 12 hours/day) over an entire year; employees were found to be required for 132 hours/year for this role based on the functional unit of 30 tonnes/year (Section 6.2.1). Therefore, the revised cost is \$9,999.88.

It was assumed that it would cost approximately \$50/tonne to compost the material (Jones et al., 2020). Composting the material allows selling the compost for a profit.

To obtain the green waste required to be mixed with the biomass it would cost approximately \$30/m³ of green waste, this is assumed using mulch pricing in the Auckland to Rotorua area (PNCC, n.d.).

$$\frac{30 \frac{t \text{ of green waste}}{yr}}{0.4 \frac{t}{m^3}} = 75 \frac{m^3}{yr} \quad (\text{Arnold Products Ltd., n.d.})$$

$$75 \frac{m^3}{yr} * 30 \frac{\$}{m^3} = 2250 \frac{\$}{yr}$$

It was assumed that the trucks used for transport in this EoL treatment had a fuel usage of 40 L/100 km, assuming two 100 km journeys per outing from the facility at three times per cycle and 5 cycles/yr., the diesel cost for the hired trucks was estimated at \$2.2/L.

$$(2.2 \frac{\$}{L} * 40 \frac{L}{100km}) * 2 \frac{100km}{journey} * 3 \frac{journeys}{cycle} * 5 \frac{cycles}{yr} * 2 trucks = \$5,280$$

Anaerobic digestion

Table 42: Operational cost estimate for the anaerobic digestion EoL treatment

Process	Measurement	Operational cost
Electricity	91.35 kWh/year	\$ 804.57
Water use	--	\$ 315.00
Maintenance	6% Capital Equipment	\$ 26,565.12
Labour	780 hrs/year	\$ 59,090.22
Cost of composting material	\$50/tonne	\$ 563.40
Transport of digestate solids to composting facility	12-14 m ³ tip truck*	\$ 3,500.00
Trade waste	\$0.57/kg BOD \$0.81/m ³	\$ 18,136.38
Diesel for transport	\$2.2/L	\$ 880.00
Fuel cost for flaring	--	\$ 2,063.95
Total	--	\$111,919.00**

Note. *From CostOwl (2022). **Rounded to the nearest whole number.

The shredder, digester, belt filter press, and conveyors are the only objects that require electricity in this EoL treatment, they each require 49.74 kWh/FU, 3.44 kWh/FU, 18.58 to 55.75 kWh/FU, and being conservative for the conveyors 1 kWh/FU. An average was taken for the belt filter press.

$$(49.73 + 3.44 + 37.165 + 1) \frac{kWh}{FU} * 30 \frac{FU}{yr} * 0.2936 \frac{\$}{kWh} = \$804.57$$

For the anaerobic digestion EoL treatment, the minimum operators required are assumed to be two technical operators of the equipment, one supervisor, and one administration employee added to the company. According to the MBIE (2020), three waste-trade/service off-site employees (assuming the supervisor is paid 55k per year and the technical hands are paid 50k per year) and one admin employee at 45k per year salaries excluding the fringe benefits tax or industry insurance, costs the company \$305,451.00 per year for labour. However, this cost is for full-time work (48 weeks/year at 12 hours/day) over an entire year; employees were found to be required for 780 hours/year for this role based on the functional unit of 30 tonnes/year (Section 6.2.2). Therefore, the revised cost is \$9,999.88.

It was assumed that it would cost approximately \$50/tonne to compost the material (Jones et al., 2020). Composting the material allows selling the compost for a profit.

$$0.3756 \frac{t \text{ of solids to be composted}}{FU} * 30 \frac{FU}{yr} * 50 \frac{\$}{t} = \$563.40$$

Trade waste is an important part of the operating costs for this EoL treatment because the liquids from digestion that are sent to the wastewater treatment plant (WWTP) have a BOD value. According to Jones et al. (2020), the trade waste charges are \$0.81/m³ + \$0.57/kg BOD (inc. GST). It is assumed that all the BOD from the fresh biomass goes into the liquid being sent to the WWTP. The BOD present in the trade waste was calculated to be 1058.5 kg BOD with the volume of liquid being 1.48 m³.

$$1000 \frac{kg}{FU} * (1 - 0.71 \text{ moisture}) = 290 \frac{kg \text{ dry matter}}{FU} = 0.29 \frac{t \text{ dry matter}}{FU}$$

$$0.29 \frac{t \text{ dry matter}}{FU} * 14.6 \frac{t VS}{t DM} = 4.234 \frac{t VS}{FU} * 1000 * 1000 = 4234000 \frac{g VS}{FU}$$

(Kortekaas et al., 1998)

$$4234000 \frac{g VS}{FU} * 0.25 \frac{g BOD}{g VS} = 1058500 \frac{g BOD}{FU} = 1058.5 \frac{kg BOD}{FU}$$

(Rudolfs, 1932)

$$1058.5 \frac{kg BOD}{FU} * 0.57 \frac{\$}{kg BOD} = 603.35 \frac{\$}{FU} \text{ for BOD charge}$$

$$1482.7 \frac{kg \text{ liquid}}{FU} = 1.483 \frac{m^3 \text{ liquid}}{FU}$$

$$1.483 \frac{m^3 \text{ liquid}}{FU} * 0.81 \frac{\$}{m^3 \text{ liquid}} = 1.20123 \frac{\$}{FU} \text{ for volume charge}$$

$$(603.35 + 1.20123) \frac{\$}{FU} * 30 \frac{FU}{yr} = \$18,136.38$$

It was assumed that the trucks used for transport in this EoL treatment had a fuel usage of 40 L/100 km, assuming two 100 km journeys per outing from the facility at three times per cycle and 5 cycles/year, the diesel cost for the hired truck was estimated at \$2.2/L.

$$(2.2 \frac{\$}{L} * 40 \frac{L}{100km}) * 2 \frac{100km}{journey} * 1 \frac{journeys}{cycle} * 5 \frac{cycles}{yr} = \$880.00$$

The fuel cost for the flare was estimated at \$1,800 per flare in 2011 (EPA, 2011). However, this value was from 2011, and an increase in 2022 prices would have occurred. Therefore, a

conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category ‘plant, machinery, and equipment’ in the price index spreadsheet.

$$\$1,800 * \frac{1212}{1057} = \$2,063.95$$

Incineration

Table 43: Operational cost estimate for the incineration EoL treatment

Process	Measurement	Operational cost
Electricity	11,663.7 kWh/year	\$ 3,424.46
Water use	--	\$ 315.00
Maintenance	6% Capital Equipment	\$ 57,535.58
Labour	420 hrs/year	\$ 47,630.52
Cost of running HIAB truck	\$2.2/L	\$ 880.00
Transport of ash to transfer station	12-14 m ³ tip truck*	\$ 3,500.00
Cost of disposing of ash at the landfill	217.50 kg/year \$207.60/tonne	\$ 95.15
Diesel for transport to transfer station	\$2.2/L	\$ 880.00
Fuel cost for flaring	--	\$ 2,063.95
Diesel for burner	\$2.2/L	\$ 3,798.84
Road user charges for truck	\$0.435/km	\$ 435.00
Total	--	\$120,559.00**

Note. *From CostOwl (2022). **Rounded to the nearest whole number.

The shredder, dryer, incinerator, diesel burner, air pumps, diesel fuel pump, and conveyors are the only objects that require electricity in this EoL treatment, they each require 49.73 kWh/FU, 48 kWh/FU, 48 kWh/FU, 48 kWh/FU, (8.8+83.26+66.16+32.84) kWh/FU, 3 kWh/FU, and being conservative for the conveyors 1 kWh/FU.

$$(49.73 + 48 + 48 + 48 + 8.8 + 83.26 + 66.16 + 32.84 + 3 + 1) \frac{kWh}{FU}$$

$$* 30 \frac{FU}{yr} * 0.2936 \frac{\$}{kWh} = \$3,424.46$$

For the incineration EoL treatment, the minimum operators required are assumed to be one technical operator of the equipment, one supervisor, two heavy vehicles licensed drivers who

are also technical operators and two administration employees. According to the MBIE (2020), two waste-trade/service off-site employees (assuming the supervisor is paid 55k per year and the technical hand is paid 50k per year), the two heavy vehicle drivers who are also technical hands are paid 50k per year and one admin employee at 45k per year salaries excluding the fringe benefits tax or industry insurance, costs the company \$457,253.00 per year for labour. However, this cost is for full-time work over an entire year. The revised labour cost for the functional unit of 30 tonnes/year, based on the processing time of one week per cycle (Section 6.2.3) is \$47,630.52 per year.

It was assumed that both the HIAB truck containing the thermal system and the truck transporting the ash to the landfill had a fuel usage of 40 L/100 km, assuming two 100 km journeys per outing from the facility once per cycle and 5 cycles/yr., the diesel cost for both the hired truck and HIAB were estimated at \$2.2/L.

$$\left(2.2 \frac{\$}{L} * 40 \frac{L}{100km}\right) * 2 \frac{100km}{journey} * 1 \frac{journeys}{cycle} * 5 \frac{cycles}{yr} = \$880.00 * 2 trucks$$

The road user charges (RUCs) were estimated using the rate up to the 20th of April 2022 for a powered vehicle with four axles, \$0.435/km (NZTA, n.d.).

The fuel cost for the flare was estimated at \$1,800 per flare (EPA, 2011). However, this value was from 2011, and an increase in 2022 prices would have occurred. Therefore, a conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category 'plant, machinery, and equipment' in the price index spreadsheet.

$$\$1,800 * \frac{1212}{1057} = \$2,063.95$$

Diesel was required for the burner inside the mobile unit, this was estimated using a diesel price of \$2.2/L.

$$99 \frac{kg diesel}{day} * 3 \frac{days}{cycle} * 5 \frac{cycles}{year} = 1485 \frac{kg diesel}{year}$$

At a density of 860 kg/m³ and a cost of \$2.2/L, it would cost \$3,798.84 per year.

$$\frac{1485 \frac{kg diesel}{year}}{860 \frac{kg}{m^3}} * 1000 * 2.2 \frac{\$}{L} = \$3,798.84$$

To dispose of the ash to landfill each cycle it will cost an estimate of \$95.15 per year assuming the refuse charge is \$207.60/tonne with a \$10 weight charge.

$$\frac{7.25 \frac{kg}{FU} * 30 \frac{FU}{year}}{1000} * 207.60 \frac{\$}{tonne} + \left(10 \frac{\$}{cycle} * 5 \frac{cycles}{year} \right) = \$95.15$$

Pyrolysis

Table 44: Operational cost estimation for the pyrolysis EoL treatment

Process	Measurement	Operational cost
Electricity	6,480 kWh/year	\$ 1,928.95
Water use	--	\$ 315.00
Maintenance	6% Capital Equipment	\$40,813.25
Labour	420 hrs/year	\$47,630.52
Road user charges	\$0.435/km	\$ 435.00
Diesel for burner	\$2.2/L	\$ 311.20
Diesel for transport of mobile unit	\$2.2/L	\$ 880.00
Fuel cost for flaring	--	\$ 2,063.95
Total	--	\$94,378.00*

Note. For this treatment, it was assumed that operating costs do not include the land spreading of the biochar because it will be sold to be land spread. However, the environmental impacts assessed for this EoL treatment in Chapter 5 include the carbon sequestration and land spreading of the biochar. *Rounded to the nearest whole number.

The shredder, dryer, pyrolyser, diesel burner, air pumps, diesel fuel pump, and conveyors are the only objects that require electricity in this EoL treatment, they each require 49.73 kWh/FU, 48 kWh/FU, 48 kWh/FU, 48 kWh/FU, 18.3 kWh/FU, 3 kWh/FU, and being conservative for the conveyors 1 kWh/FU.

$$(49.73 + 48 + 48 + 48 + 18.3 + 3 + 1) \frac{kWh}{FU} * 30 \frac{FU}{yr} * 0.2936 \frac{\$}{kWh} = \$1,928.95$$

For the pyrolysis EoL treatment, the minimum operators required are assumed to be one technical operator of the equipment, one supervisor, two heavy vehicles licensed drivers who are also technical operators and two administration employees. According to the MBIE (2020), two waste-trade/service off-site employees (assuming the supervisor is paid 55k per year and the technical hand is paid 50k per year), the two heavy vehicle drivers who are also technical hands are paid 50k per year and one admin employee at 45k per year salaries excluding the fringe benefits tax or industry insurance, costs the company \$457,253.00 per year for labour. However, this cost is for full-time work over an entire year. The revised labour cost for the

functional unit of 30 tonnes/year, based on the processing time of one week per cycle (Section 6.2.3) is \$47,630.52 per year.

It was assumed that the HIAB truck containing the thermal system had a fuel usage of 40 L/100 km, assuming two 100 km journeys per outing from the facility once per cycle and 5 cycles/yr., the diesel cost for the HIAB was estimated at \$2.2/L.

$$\left(2.2 \frac{\$}{L} * 40 \frac{L}{100km}\right) * 2 \frac{100km}{journey} * 1 \frac{journeys}{cycle} * 5 \frac{cycles}{yr} = \$880.00$$

The road user charges (RUCs) were estimated using the rate up to the 20th of April 2022 for a powered vehicle with four axles, \$0.435/km (NZTA, n.d.).

The fuel cost for the flare was estimated at \$1,800 per flare (EPA, 2011). However, this value was from 2011, and an increase in 2022 prices would have occurred. Therefore, a conversion of 1212/1057 was used to convert the cost to March 2022 values based on the category 'plant, machinery, and equipment' in the price index spreadsheet.

$$\$1,800 * \frac{1212}{1057} = \$2,063.95$$

Diesel was required for the burner inside the mobile unit, this was estimated using a diesel price of \$2.2/L.

$$8.11 \frac{kg \text{ diesel}}{day} * 3 \frac{days}{cycle} * 5 \frac{cycles}{year} = 121.65 \frac{kg \text{ diesel}}{year}$$

At a density of 860 kg/m³ and a cost of \$2.2/L, it would cost \$311.20 per year.

$$\frac{121.65 \frac{kg \text{ diesel}}{year}}{860 \frac{kg}{m^3}} * 1000 * 2.2 \frac{\$}{L} = \$311.20$$

Appendix N.3: Revenue

Landfill - 60% of the avoided landfill charge

For 30 tonnes of cannabis residues are landfilled per year, at \$207.60/tonne with a \$10 weight charge per dump.

$$207.60 \frac{\$}{tonne} * 30 \frac{tonnes}{year} + 10 \frac{\$}{weight} * 3 \frac{weights}{cycle} * 5 \frac{cycles}{year} = 6378 \frac{\$}{year}$$

Of this landfill charge, it is assumed that 60% can be charged to the cultivation facility for the mobile unit EoL treatments to dispose of the cannabis residues. The stationary EoL treatments, of anaerobic digestion and composting are not able to charge this as they are assumed to be occurring at the cultivation facility.

$$\frac{\$6378}{30 \frac{\text{tonnes}}{\text{year}}} * 60\% = 127.56 \frac{\$}{FU}$$

Composting

Rotorua sold garden waste compost at \$96/m³ in 2021 (*Gardening and landscaping products in Rotorua*, n.d.). Assuming an average compost density of 537.50 kg/m³ (Khater, 2015).

$$\left(\frac{1000 \frac{\text{kg}}{\text{tonne}}}{537.50 \frac{\text{kg}}{\text{m}^3}} \right) = 1.86 \frac{\text{m}^3}{\text{tonne}}$$

$$96 \frac{\$}{\text{m}^3} * 1.86 \frac{\text{m}^3}{\text{tonne}} = 178.60 \frac{\$}{\text{tonne of compost}}$$

$$\frac{178.60}{2} \frac{\frac{\$}{\text{tonne of compost}}}{\frac{\text{tonnes of compost produced}}{FU}} = 89.30 \frac{\$}{FU}$$

Anaerobic Digestion

The products from the anaerobic digestion EoL treatment that are able to be sold are the residue in the digestate that is sent to the compost facility, and the heat produced from burning the biogas. The burnt biogas heat can only be sold if the cultivation facility does not utilise the heat because this EoL treatment completed at the cultivation facility.

The residue in the digestate which is sent to the compost facility and has roughly the same nutrient value as the cannabis residue discussed above for the composting scenario. Therefore, the revenue obtainable from the digestate, is calculated to be \$67.08/FU.

$$178.60 \frac{\$}{\text{tonne of compost}} * \frac{375.60 \text{ solids}}{1000} \frac{FU}{FU} = 67.08 \frac{\$}{FU}$$

The biogas is combusted to make heat and if it is sold it has a value of \$10/GJ. The revenue value can be calculated assuming 700 kWh/t cannabis plant residue heat energy, the same heat energy as used for grape marc in Fabbri et al. (2015). The conversion is 1 kWh = 0.0036 GJ. If so, the heat revenue is calculated to be \$25.20/FU.

$$30 \frac{\text{tonne}}{\text{year}} * 700 \frac{\text{kWh}}{\text{tonne}} * 0.0036 \frac{\text{GJ}}{\text{kWh}} * 10 \frac{\$}{\text{GJ}} = \$756 \text{ or } 25.20 \frac{\$}{\text{FU}}$$

Incineration

The fee of 60% of the landfill charges, \$127.56/FU, applies here as revenue to the incineration operator, less the cost of sending ash to landfill, calculated within the operating costs above at \$498/FU. Incineration also produces heat, which is not captured here because the incinerator is assumed to be a small mobile unit, unlike the stationary anaerobic digester. Also, ash has nutrient value and so if the ash was sent to be land-spread, additional revenue can be gained. Expecting that the ash has less value than the compost, at \$30/t compost equivalent compared to \$178.60/t compost, or approximately 17% of the value, the ash-as-nutrient revenue can be calculated.

$$(89.30 \frac{\$}{\text{FU}} * 17\%) + 127.56 \frac{\$}{\text{FU}} = 138.96 \frac{\$}{\text{FU}}$$

Pyrolysis

There are three revenue scenarios that can occur in the pyrolysis EoL treatment; the biochar can either be sold as a fuel for heating, land spread as a fertiliser, or it can be land spread as a fertiliser and include the carbon sequestration value.

According to Jones et al. (2020), the revenue range of biochar is from the assumption that it has a heating value of 30 GJ/t which had a price of \$10/GJ (\$300/t biochar) and if the biochar is sold at the price of wood pellets used in pellet burners (\$675/t biochar). Even though these prices are from 2020, it was assumed for this study that they were still relevant. Therefore, the biochar could be sold at either \$128.02/FU (at \$10/GJ) or \$196.07/FU (at \$675/t biochar), exclusive of the landfill fee charged to the cultivation facility.

$$300 \frac{\$}{\text{t biochar}} * \frac{101.5 \frac{\text{kg biochar}}{\text{FU}}}{1000 \frac{\text{kg}}{\text{t}}} = 30.45 \frac{\$}{\text{FU}} \text{ at } 10 \frac{\$}{\text{GJ}}$$

$$675 \frac{\$}{\text{t biochar}} * \frac{101.5 \frac{\text{kg biochar}}{\text{FU}}}{1000 \frac{\text{kg}}{\text{t}}} = 68.51 \frac{\$}{\text{FU}} \text{ at } 675 \frac{\$}{\text{t biochar}}$$

If the biochar is land spread, at an assumed \$87/t of biochar (Jones et al., 2020) then revenue of \$8.83/FU will be made.

$$87 \frac{\$}{t \text{ biochar}} * \frac{101.5 \frac{kg \text{ biochar}}{FU}}{1000} = 8.83 \frac{\$}{FU} \text{ excl. avoided landfill fee}$$

According to Jones et al. (2020), if the biochar is land spread and carbon sequestration is incorporated, then the revenue would have been \$163.66/t biochar assuming 80% of the embodied carbon is recalcitrant. However, subtracting the land-spread portion to obtain an intrinsic carbon value of \$76.66/t biochar allows the intrinsic carbon value of the cannabis plant residue biochar to be calculated at \$125.84/t biochar. New Zealand Units (NZU) were at \$27/t CO2-eq. in 2020, and in 2022 they were at \$70/t CO2-eq.; this is an inflation of 164%.

$$163.66 \frac{\$}{t \text{ biochar}} - 87 \frac{\$}{t \text{ biochar land - spread}} = 76.66 \frac{\$ \text{ intrinsic carbon value}}{t \text{ biochar}}$$

$$76.66 \frac{\$ \text{ intrinsic carbon value}}{t \text{ biochar}} * 164\% = 125.84 \frac{\$ \text{ intrinsic carbon value}}{t \text{ biochar}}$$

$$\begin{aligned} 125.84 \frac{\$}{t \text{ biochar}} * \frac{\left(101.50 \frac{kg \text{ biochar}}{FU}\right)}{1000} + 8.83 \frac{\$}{FU} \\ = 21.60 \frac{\$}{FU} \text{ (excl. avoided landfill fee)} \end{aligned}$$

Appendix O: Cash flow tables

Table 45: Landfill EoL treatment cash flow table over 15 years

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$578,677.82															
Working Capital	WC	-\$86,801.67															\$86,801.67
Total Capital	TC	\$665,479.50															
Borrowed Capital	BC	\$332,739.75															-\$332,739.75
Equity Capital	EC	\$332,739.75															
Salvage Value	SV																\$47,973.29
Revenue	R		\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Expenses	E		\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27	\$102,900.27
Interest on Borrowed capital	I		\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99	\$16,636.99
Profit before Tax	PT		-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26	-\$119,537.26
Depreciation (straight line method)	D		-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74	-\$41,776.74
Taxable Profit	TP		-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51	-\$77,760.51
Tax	T		\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94	\$21,772.94
Net Profit	NP		-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20	-\$141,310.20
Cash Flow		-\$332,739.75	-\$474,049.95	-\$615,360.15	-\$756,670.35	-\$897,980.55	-\$1,039,290.75	-\$1,180,600.95	-\$1,321,911.15	-\$1,463,221.35	-\$1,604,531.55	-\$1,745,841.75	-\$1,887,151.95	-\$2,028,462.15	-\$2,169,772.35	-\$2,311,082.54	-\$2,650,357.53

Table 46: Composting EoL treatment cash flow table over 15 years

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$572,770															
Working Capital	WC	-\$85,916															\$85,916
Total Capital	TC	\$658,686															
Borrowed Capital	BC	\$329,343															-\$329,343
Equity Capital	EC	\$329,343															
Salvage Value	SV																\$47,484
Revenue	R		\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679	\$2,679
Expenses	E		\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976	\$44,976
Interest on Borrowed capital	I		\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,467	\$16,637	\$16,637	\$16,637	\$16,637	\$16,637
Profit before Tax	PT		-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,764	-\$58,934	-\$58,934	-\$58,934	-\$58,934	-\$58,934
Depreciation (straight line method)	D		\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019	\$35,019
Taxable Profit	TP		-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,783	-\$93,953	-\$93,953	-\$93,953	-\$93,953	-\$93,953
Tax	T		-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,259	-\$26,307	-\$26,307	-\$26,307	-\$26,307	-\$26,307
Net Profit	NP		-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,505	-\$32,627	-\$32,627	-\$32,627	-\$32,627	-\$32,627
Cash Flow		-\$329,343	-\$361,847	-\$394,352	-\$426,857	-\$459,361	-\$491,866	-\$524,371	-\$556,875	-\$589,380	-\$621,885	-\$654,389	-\$687,016	-\$719,643	-\$752,270	-\$784,897	-\$1,013,468

Table 47: Anaerobic digestion EoL treatment cash flow table over 15 years when the biogas is burnt, and the heat is sold

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$2,136,279															
Working Capital	WC	-\$320,442															\$320,442
Total Capital	TC	\$2,456,720															
Borrowed Capital	BC	\$1,228,360															-\$1,228,360
Equity Capital	EC	\$1,228,360															
Salvage Value	SV																\$177,101
Revenue	R		\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756	\$756
Expenses	E		\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919
Interest on Borrowed capital	I		\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418
Profit before Tax	PT		-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581	-\$172,581
Depreciation (straight line method)	D		-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225
Taxable Profit	TP		-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355	-\$18,355
Tax	T		-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140	-\$5,140
Net Profit	NP		-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441	-\$167,441
Cash Flow		-\$1,228,360	-\$1,395,801	-\$1,563,243	-\$1,730,684	-\$1,898,125	-\$2,065,566	-\$2,233,007	-\$2,400,448	-\$2,567,890	-\$2,735,331	-\$2,902,772	-\$3,070,213	-\$3,237,654	-\$3,405,095	-\$3,572,536	-\$4,470,795

Table 48: Anaerobic digestion EoL treatment cash flow table over 15 years when the digestate solids are composted and sold

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$2,136,279															
Working Capital	WC	-\$320,442															\$320,442
Total Capital	TC	\$2,456,720															
Borrowed Capital	BC	\$1,228,360															-\$1,228,360
Equity Capital	EC	\$1,228,360															
Salvage Value	SV																\$177,101
Revenue	R			\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013	\$2,013
Expenses	E			\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919
Interest on Borrowed capital	I			\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418
Profit before Tax	PT			-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324	-\$171,324
Depreciation (straight line method)	D			-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225
Taxable Profit	TP			-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099	-\$17,099
Tax	T			-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788	-\$4,788
Net Profit	NP			-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536	-\$166,536
Cash Flow		-\$1,228,360	-\$1,394,897	-\$1,561,433	-\$1,727,970	-\$1,894,506	-\$2,061,043	-\$2,227,579	-\$2,394,116	-\$2,560,652	-\$2,727,188	-\$2,893,725	-\$3,060,261	-\$3,226,798	-\$3,393,334	-\$3,559,871	-\$4,457,225

Table 49: Anaerobic digestion EoL treatment cash flow table over 15 years when the biogas is burnt, and the heat is sold & the digestate solids are composted and sold

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$2,136,279															
Working Capital	WC	-\$320,442															\$320,442
Total Capital	TC	\$2,456,720															
Borrowed Capital	BC	\$1,228,360															-\$1,228,360
Equity Capital	EC	\$1,228,360															
Salvage Value	SV																\$177,101
Revenue	R		\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769	\$2,769
Expenses	E		\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919	\$111,919
Interest on Borrowed capital	I		\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418	\$61,418
Profit before Tax	PT		-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568	-\$170,568
Depreciation (straight line method)	D		-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225	-\$154,225
Taxable Profit	TP		-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343	-\$16,343
Tax	T		-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576	-\$4,576
Net Profit	NP		-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992	-\$165,992
Cash Flow		-\$1,228,360	-\$1,394,352	-\$1,560,345	-\$1,726,337	-\$1,892,329	-\$2,058,321	-\$2,224,313	-\$2,390,305	-\$2,556,297	-\$2,722,290	-\$2,888,282	-\$3,054,274	-\$3,220,266	-\$3,386,258	-\$3,552,250	-\$4,449,060

Table 50: Incineration EoL treatment cash flow table over 15 years when the ash is sent to landfill including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$3,081,528															
Working Capital	WC	-\$462,229															\$462,229
Total Capital	TC	\$3,543,758															
Borrowed Capital	BC	\$1,771,879															-\$1,771,879
Equity Capital	EC	\$1,771,879															
Salvage Value	SV																\$389,551
Revenue	R		\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732	\$3,732
Expenses	E		\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083	\$116,083
Interest on Borrowed capital	I		\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594
Profit before Tax	PT		-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946	-\$200,946
Depreciation (straight line method)	D		\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465	\$173,465
Taxable Profit	TP		-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411	-\$380,411
Tax	T		-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515	-\$106,515
Net Profit	NP		-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431	-\$94,431
Cash Flow		-\$1,771,879	-\$1,866,309	-\$1,960,740	-\$2,055,171	-\$2,149,601	-\$2,244,032	-\$2,338,463	-\$2,432,893	-\$2,527,324	-\$2,621,754	-\$2,716,185	-\$2,810,616	-\$2,905,046	-\$2,999,477	-\$3,093,907	-\$4,108,437

Table 51: Incineration EoL treatment cash flow table over 15 years when the ash is land-spread including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	~\$3,081,528															
Working Capital	WC	~\$462,229															\$462,229
Total Capital	TC	\$3,543,758															
Borrowed Capital	BC	\$1,771,879															~\$1,771,879
Equity Capital	EC	\$1,771,879															
Salvage Value	SV																\$389,551
Revenue	R		\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169	\$4,169
Expenses	E		\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559	\$120,559
Interest on Borrowed capital	I		\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594	\$88,594
Profit before Tax	PT		~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984	~\$204,984
Depreciation (straight line method)	D		\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465	\$179,465
Taxable Profit	TP		~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449	~\$384,449
Tax	T		~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646	~\$107,646
Net Profit	NP		~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338	~\$97,338
Cash Flow		~\$1,771,879	~\$1,869,217	~\$1,966,555	~\$2,063,893	~\$2,161,230	~\$2,258,568	~\$2,355,906	~\$2,453,244	~\$2,550,582	~\$2,647,920	~\$2,745,258	~\$2,842,596	~\$2,939,933	~\$3,037,271	~\$3,134,609	~\$4,152,046

Table 52: Pyrolysis EoL treatment cash flow table over 15 years when biochar is sold as fuel at \$10/GJ including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	~\$1,736,774															
Working Capital	WC	~\$260,516															\$260,516
Total Capital	TC	\$1,997,291															
Borrowed Capital	BC	\$998,645															~\$998,645
Equity Capital	EC	\$998,645															
Salvage Value	SV																\$278,068
Revenue	R		\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740	\$4,740
Expenses	E		\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378
Interest on Borrowed capital	I		\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932
Profit before Tax	PT		~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570	~\$139,570
Depreciation (straight line method)	D		\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247
Taxable Profit	TP		~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817	~\$236,817
Tax	T		~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309	~\$66,309
Net Profit	NP		~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261	~\$73,261
Cash Flow		~\$998,645	~\$1,071,906	~\$1,145,168	~\$1,218,429	~\$1,291,690	~\$1,364,951	~\$1,438,212	~\$1,511,473	~\$1,584,734	~\$1,657,995	~\$1,731,256	~\$1,804,517	~\$1,877,779	~\$1,951,040	~\$2,024,301	~\$2,557,623

Table 53: Pyrolysis EoL treatment cash flow table over 15 years when biochar is sold as fuel at \$675/t of biochar including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$1,736,774															
Working Capital	WC	-\$260,516															\$260,516
Total Capital	TC	\$1,997,291															
Borrowed Capital	BC	\$998,645															-\$998,645
Equity Capital	EC	\$998,645															
Salvage Value	SV																\$278,068
Revenue	R		\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882	\$5,882
Expenses	E		\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378
Interest on Borrowed capital	I		\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932
Profit before Tax	PT		-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428	-\$138,428
Depreciation (straight line method)	D		\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247
Taxable Profit	TP		-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675	-\$235,675
Tax	T		-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989	-\$65,989
Net Profit	NP		-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439	-\$72,439
Cash Flow		-\$998,645	-\$1,071,084	-\$1,143,523	-\$1,215,962	-\$1,288,401	-\$1,360,840	-\$1,433,279	-\$1,505,718	-\$1,578,157	-\$1,650,596	-\$1,723,035	-\$1,795,474	-\$1,867,913	-\$1,940,352	-\$2,012,791	-\$2,545,290

Table 54: Pyrolysis EoL treatment cash flow table over 15 years when biochar is land-spread including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$1,736,774															
Working Capital	WC	-\$260,516															\$260,516
Total Capital	TC	\$1,997,291															
Borrowed Capital	BC	\$998,645															-\$998,645
Equity Capital	EC	\$998,645															
Salvage Value	SV																\$278,068
Revenue	R		\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092	\$4,092
Expenses	E		\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378
Interest on Borrowed capital	I		\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932
Profit before Tax	PT		-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218	-\$140,218
Depreciation (straight line method)	D		\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247
Taxable Profit	TP		-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466	-\$237,466
Tax	T		-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490	-\$66,490
Net Profit	NP		-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728	-\$73,728
Cash Flow		-\$998,645	-\$1,072,373	-\$1,146,101	-\$1,219,830	-\$1,293,558	-\$1,367,286	-\$1,441,014	-\$1,514,742	-\$1,588,470	-\$1,662,198	-\$1,735,926	-\$1,809,654	-\$1,883,382	-\$1,957,110	-\$2,030,839	-\$2,564,627

Table 55: Pyrolysis EoL treatment cash flow table over 15 years when biochar is land-spread, and carbon sink value added including the landfill avoidance fee

Item	Symbol	Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8	Year 9	Year 10	Year 11	Year 12	Year 13	Year 14	Year 15
Fixed Capital	FC	-\$1,736,774															
Working Capital	WC	-\$260,516															\$260,516
Total Capital	TC	\$1,997,291															
Borrowed Capital	BC	\$998,645															-\$998,645
Equity Capital	EC	\$998,645															
Salvage Value	SV																\$278,068
Revenue	R		\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475	\$4,475
Expenses	E		\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378	\$94,378
Interest on Borrowed capital	I		\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932	\$49,932
Profit before Tax	PT		-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835	-\$139,835
Depreciation (straight line method)	D		\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247	\$97,247
Taxable Profit	TP		-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082	-\$237,082
Tax	T		-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383	-\$66,383
Net Profit	NP		-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452	-\$73,452
Cash Flow		-\$998,645	-\$1,072,098	-\$1,145,550	-\$1,219,002	-\$1,292,454	-\$1,365,906	-\$1,439,359	-\$1,512,811	-\$1,586,263	-\$1,659,715	-\$1,733,167	-\$1,806,620	-\$1,880,072	-\$1,953,524	-\$2,026,976	-\$2,560,489

Appendix P: Interview questions

Interview 1

1. What cultural considerations need to be considered in research projects?
2. What are the benefits of including cultural considerations in projects?
3. What would be a cultural measure of success?
4. How can te ao Māori (the Māori worldview) inform this project?
5. What are the Māori ideals, principles, or views relevant to this project?
6. Can some of the Māori principles be grouped together?
7. Do you think it would be helpful if a quantitative analysis of the principles by rating or weighting each one and then summing the results?
8. Would this weighting of the principles added into a matrix for each EoL treatment benefit the project's purpose?
9. Looking at each consequential diagram, what do you think the impacts of each are in relation to Māori principles?
10. On a separate note, do you have any ideas on what social impacts could benefit this project?

Interview 2

1. Do these described values seem appropriate to represent those upheld by the Māori people? Do you have any comments on these?
2. To what extent does the landfill EoL treatment uphold each of these values?
3. To what extent does the composting EoL treatment uphold each of these values?
4. To what extent does the anaerobic digestion EoL treatment uphold each of these values?
5. To what extent does the incineration EoL treatment uphold each of these values?
6. To what extent does the pyrolysis EoL treatment uphold each of these values?